Greenhouse Gas Emissions Standards for Heavy-Duty Vehicles: Phase 3

Regulatory Impact Analysis

United States
Environmental Protection
Agency

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Assessment and Standards Division
Office of Transportation and Air Quality
U.S. Environmental Protection Agency

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Executive Summary

The Environmental Protection Agency (EPA) is promulgating new greenhouse gas (GHG) emissions standards for model year (MY) 2032 and later heavy-duty highway vehicles that phase in starting as early MY 2027 for certain vehicle categories. The phase in revises certain MY 2027 GHG standards that were established previously under EPA's Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles - Phase 2 rule ("HD GHG Phase 2"). Although there have been significant emissions reductions achieved by previous rulemakings, GHG emissions from HD vehicles continue to adversely impact public health and welfare, and there is a critical need for further GHG reductions. The transportation sector is the largest U.S. source of GHG emissions, representing 29 percent of total GHG emissions.[1] Within the transportation sector, heavy-duty vehicles are the second largest contributor to GHG emissions and are responsible for 25 percent of GHG emissions in the sector.[2] GHG emissions have significant impacts on public health and welfare as evidenced by the well-documented scientific record and as set forth in EPA's Endangerment and Cause or Contribute Findings under Section 202(a) of the CAA.[3] Additionally, major scientific assessments continue to be released that further advance our understanding of the climate system and the impacts that GHGs have on public health and welfare both for current and future generations.

We estimate this rule will achieve approximately 1 billion metric tons in net CO_{2}-equivalent emission reductions from 2027 through 2055 and would continue to provide reductions thereafter. These anticipated GHG emission reductions will make an important contribution to efforts to limit climate change and its anticipated impacts benefiting all U.S. residents, including populations such as people of color, low-income populations, tribes and Indigenous communities, and/or children that may be especially vulnerable to various forms of damages associated with climate change. In our modeled potential compliance pathway, we project that manufacturers' compliance with the final GHG emission standards will lead to an increase in HD ZEVs relative to our reference case (i.e., without the rule), which will also result in downstream reductions of vehicle emissions of non-GHG pollutants that contribute to ambient concentrations of ozone, particulate matter ($PM_{2.5}$), nitrogen dioxide (NO_2), CO, and air toxics. Exposure to these non-GHG pollutants is linked to adverse human health impacts such as premature death as well as other adverse public health and environmental effects.

The health and environmental effects associated with GHG emissions are a classic example of a negative externality (an activity that imposes uncompensated costs on others). With a negative externality, an activity's social cost (the cost borne to society imposed as a result of the activity taking place) exceeds its private cost (the cost to those directly engaged in the activity). In this case, as described below and in Chapter 5, GHG emissions from heavy-duty vehicles impose public health and environmental costs on society. However, these added costs are not reflected in the costs of those using these vehicles. The current market and regulatory scheme do not correct this externality because firms in the market are rewarded for minimizing their production costs, including the costs of pollution control, and do not benefit from reductions in emissions. In

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[1] EPA (2023). Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2021 (EPA-430-R-23-002, published April 2023).

[2] *Id*.

[3] 74 FR 66496, December 15, 2009; *see also* 81 FR 54422, August 15, 2016.

addition, firms that may take steps to reduce air pollution may find themselves at a competitive disadvantage compared to firms that do not. The GHG emission standards that EPA is finalizing help address this market failure and reduce the negative externality from these emissions by providing a regulatory incentive for vehicle manufacturers to produce engines that emit fewer harmful pollutants and for vehicle owners to use those cleaner engines.

This Regulatory Impact Analysis (RIA) contains supporting documentation for the EPA final rulemaking and addresses requirements in Clean Air Act Section 317 and requirements under Executive Order (E.O.) 12866 to estimate the benefits and costs of major new pollution control regulations. The preamble to the Federal Register notice associated with this document provides the full context for the EPA final rule, including statutory and executive order reviews in Section X, and it references this RIA throughout.

This document contains the following Chapters:

Chapter 1 Industry Characterization and Technologies to Reduce Greenhouse Gas Emissions

This chapter provides an overview of the HD industry, GHG-reducing technologies, and market information for each of the affected industries for background information purposes. To assess the impacts of GHG regulations upon the affected industries, it is important to understand the nature of the industries impacted by the regulations. These industries include the manufacturers of Class 2b/3 incomplete vehicles through Class 8 trucks, engines, and on-road equipment. Users of these vehicles, including large fleets and corporations, have become increasingly interested in incorporating GHG-reducing technologies for internal combustion engine (ICE)-powered vehicles (e.g., hybrids, hydrogen ICEs) and zero-emission vehicles (ZEVs) into their operation – and technologies for vehicles with ICE, along with a range of electrification, exist today and continue to evolve to further reduce and eliminate exhaust emissions from new motor vehicles. We discuss these technologies in detail in this chapter.

Chapter 2 Technology Assessment

This chapter describes the operational characteristics and costs that we used to estimate the heavy-duty technologies' feasibility and suitability and the analysis for the modeled potential compliance pathway's technology package that supports the feasibility of the final standards for MYs 2027 through 2032. Our analysis for this final rule further shows that a diverse range of HD vehicle technologies are feasible and may be used to comply with the final standards to reduce GHG emissions, including ICE (including alternative-fueled), hybrid, and plug-in hybrid vehicle technologies, hydrogen-fueled ICE technologies (H2 ICE), BEV technologies, and FCEV technologies. To conduct the analysis, EPA developed a flexible spreadsheet-based framework called the Heavy-Duty Technology Resource Use Case Scenario (HD TRUCS) tool.

HD TRUCS evaluates the design features needed to meet the energy and power demands of various HD vehicle types. To build technology packages using HD TRUCS, we created 101 representative vehicles in HD TRUCS that cover the full range of weight classes within the scope of the final standards (Class 2b through 8 vocational vehicles and tractors). The representative vehicles cover many aspects of work performed by the industry. This work was translated into total energy and power demands per vehicle type based on everyday use of HD vehicles, ranging from moving goods and people to mixing cement. We then identified the technical properties and costs required to meet the vehicles' operational needs using GHG-reducing technologies under the final standards.

Chapter 3 Program Costs

This chapter presents estimates of the technology package, manufacturer, consumer, and social costs. In addition, the manufacturer and consumer cost analyses quantitatively include three tax credits from the Inflation Reduction Act as appropriate, specifically the battery tax credit under section 13502 (for both manufacturer and consumer costs), the vehicle tax credit under section 13403 (for consumer costs), and electric vehicle supply equipment (EVSE) tax credit under section 13404 (for consumer costs). The technology package costs are presented as direct manufacturing costs and associated indirect costs, which together represent the estimated costs incurred by manufacturers (i.e., regulated entities) to comply with the final standards.

Chapter 4 Emission Inventories

This chapter presents our analysis of the national emissions impacts of GHGs from the final rule for calendar years 2027 through 2055 from both downstream and some upstream sources. We estimated onroad downstream national inventories using an updated version of EPA's Motor Vehicle Emission Simulator (MOVES) model (MOVES4.R3), and we estimated upstream emissions sources using the 2022 post-IRA version of the Integrated Planning Model (IPM) combined with our estimate of the final rule's impacts on refinery emissions.

Chapter 5 Health and Environmental Impacts

This chapter presents a discussion of the climate change impacts of GHGs; health and environmental effects associated with exposure to ambient concentrations of non-GHG pollutants; as well as environmental justice impacts from the emissions changes associated with the final rulemaking. The discussion of health impacts is mainly focused on describing the effects of air pollution on the population in general. Additionally, children are recognized to have increased vulnerability and susceptibility related to air pollution and other environmental exposures; this and effects for other vulnerable and susceptible groups are discussed in this chapter.

Chapter 6 Economic and Other Impacts

This chapter discusses potential impacts of the final rule on vehicle sales including potential shifts among modes and classes of vehicles, and between domestic and foreign sales. It also discusses the acceptance of GHG-reducing technologies by HD purchasers and the potential for rebound effects on vehicle miles traveled. This chapter then discusses the potential impacts of the final rule on employment. Finally, this chapter discusses the impacts of the final rule on U.S. oil imports and electricity consumption.

Chapter 7 Benefits

This chapter describes benefits attributable to the final rule from three sources: climate benefits, criteria pollutant health benefits, and energy security benefits. We estimate the social benefits of GHG reductions expected to occur as a result of the final standards using estimates of the social cost of greenhouse gases (SC-GHG), specifically using the social cost of carbon (SC-CO_2), social cost of methane (SC-CH_4), and social cost of nitrous oxide (SC-N_2O). We monetize the economic benefits from improvements in human health resulting from criteria pollutant emissions reductions using $PM_{2.5}$-related benefit-per-ton values. This chapter also describes energy security impacts, including monetized benefits, associated with an expected reduction in demand for liquid fuels.

Chapter 8 Net Benefits

This chapter compares the estimated range of total benefits to total costs associated with the final rule. Benefits include those associated with reductions of GHGs, monetized health benefits from changes in $PM_{2.5}$, energy security benefits, fuel savings, and vehicle-related operational savings. Total costs include costs for both new technology and the operating costs associated with that new technology. The chapter presents three different methods for comparing benefits to costs.

Chapter 9 Small Business Analysis

This chapter presents an analysis of the potential impacts of the final rule on small entities that will be subject to the HD vehicle provisions of this final rule. The small businesses considered in this analysis include manufacturers of the following types: heavy-duty conventional vehicles and heavy-duty electric vehicles. The analysis estimates that no small entities in these manufacturer categories will experience an impact of 3% or more of their annual revenue as a result of our final rule.

Chapter 1 Industry Characterization and Technologies to Reduce GHG Emissions

1.1 Introduction

To assess the impacts of the final greenhouse gas (GHG) regulations upon the affected industries, it is important to understand the nature of the industries impacted by the regulations. These industries include the manufacturers of Class 2b/3 incomplete vehicles[4] through Class 8 trucks, engines, and on-road equipment. Users of these vehicles, including large fleets and corporations, have become increasingly interested in incorporating highway heavy-duty (HD) vehicles using zero emissions vehicle (ZEV) technologies into their operations. To meet this demand, many HD vehicle manufacturers and suppliers have been conducting research on battery electric vehicle (BEV) technologies and hydrogen fuel cell electric vehicle (FCEV) technologies. Initial vehicles from this research investment are now entering the market. Adoption of these ZEVs requires the establishment of HD vehicle charging and hydrogen refueling infrastructure. This chapter provides an overview of the heavy-duty industry, an overview of GHG-reducing technologies, and market information for each of the affected industries for background information purposes.

1.2 Heavy-duty Vehicle Industry

Heavy-duty vehicles perform many different types of work including moving people and goods, cleaning streets, and providing access to fix utilities. Here we focus on the size of the goods-moving market to highlight the importance and impact of the sector.

1.2.1 Freight Work Performed by and Operation of Heavy-duty Trucks

In 2021, heavy-duty trucks carried 65 percent of all freight moved in the U.S. by tonnage and 63 percent by value in the U.S, and heavy-duty trucks are expected to move freight at an even greater rate in the future. According to the U.S. Department of Transportation's (DOT's) Federal Highway Administration (FHWA), the U.S. transportation system moved, on average, an estimated 53.6 million tons of goods worth an estimated $54 billion (in U.S. 2021$) per day in 2021. Of this, heavy-duty trucks moved over 12 billion tons of freight worth an estimated $11 trillion in 2021, or an average of nearly 33 million tons of freight worth $30 billion per day. The FHWA's 2022 Freight Analysis Framework estimates that this tonnage will increase about 1.6 percent per year from 2023 to 2050, and that the value of the freight moved is increasing faster

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[4] Complete heavy-duty vehicles at or below 14,000 lbs. GVWR are chassis-certified under 40 CFR part 86, while incomplete vehicles at or below 14,000 lbs. GVWR may be certified to either 40 CFR part 86 (meeting standards under subpart S) or 40 CFR part 1037 (installed engines would then need to be certified under 40 CFR part 1036). Class 2b and 3 vehicles are primarily chassis-certified complete commercial pickup trucks and vans. We separately proposed a combined light-duty and medium-duty rulemaking to set more stringent standards for complete and incomplete vehicles at or below 14,000 lbs. GVWR that are certified under 40 CFR part 86, subpart S. The standards finalized in this rule will apply for all heavy-duty vehicles above 14,000 lbs. GVWR, except as noted in 40 CFR 1037.150(l). The final standards in this rule will also apply for incomplete heavy-duty vehicles at or below 14,000 lbs. GVWR if vehicle manufacturers opt to certify those vehicles under 40 CFR part 1037 instead of certifying under 40 CFR part 86, subpart S.

than the tons transported. Figure 1-1 shows the total tons of freight moved by each mode of freight transportation in 2021, and projections for 2030 and 2050.[5]

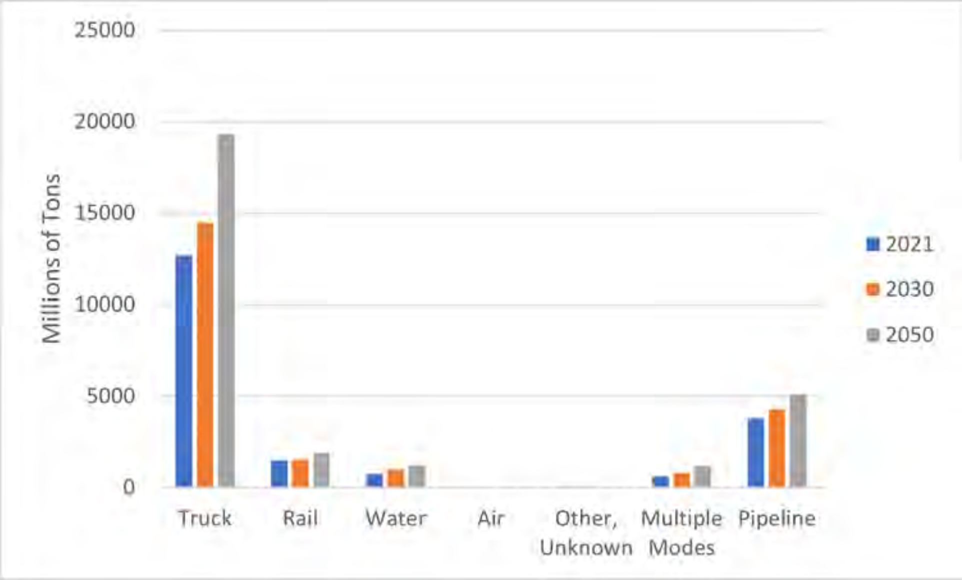

Figure 1-1 Total Weight of Shipments by Transportation Mode

According to the 2020 Highway Statistics published by the U.S. FHWA,[6] in 2020 there were just over 2.9 million combination tractors (e.g. Class 7 and 8) registered in the U.S out of a total of over 13 million trucks of all types (private and commercial) registered in the U.S. Table 1-1 presents the number of trucks compared to the number of vessels and other modes of transportation that move freight.[6]

Table 1-1 Number of U.S. Vehicles, Vessels, and Other Conveyances: 2000-2020

Mode of Transportation	Classification	2000	2010	2020
Highway	Trucks	8,022,649	10,770,054	13,479,382
	Trucks, single-unit 2-axle 6-tire or more	5,926,030	8,217,189	10,500,105
	Trucks, combination	2,096,619	2,552,865	2,979,277
	Total highway vehicles	225,821,241	250,070,048	275,924,442
Rail	Locomotive, Class 1	20,028	23,893	23,544
	Freight cars, total	1,380,796	1,309,029	1,658,423
	Freight cars, Class	560,154	397,730	252,400
	Freight cars, Nonclass	132,448	101,755	
	Freight cars, car companies and shippers	688,194	809,544	
Water	Nonself-propelled vessels	31,372	30,265	34,168
	Self-propelled vessels	9,293	9,618	10,333
	Total vessels	40,665	39,883	44,501

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[5] U.S. Department of Transportation, Bureau of Transportation Statistics, Freight Facts and Figures 2022. Available online: https://data.bts.gov/stories/s/Moving-Goods-in-the-United-States/bcyt-rqmu.

[6] U.S. Department of Transportation, Bureau of Transportation Statistics, Freight Facts and Figures 2020. “Number of trucks, locomotives, rail cars, and vessels” Available online: https://data.bts.gov/stories/s/Freight-Transportation-System-Extent-Use/r3vy-npqd.

In terms of growing international trade, trucks are the most common mode used to move imports and exports between both borders and inland locations. Table 1-2 shows the tons and value moved by truck compared to other transportation methods.

Table 1-2 Domestic Mode of Exports and Imports by Tonnage and Value from 2020-2055[7]

Domestic Mode	Tons (thousands)			Value (millions of 2017 $)		
	2020	**2030**	**2050**	**2020**	**2030**	**2050**
Grand Total	2,308,598	2,891,495	3,979,273	3,599,583	4,866,814	7,861,618
Truck	956,117	1,154,776	1,759,076	2,318,916	3,060,420	5,041,065
Rail	425,270	493,251	764,314	323,598	397,136	655,231
Water	182,221	290,304	382,976	76,488	133,005	190,200
Air (including truck-air)	4,401	5,363	8,806	458,346	614,850	1,012,423
Multiple modes and mail	132,907	181,206	269,643	226,276	386,166	644,729
Pipeline	484,425	632,470	688,627	146,840	182,538	197,914
Other and unknown	3,262	10,317	17,135	10,786	52,763	91,445
No domestic mode	119,995	123,808	88,696	38,334	39,937	28,611

Conversely, transportation of foreign trade is dominated by movement via water with trucks hauling approximately 11 percent of imported freight followed by pipeline and rail. As of 2022, Canada was the top trading partner with the U.S. in terms of the value of the merchandise traded ($361 billion in U.S. 2017$), Mexico was second ($219 billion in U.S. 2017$), Japan was third ($188 billion in U.S. 2017$). Truck traffic is the most heavily utilized transportation mode from the two North American trade partners, Mexico, and Canada. As of 2021, almost 63 percent of the value and over 29 percent of the total imported and exported freight moved between the U.S., Canada, and Mexico was hauled by truck, as shown in Figure 1-2.[8]

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[7] U.S. Department of Transportation, Bureau of Transportation Statistics, Freight Facts and Figures 2022. Available online: https://data.bts.gov/stories/s/Moving-Goods-in-the-United-States/bcyt-rqmu.

[8] U.S. Department of Transportation, Bureau of Transportation Statistics 2019. Available online: https://data.bts.gov/stories/s/International-Freight-Gateways/4s7k-yxvu.

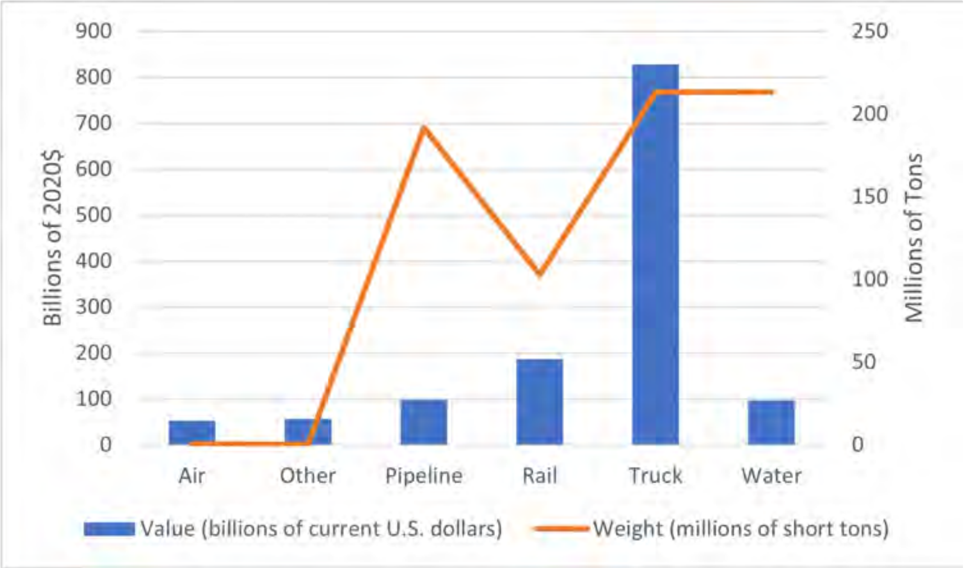

Figure 1-2 Value of Freight Moved Between the U.S., Canada, and Mexico

1.2.2 Existing Heavy-Duty Truck Market Benchmarking

The heavy-duty vehicle segment is a dynamic industry that includes a variety of types of vehicles and possible configurations. This final program will address heavy-duty vehicles that fall into the following regulatory categories established by EPA: vocational vehicles in Classes 2b–8 and tractors in Classes 7 and 8.

Class 2b and 3 vocational vehicles at issue in this final program include certain incomplete[9] pickups, incomplete vans, and vocational vehicles such as heavy-duty work truck-type pickups and related van-type vehicles that are in a limited build configuration and ready to receive final outfitting by body building companies. The latter case involves the manufacture of vehicles that may be used for a variety of commercial purposes, including use as ambulances, shuttle buses, etc. Class 4–8 vocational vehicles encompass a wide range of heavy-duty vehicles such as delivery trucks, school buses, etc. Combination tractors typically operate as either short-haul or long-haul trucks. Combination tractors are designed either with sleeping quarters (sleeper cab) or without sleeping quarters (day cab). Generally, day cab tractors are used to haul trailers over shorter distances, typically into metropolitan areas. Sleeper cab tractors generally haul trailers longer distances between cities and states with trips well over 1,000 miles in length.

To understand the existing heavy-duty industry, we performed an analysis of current internal combustion engine (ICE) powered heavy-duty vehicles in the market and their capabilities to generate typical power requirements and rates of energy consumption. This information was then used to help inform our decisions on technical feasibilities of HD vehicle technologies, including

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[9] As explained and defined in 40 CFR 1037.801, the primary use of the term “incomplete vehicle” is to distinguish whether a vehicle is complete when it is first sold as a vehicle, where an incomplete vehicle is defined as not a complete vehicle and a complete vehicle is defined as a functioning vehicle that has the primary load carrying device or container (or equivalent equipment) attached. Incomplete vehicles may also be cab-complete vehicles.

zero-emission vehicle (ZEV) technologies,[10] to include in the technology packages for the final program (which form a potential compliance pathway to demonstrate the feasibility of the final GHG emission standards) using an internally developed tool discussed in detail in RIA Chapter 2.

We selected 76 ICE vehicles that represent much of the heavy-duty industry and that also had similar ZEV options available in MY 2021. Some of these vehicle types can be used for multiple duty cycles. Table 1-3 lists the publicly available information collected to benchmark basic powertrain and performance criteria including make; model; vehicle type; weight class; fuel type; engine manufacturer, model, displacement, mass, power, and torque; transmission make, model, and mass; fuel tank size; mass of fuel; Diesel Exhaust Fluid (DEF) tank size; mass of DEF; total mass of the engine, transmission, fuel, and DEF; vehicle minimum wheelbase; and vehicle width.

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[10] We use the term ZEV to refer to technologies that result in zero tailpipe emissions. Example ZEV technologies include battery electric vehicles and fuel cell vehicles.

Table 1-3 Benchmarked Conventional Vehicles with Similar ZEV Options

Vehicle			Engine						Transmission			Fuel			DEF		Total System Mass (kg)	Min. Wheel-base (m)	Vehicle Width (m)
Model	Type	Wgt Class	MFR	Model	Disp (L)	Mass (kg)	Power (kW)	Torque (Nm)	MFR	Model	Mass (kg)	Type	Tank Size (L)	Mass (kg)	Tank Size (L)	Mass (kg)			
Vision	School Bus	7	Ford	NA	7.3	281	261	635	Ford	6R140	141	Propane	254	129	NA	NA	551	4.3	2.4
Vision	School Bus	7	Ford	NA	7.3	281	261	635	Ford	6R140	141	Gas	227	171	NA	NA	593	4.3	2.4
Vision	School Bus	7	Cummins	B6.7	6.7	485	194	895	Allison	3000	243	Diesel	227	193	57	232	1153	4.3	2.4
All American	School Bus	7, 8	Cummins	B6.7	6.7	485	224	895	Allison	3000	243	Diesel	227	193	57	232	1153	3.6	2.4
All American	School Bus	7, 8	Cummins	L9	9	769	224	1166	Eaton	Procision	165	Diesel	227	193	57	232	1359	3.6	2.4
All American	School Bus	7, 8	Cummins	ISL-G	9	469	209	1220	Allison	3000	243	NG	235	159	NA	NA	1171	3.6	2.4
Micro Bird G5	School Bus	3, 4	Chevy	NA	6.6	NA	299	629	NA	NA	NA	Gas	121	91	NA	NA	91	3.5	2.4
Micro Bird G5	School Bus	3, 4	Ford	NA	7.3	281	261	635	Ford	6R140	141	Gas	151	114	NA	NA	536	3.5	2.4
Axess 35'	Transit Bus	8	Cummins	L9	9	769	224	1166	Allison	B400R	297	Diesel	454	386	NA	NA	1452	5.5	2.6
Axess 35'	Transit Bus	8	Cummins	L9N	9	769	209	1220	Allison	B400R	297	NG	NA	NA	NA	NA	1066	5.5	2.6
Axess 40'	Transit Bus	8	Cummins	L9	9	769	224	1166	Allison	B400R	297	Diesel	454	386	NA	NA	1452	7	2.6
Axess 40'	Transit Bus	8	Cummins	L9N	9	769	229	1220	Allison	B400R	297	NG	NA	NA	NA	NA	1066	7	2.6
E-Z Rider II 30'	Transit Bus	8	Cummins	B6.7	6.7	485	224	895	Allison	B400R	297	Diesel	303	258	NA	NA	1040	4.1	2.6
E-Z Rider II 30'	Transit Bus	8	Cummins	L9	9	769	224	1166	Allison	B400R	297	Diesel	303	258	NA	NA	1324	4.1	2.6
E-Z Rider II 32'	Transit Bus	8	Cummins	B6.7	6.7	485	224	895	Allison	B400R	297	Diesel	303	258	NA	NA	1040	4.3	2.6
E-Z Rider II 32'	Transit Bus	8	Cummins	L9	9	769	224	1166	Allison	B400R	297	Diesel	303	258	NA	NA	1324	4.3	2.6
E-Z Rider II 35'	Transit Bus	8	Cummins	B6.7	6.7	485	224	895	Allison	B400R	297	Diesel	303	258	NA	NA	1040	5..6	2.6

Engine				Transmission			Fuel			DEF		Total System Mass (kg)	Min. Wheel-base (m)	Vehicle Width (m)	Make
Disp (L)	Mass (kg)	Power (kW)	Torque (Nm)	MFR	Model	Mass (kg)	Type	Tank Size (L)	Mass (kg)	Tank Size (L)	Mass (kg)				
9	769	224	1166	Allison	B400R	297	Diesel	303	258	NA	NA	1324	5.6	2.6	Blue Bird[11]
3.5	204	224	542	Ford	10R140	150	Gas	95	71	NA	NA	425	3.3	2.1	Blue Bird[12]
3.5	204	205	355	Ford	10R140	150	Gas	95	71	NA	NA	425	3.3	2.1	Blue Bird[12]
6.7	499	246	1119	Ford	10R140	150	Diesel	151	129	NA	NA	777	3.7	1.9	Blue Bird[13]
7.3	281	261	635	Ford	10R140	150	Gas	151	114	NA	NA	545	3.7	1.9	Blue Bird[9]
6.7	499	246	1119	Ford	10R140	150	Diesel	151	129	NA	NA	777	3.7	1.9	Blue Bird[9]
7.3	281	261	635	Ford	10R140	150	Gas	151	114	NA	NA	545	3.7	1.9	Blue Bird [14]
6.7	499	246	1119	Ford	10R140	150	Diesel	151	129	NA	NA	777	3.7	1.9	Blue Bird[14]
7.3	281	261	635	Ford	10R140	150	Gas	151	114	NA	NA	545	3.7	1.9	Eldorado National [15]
7.3	281	261	635	Ford	6R140	141	Gas	151	114	NA	NA	536	4	2.3	Eldorado National[15]
7.3	281	261	635	Ford	6R140	141	Gas	303	229	NA	NA	650	4	2.3	Eldorado National[15]
7.3	281	261	635	Ford	6R140	141	Gas	151	114	NA	NA	536	3.5	2	Eldorado National[15]
12.8	1128	377	2508	Detroit Diesel	DT12-HE	295	Diesel	379	322	NA	NA	1745	2.9	1.8	Eldorado national [16]
12.8	1128	391	2508	Detroit Diesel	DT12-HE	295	Diesel	379	322	NA	NA	1745	2.9	1.8	Eldorado National[16]
14.8	1233	377	2373	Detroit Diesel	DT12-HE	295	Diesel	379	322	NA	NA	1850	2.9	1.8	Eldorado National[16]
15.6	1287	447	2779	Detroit Diesel	DT12-HE	295	Diesel	379	322	NA	NA	1904	2.9	1.8	Eldorado National[16]
12	1017	373	2305	Eaton	Endurant	299	Diesel	379	322	NA	NA	1638	2.9	1.8	Eldorado National[16]

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[11] Blue Bird. Brochure: Vision—Propane. 2021. Available online: https://www.blue-bird.com/images/brochures/Propane_Vision_Single_Sheet_2021-0121.pdf.

[12] Blue Bird. Brochure: Vision—Gasoline. 2021. Available online: https://www.blue-bird.com/images/brochures/Gasoline_Vision_Single_Sheet_2021-0121.pdf.

[13] Blue Bird. Brochure: All American. 2018. Available online: https://www.blue-bird.com/images/brochures/allamerican-web-ready.pdf.

[14] Blue Bird. Brochure: Micro Bird G5—School Bus. Available online: https://www.blue-bird.com/images/brochures/G5_School.pdf.

[15] ENC, REV Group. Axess: The Safest Heavy-Duty Workhorse Available. Available online: https://www.eldorado-ca.com/heavy-duty-bus.

[16] ENC, REV Group. E-Z Rider II: The Gold Standard. Available online: https://www.eldorado-ca.com/mid-size-public-bus-transportation.

DEF		Total System Mass (kg)	Min. Wheel-base (m)	Vehicle Width (m)	Vehicle					
Tank Size (L)	Mass (kg)				Make	Model	Type	Wgt Class	MFR	Model
NA	NA	2051	2.9	1.8	Eldorado National[16]	E-Z Rider II 35'	Transit Bus	8	Cummins	L9
NA	NA	1892	2.8	2.6	Ford[17]	Transit	Panel Van	4	Ford	3.5 Ecoboos
NA	NA	1533	2.8	2.6	Ford[17]	Transit	Panel Van	4	Ford	3.5 PFDI
NA	NA	825	4.5	2.4	Ford[18]	F-450	Straight Truck	4	Ford	6.7 Powerst
NA	NA	318	4.5	2.4	Ford[18]	F-450	Straight Truck	4	Ford	NA
NA	NA	536	4	2.5	Ford[19]	F-550	Straight Truck	5	Ford	6.7 Powerst
NA	NA	656	4	2.5	Ford[19]	F-550	Straight Truck	5	Ford	NA
NA	NA	1072	4.1	2.5	Ford[20]	F-600	Straight Truck	6	Ford	6.7 Powerst
NA	NA	1008	4.1	2.5	Ford[20]	F-600	Straight Truck	6	Ford	NA
NA	NA	642	4.5	2.5	Ford[21]	F-53	Panel Van	5, 6	Ford	NA
NA	NA	1040	4.1	2.6	Ford[22]	F-59	Panel Van	5, 6	Ford	NA
NA	NA	1040	4.1	2.6	Ford[23]	E-Series Cutaway	Panel Van	3, 4	Ford	NA
NA	NA	1288	3.3	2.5	Freightliner[24]	Cascadia	Tractor	8	Detroit Diesel	DD13
NA	NA	298	3.3	2.5	Freightliner[25]	Cascadia	Tractor	8	Detroit Diesel	DD13 Gen5
NA	NA	298	3.3	2.5	Freightliner[26]	Cascadia	Tractor	8	Detroit Diesel	DD15
NA	NA	298	3.3	2.5	Freightliner[27]	Cascadia	Tractor	8	Detroit Diesel	DD16
NA	NA	298	3.3	2.5	Freightliner[28]	Cascadia	Tractor	8	Cummins	X12

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[17] Ford. 2023 Transit Cargo Van. Available online: https://www.ford.com/commercial-trucks/transit-cargo-van/models/transit-van/.

[18] Ford. F-450 XL. Available online: https://www.ford.com/commercial-trucks/chassis-cab/models/f450-xl/.

[19] Ford. F-550 XL. Available online: https://www.ford.com/commercial-trucks/chassis-cab/models/f550-xl/.

[20] Ford. F-600 XL. Available online: https://www.ford.com/commercial-trucks/chassis-cab/models/f600-xl/.

[21] Ford. 2022 F-53 Motorhome Stripped Chassis. Available online: https://www.ford.com/commercial-trucks/f-series-stripped-chassis/models/f53-motorhome/.

[22] Ford. 2023 F59 Commercial Stripped Chassis. Available online: https://www.ford.com/commercial-trucks/f-series-stripped-chassis/models/f59-commercial/?gnav=vhpnav-specs.

[23] Ford. 2023 E-450 Stripped Chassis. Available online: https://www.ford.com/commercial-trucks/e-series-stripped-chassis/models/e450-drw/.

[24] Freightliner. The Detroit DD13 Engine: A 13 Liter Powerhouse. Available online: https://freightliner.com/demand-detroit/engines/dd13/.

[25] Freightliner. The Detroit DD13 Gen 5 Engine: The Best Just Got Even Better. Available online: https://freightliner.com/demand-detroit/engines/dd13-gen-5/.

[26] Freightliner. The Detroit DD15 Engine: More Power, Less Weight. Available online: https://freightliner.com/demand-detroit/engines/dd15/.

[27] Freightliner. The Detroit DD16 Engine: Heavy-Duty Power. Available online: https://freightliner.com/demand-detroit/engines/dd16/.

[28] Cummins. Brochure: X12. Available online:https://freightliner.com/cummins-on-highway/.

Vehicle			Engine						Transmission			Fuel		
Model	Type	Wgt Class	MFR	Model	Disp (L)	Mass (kg)	Power (kW)	Torque (Nm)	MFR	Model	Mass (kg)	Type	Tank Size (L)	Mass (kg)
Cascadia	Tractor	8	Cummins	X15	15	1430	373	2508	Eaton	Endurant	299	Diesel	379	322
M2 112	Straight Truck	7, 8	Detroit Diesel	DD13	12.8	1128	377	2508	Eaton	UltraShift Plus VCS	442	Diesel	379	322
M2 112	Straight Truck	7, 8	Cummins	L9	9	769	283	1559	Eaton	UltraShift Plus VCS	442	Diesel	379	322
MT45	Straight Truck	5	Cummins	ISB 6.7	6.7	485	224	895	Allison	2200	147	Diesel	227	193
MT45	Straight Truck	5	GM	NA	6	NA	230	498	Allison	2200	147	Gas	227	171
Trolley	Transit Bus	4	Ford	NA	7.3	281	261	644	Ford	6R140	141	Gas	151	114
Villager	Transit Bus	6, 7	Ford	NA	7.3	281	261	644	Allison	2200	147	Gas	303	229
Mainstreet	Transit Bus	6, 7	Cummins	ISB 6.7	6.7	485	179	759	Allison	B300	197	Diesel	341	290
Streetcar	Transit Bus	7, 8	Cummins	ISB 6.7	6.7	485	179	759	Allison	B300	197	Diesel	265	225
View	Transit Bus	6	Ford	NA	7.3	281	261	644	Allison	2200	147	Gas	284	214
Commuter	Transit Bus	7, 8	Cummins	ISB 6.7	6.7	485	179	759	Allison	B400R	297	Diesel	303	258
Urban	Transit Bus	7, 8	Cummins	ISB 6.7	6.7	485	179	759	Allison	B400R	297	Diesel	303	258
Xcient	Straight Truck	8	Hyundai	D6AC	11.2	990	250	1373	NA	NA	NA	Diesel	350	298
Xcient	Straight Truck	8	Hyundai	D6HB38	9.9	NA	280	1569	NA	NA	NA	Diesel	350	298
Xcient	Straight Truck	8	Hyundai	D6HA38	9.9	NA	280	1569	NA	NA	NA	Diesel	350	298
Xcient	Straight Truck	8	Hyundai	D6HA40A	9.9	NA	295	1745	NA	NA	NA	Diesel	350	298
Xcient	Straight Truck	8	Hyundai	D6CB41	12.3	NA	302	1844	NA	NA	NA	Diesel	350	298

Transmission		Fuel			DEF		Total System Mass (kg)	Min. Wheel-base (m)	Vehicle Width (m)	Make
Model	Mass (kg)	Type	Tank Size (L)	Mass (kg)	Tank Size (L)	Mass (kg)				
2550	147	Diesel	114	97	NA	NA	773	3.8	2.1	Freightliner[29]
2100	147	Diesel	170	145	28	116	929	3.7	2.1	Freightliner[30]
2500	147	Diesel	170	145	28	116	929	3.7	2.1	Freightliner[31]
TX12	298	Diesel	379	322	79	325	2079	5.9	2.6	Freightliner[32]
TX12	298	Diesel	379	322	79	325	1942	5.9	2.6	Freightliner[32]
4500	439	Diesel	379	322	NA	NA	1762	4.4	2.5	Hometown Manufacturing [33]
M038S6 Duonic	NA	Diesel	114	97	12	49	146	2.8	2.4	Hometown Manufacturing [34]
NA	NA	Diesel	693	589	NA	NA	1606	8	2.6	Hometown Manufacturing [35]
B500	439	Diesel	723	615	57	232	2302	8	2.6	Hometown Manufacturing [36]
Advantage	245	Diesel	341	290	42	170	1191	3.3	2.1	Hometown Manufacturing [37]
Advantage	245	Diesel	341	290	42	170	1474	3.3	2.1	Hometown Manufacturing [38]
NA	NA	Diesel	95	81	NA	NA	81	3.6	2.4	Hometown Manufacturing [39]
NA	NA	Diesel	379	322	NA	NA	1091	5.8	2.6	Hyundai[40]
Ecolife	354	Diesel	473	402	NA	NA	1525	6.2	2.6	Hyundai[40]
2500	147	Diesel	170	145	NA	NA	813	3.1	2.6	Hyundai[40]
4500	439	Diesel	379	322	NA	NA	1759	NA	2.6	Hyundai[40]
Endurant	299	Diesel	379	322	NA	NA	1755	NA	2.4	Hyundai[40]

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[29] Cummins. X15 Efficiency Series (2020). Available online: https://www.cummins.com/engines/x15-efficiency-series.

[30] Freightliner. Freightliner M2 112 Plus Specs. Available onlinehttps://freightliner.com/trucks/m2-112-plus/specifications/#tab-3.

[31] Cummins. L9 for Medium-Duty (2021). Available online: https://www.cummins.com/engines/l9-2021.

[32] Freightliner—Custom Chassis. MT Power. Available online: https://www.fccccommercial.com/chassis/mt/power/#gaspower.

[33] Hometown Manufacturing. Explore the Carriage. Available online: https://hometown-mfg.com/trolleys/carriage.

[34] Hometown Manufacturing. Explore the Villager—Full Electric Available. Available online: https://hometown-mfg.com/trolleys/villager.

[35] Hometown Manufacturing. Explore the Mainstreet. Available online: https://hometown-mfg.com/trolleys/mainstreet.

[36] Hometown Manufacturing. Explore the Streetcar—Full Electric Available. Available online: https://hometown-mfg.com/trolleys/streetcar.

[37] Hometown Manufacturing. Explore the View—Full Electric Available. Available online: https://hometown-mfg.com/buses/view.

[38] Hometown Manufacturing. Explore the Commuter. Available online: https://hometown-mfg.com/buses/commuter.

[39] Hometown Manufacturing. Explore the Low Floor Urban—Full Electric Available. Available online: https://hometown-mfg.com/buses/urban.

[40] Hyundai. Xcient. Available online: https://trucknbus.hyundai.com/global/en/products/truck/xcient.

Vehicle			Engine						
Model	Type	Wgt Class	MFR	Model	Disp (L)	Mass (kg)	Power (kW)	Torque (Nm)	MFR
NPR-HD	Straight Truck	4	Isuzu	NA	5.2	530	160	613	Allison
K270	Straight Truck	6	PACCAR	PX-7	6.7	522	186	895	Allison
K370	Straight Truck	7	PACCAR	PX-7	6.7	522	186	895	Allison
T680	Tractor	8	PACCAR	MX-13	12.9	1134	380	2508	PACCAR
T680	Tractor	8	PACCAR	MX-11	10.8	998	339	2305	PACCAR
LR	Refuse Truck	8	Mack	MP 7	11	1001	265	1661	Allison
FE180	Straight Truck	5	Fuso	4P10-T5	3	NA	120	400	NA
J4500	Coach Bus	8	Cummins	X12	12	1017	339	2102	NA
D45 CRT	Coach Bus	8	Cummins	X12	12	1017	306	1966	Allison
MV	Straight Truck	8	Cummins	B6.7	6.7	485	149	705	Eaton
MV	Straight Truck	8	Cummins	L9	9	769	194	976	Eaton
CE	Straight Truck	4, 5	International	6.6	6.6	NA	261	949	NA
Xcelsior	Transit Bus	8	Cummins	L9	9	769	194	976	NA
LFS	Transit Bus	8	Cummins	L9	9	769	194	1166	ZF
220	Straight Truck	7, 8	PACCAR	PX-7	6.7	522	186	895	Allison
520	Straight Truck	8	PACCAR	MX-11	10.8	998	339	2305	Allison
579	Tractor	8	PACCAR	MX-13	12.9	1134	380	2508	Eaton

Trans	Fuel			DEF		Total System Mass (kg)	Min. Wheel-base (m)	Vehicle Width (m)	Make
Mass (kg)	Type	Tank Size (L)	Mass (kg)	Tank Size (L)	Mass (kg)				
299	Diesel	379	322	NA	NA	1619	NA	2.4	Isuzu[41]
299	Diesel	379	322	NA	NA	1390	NA	2.4	Kenworth[42]
299	Diesel	379	322	NA	NA	2051	NA	2.4	Kenworth[42]
NA	Diesel	NA	NA	NA	NA	539	4	2.4	Kenworth[43]
NA	Diesel	NA	NA	NA	NA	485	4	2.4	Kenworth[43]
324	Diesel	379	322	NA	NA	1671	3.5	2.3	Mack[44]
324	Diesel	379	322	NA	NA	1828	3.5	2.3	Mitsubishi Fuso [45]
297	Diesel	189	161	23	93	1036	2.9	2.5	Motorcoach Industries [46]
									Motorcoach Industries [47]
									International[48]
									International[49]
									International[50]
									New Flyer [51]
									Nova Bus [52]
									Peterbilt[53]
									Peterbilt[54]
									Peterbilt[55]

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[41] Isuzu. The New 2022i N-Series Diesel—The Trucks to Trust. Available online: https://www.isuzucv.com/en/nseries/nseries_diesel.

[42] Kenworth. Brochure: K270/K370. 2014. Available online: https://kenworth.com/media/z1adxjnb/k270-k370-june-2014.pdf.

[43] Kenworth. T680 Next Gen. Available online: https://kenworth.com/trucks/t680-next-gen/.

[44] Mack. MP7. Available online: https://www.macktrucks.com/powertrain-and-suspensions/engines/mp7/.

[45] Mitsubishi Fuso Truck of America, Inc. Brochure: 2017 FE180. Available online: https://www.mitfuso.com/files/FUSO-FE180-DataSheet-EN-US.pdf.

[46] MCI. Brochure: MCI J-Series. 2021. Available online: https://www.mcicoach.com/site-content/uploads/2021/05/MCI-JSeries-brochure-FINAL-1.pdf.

[47] MCI. Brochure: MCI D45 CRD Specification Sheet. 2021. Available online: https://www.mcicoach.com/site-content/uploads/2021/06/MCI-D45-CRT-2021-07-19.pdf.

[48] International Trucks. MV Series. Available online: https://www.internationaltrucks.com/trucks/mv-series..

[49] International Trucks. Cummins L9. Available online: https://www.internationaltrucks.com/engines/cummins-l9.

[50] International Trucks. Explore the CV Series. Available online: https://www.internationaltrucks.com/trucks/cv-series/detailed-specs.

[51] New Flyer. Clean diesel mobility: Xcelsior Clean Diesel. Available online: https://www.newflyer.com/bus/xcelsior-diesel/.

[52] Nova Bus. Nova LFS Diesel. Available online: https://novabus.com/blog/bus/lfs_diesel/.

[53] Peterbilt. Model 220: Options & Specifications. Available online: https://www.peterbilt.com/trucks/medium-duty/model-220/options-specs.

[54] Peterbilt. Model 520: Brochures. Available online: https://www.peterbilt.com/trucks/vocational/model-520/downloads.

[55] Peterbilt. Model 579: Options & Specifications. Available online: https://www.peterbilt.com/trucks/highway/model-579/options-specs.

Vehicle				Engine							
Make	Model	Type	Wgt Class	MFR	Model	Disp (L)	Mass (kg)	Power (kW)	Torque (Nm)	MFR	Model
Peterbilt[55]	579	Tractor	8	PACCAR	MS-11	10.8	998	339	2305	Eaton	Endurant
Peterbilt[56]	579	Tractor	8	PACCAR	PX-9	8.8	769	336	1695	Eaton	Endurant
Peterbilt[55]	579	Tractor	8	Cummins	X15	15	1430	421	2779	Eaton	Endurant
Thomas Built Buses[57]	C2	School Bus	8	Detroit Diesel	DD5	5.1	539	179	895	NA	NA
Thomas Built Buses[57]	C2	School Bus	8	Cummins	B6.7	6.7	485	194	895	NA	NA
Volvo[58]	VNR	Tractor	8	Volvo	D11	11	1025	317	2102	Eaton	RT13
Volvo[58]	VNR	Tractor	8	Volvo	D13	13	1182	373	2508	Eaton	RT13
AutoCar[59]	ACTT 4X2	Yard Tractor	8	Cummins	B6.7	6.7	485	194	895	Allison	3500

1.2.3 Heavy-duty Vehicle Sales

The U.S. Energy Information Administration's (EIA's) Annual Energy Outlook (AEO) sales estimates[60] from the 2023 AEO report ("AEO 2023")[61] were used to characterize sales in the HDV market. The overall vehicle class sales percentages for calendar year (CY) 2023 are shown in Figure 1-3. Total heavy-duty sales in 2023 were over 730,000 units, with 35.8 percent

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[56] PACCAR Engine. Available online: https://paccarpowertrain.com/wp-content/uploads/2022/03/PAC56_PX9SpecSheet_2021_Final_HighResDigital.pdf

[57] Thomas Built Buses. Saf-T-Liner C2 School Bus. Available online: https://thomasbuiltbuses.com/school-buses/saf-t-liner-c2/.

[58] Volvo Trucks USA. VNR: It's Time to Meet the Family—Specifications. Available online: https://www.volvotrucks.us/trucks/vnr/specifications/.

[59] Autocar, LLC. ACTT 4X2. Available online: https://d3w5dxa1iffln.cloudfront.net/media/1754/actt_4x2_dot_specs_v2.pdf.

[60] Although AEO sales estimates for heavy-duty vehicles do not include buses, RVs, and emergency vehicles, the sales estimates are still useful in predicting trends in the heavy-duty market by overall percentage of new vehicle sales in different weight classes as well as percentage of new vehicle sales by energy type.

[61] U.S. Energy Information Administration, Annual Energy Outlook 2023, Table 49: Freight Transportation Energy Use available here: https://www.eia.gov/outlooks/aeo/data/browser/#/?id=58-AEO2023&cases=ref2023&sourcekey=0

belonging to Class 3 vehicles (including complete and incomplete), 25.5 percent belonging to Class 4–6 vehicles, and 38.7 percent belonging to Class 7–8 vehicles. Comparatively, by 2050 projected sales for Class 3 heavy-duty vehicles (including complete and incomplete) will increase to 45.1 percent while Class 4–6 sales will increase to 27.1 percent and Class 7–8 vehicles will decrease to 27.8 percent, see Figure 1-3.

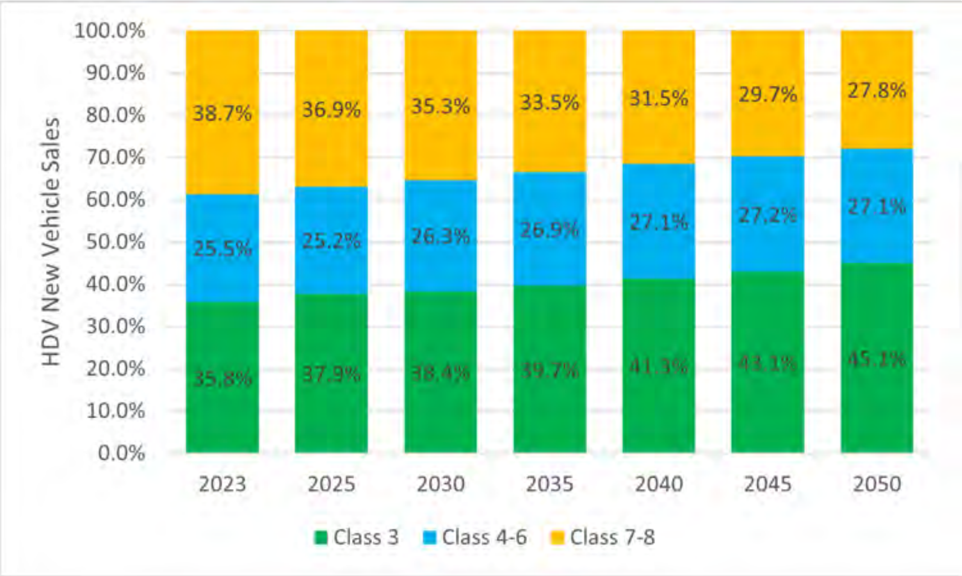

Figure 1-3 2023 HD Sales Percentages by AEO Categories (AEO 2023)

As shown in Figure 1-4, AEO 2023 estimates for the full range of Class 3 vehicles show that there will be no BEV or FCEV vehicle sales in 2023, hybrid sales will be 0.2% of sales and alternative fuel vehicles will make up 4.6% of sales. AEO 2023 estimates Class 4–6 vehicles BEV and FCEV sales comprise less than 0.1 percent of total sales in 2023. Hybrid sales also are estimated to make up less than 0.1 percent of sales while alternate fuel vehicles make up 2.1 percent of vehicle sales in 2023 for Class 4–6 vehicles. AEO 2023 estimates for Class 7–8 vehicles are that BEV, FCEV, and hybrid sales make up less than 0.1 percent and alternate fuel vehicles are 1.5 percent of sales in 2023.

AEO 2023 estimates for 2050 show that for Class 3 vehicles, BEVs and FCEVs will still have no sales, as shown in Figure 1-4. Hybrid vehicles are estimated to make up about 1 percent of sales and alternate fuel vehicles make up 4.2 percent of sales in 2050 for Class 3 vehicles. For Class 4–6 vehicles in 2050, BEV sales are estimated in AEO 2023 to still be less than 0.1 percent of total sales while FCEVs will be less than 1 percent, as shown in Figure 1-4. In 2050, hybrid sales are estimated to still make up less than 1 percent of sales while alternate fuel vehicles are estimated to increase to 6.6 percent of vehicle sales for Class 4–6 vehicles. For Class 7–8 vehicles, AEO 2023 estimates that BEV and FCEV sales will continue to make up less than 0.3 percent of sales in 2050, as shown in Figure 1-4. In 2050, hybrid sales are expected to be less than 0.5 percent of sales and alternate fuel vehicles are expected to increase to 2.8 percent of sales for Class 7–8 vehicles.

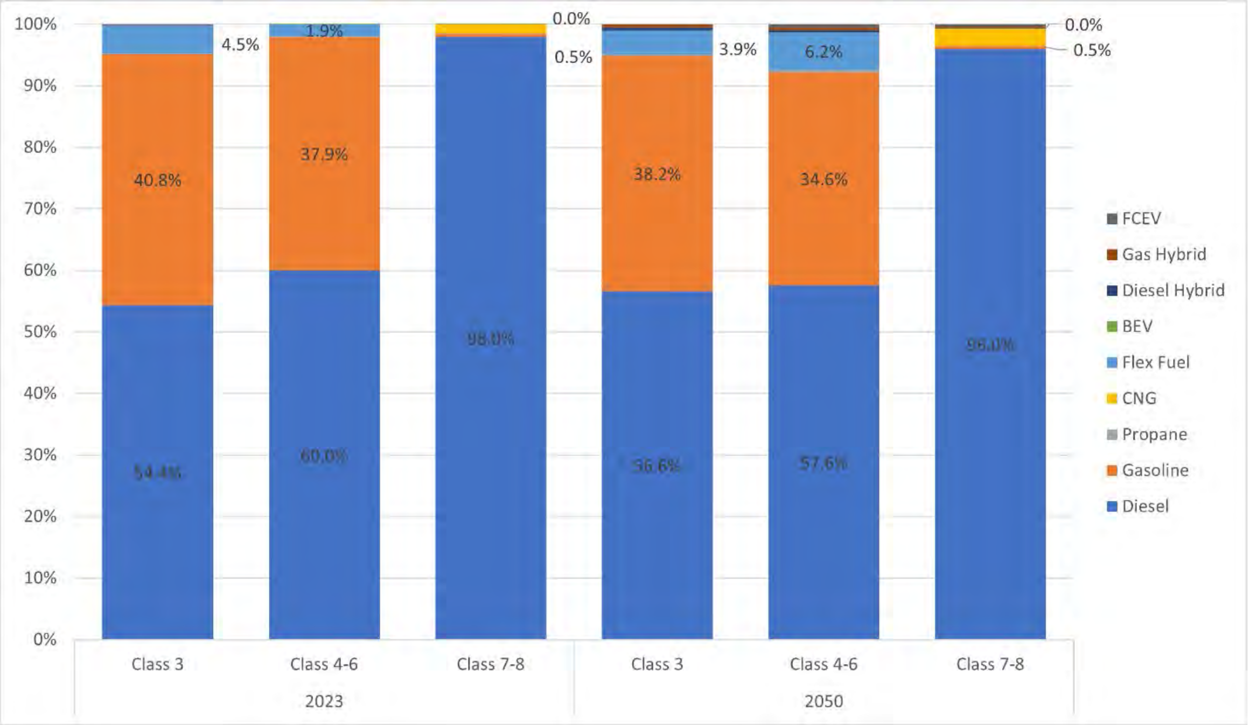

Figure 1-4 AEO 2022 Sales Percent by Weight Class and Energy Use for 2023 and 2050 (AEO 2023)

Table 1-4 contains the raw values of projections from AEO 2023.[62] Their projections do not include any assumptions for new regulations beyond those established by November 2022.[63] The Bipartisan Infrastructure Law and the Inflation Reduction Act are both included in AEO 2023 as they were passed in November of 2021 and August of 2022 respectively. The 2050 Class 3–6 vehicle sales are 1.5 times the 2023 sales levels and Classes 7–8 include about a 12 percent decrease in sales between 2023 and 2050. Alternative fuel vehicles are also projected to increase from 2023 to 2050 with a 1.4 times increase for Class 3, a 5.1 times increase for Classes 4–6, and a 1.7 times increase for Classes 7–8. Hybrids increase from about 650 sales in 2023 to almost 4,000 sales in 2050 for Class 3, increase from 0 sales in 2023 to over 1,700 sales for Classes 4–6, and increase from 0 sales in 2022 to almost 900 sales in 2050 for Classes 7–8. Fuel cells are not seen as an option for Class 3 vehicles but are expected to increase from 0 sales in 2023 to over 1,300 sales in 2050 for Classes 4–6 and from 0 sales in 2023 to over 800 sales in 2050 for Classes 7–8.

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[62] U.S. Energy Information Administration, Annual Energy Outlook, Table 49: Freight Transportation Energy Use. Available here: https://www.eia.gov/outlooks/aeo/data/browser/#/?id=58-AEO2022&region=0.

[63] For example, California has adopted the Advanced Clean Truck (ACT) Regulation, which includes a manufacturer requirement for zero-emission truck sales. ACT is not included in AEO 2022. EPA granted the ACT rule waiver requested by California under CAA section 209(b) on March 30, 2023. 88 FR 20688, April 6, 2023 (signed by the Administrator on March 30, 2023). ACT and other state's efforts to increase ZEV sales are discussed in greater detail in RIA Chapter 1.3.3.

Table 1-4 AEO 2023 Sales Projections in Thousands by Weight Class and Energy Use from 2023 - 2050

Heavy-duty Vehicle Sales (thousands)												
Weight Class	**Class 3**				**Class 4 – 6**				**Class 7 and 8**			
Year	**2023**	**2030**	**2040**	**2050**	**2023**	**2030**	**2040**	**2050**	**2023**	**2030**	**2040**	**2050**
Diesel	142.57	166.84	195.80	227.60	111.86	121.07	131.93	139.16	277.07	268.67	257.36	238.36
Gasoline	106.85	118.57	134.13	153.52	70.74	74.62	79.84	83.55	1.47	1.37	1.30	1.20
Propane	0.28	0.32	0.59	1.23	0.19	0.24	0.49	0.78	0.17	0.16	0.15	0.14
Compressed Natural Gas	0.00	0.00	0.00	0.00	0.08	0.03	0.01	0.00	4.04	2.91	4.46	6.90
Flex Fuel	11.86	11.59	13.88	15.73	3.56	6.93	13.42	15.09	0.00	0.00	0.00	0.00
Battery Electric	0.00	0.00	0.00	0.00	0.06	0.02	0.01	0.00	0.04	0.02	0.00	0.00
Diesel Hybrid	0.32	0.41	0.96	1.84	0.00	0.25	0.41	0.72	0.00	0.13	0.19	0.35
Gasoline Hybrid	0.33	0.39	1.02	2.04	0.00	0.22	0.49	1.00	0.00	0.26	0.35	0.54
Fuel Cell	0.00	0.00	0.00	0.00	0.00	0.43	0.73	1.35	0.00	0.43	0.53	0.82

1.3 Current Regulations and Federal Support for Reducing Heavy-Duty Vehicle GHG Emissions

In this section, we discuss the EPA greenhouse gas emission regulations for heavy-duty engines and vehicles, recent Federal Government legislation to support reductions in greenhouse gas emissions, and the California Air Resources Board's Advanced Clean Trucks program.

1.3.1 Phase 2 EPA GHG Emission Standards for Heavy-Duty Vehicles and Engines

The Heavy-Duty Greenhouse Gas Phase 2 ("HD GHG Phase 2") program sets CO_2 standards separately for vehicles and engines. The phase in of the standards began in MY 2021 followed by more stringent standards in MY 2024 and MY 2027. The Phase 2 heavy-duty vehicle (HDV) emission standards are sub-categorized within the following groups: Vocational Vehicles (segmented as specified in Table 1-5), Custom Chassis (segmented as specified in Table 1-6), and Class 7 and Class 8 Tractors (segmented as specified in Table 1-7). The vehicle emission standards finalized in this rulemaking will follow the vehicle classification used in the HD GHG Phase 2 CO_2 emission standards as defined in 40 CFR 1037.140. This final rule revises many of these Phase 2 MY 2027 standards in the tables, as described in preamble Section II and RIA Chapter 2.10.[64]

Table 1-5 Phase 2 CO_2 Standards for Model Year (MY) 2027 and Later Vocational Vehicles (g/ton-mile)

Engine Cycle	Vehicle size	Multi-purpose	Regional	Urban
Compression-ignition	Light HDV	330	291	367
Compression-ignition	Medium HDV	235	218	258
Compression-ignition	Heavy HDV	230	189	269
Spark-ignition	Light HDV	372	319	413
Spark-ignition	Medium HDV	268	247	297

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[64] See 81 FR 73478, October 25, 2016.

Table 1-6 Phase 2 Custom Chassis CO_2 Emission Standards for Model Year (MY) 2027 and Later (g/ton-mile)

Vehicle Type	Assigned vehicle service class	MY 2027+
School bus	Medium HDV	271
Motor home	Medium HDV	226
Coach bus	Heavy HDV	205
Other bus	Heavy HDV	286
Refuse hauler	Heavy HDV	298
Concrete mixer	Heavy HDV	316
Mixed-use vehicle	Heavy HDV	316
Emergency vehicle	Heavy HDV	319

Table 1-7 Phase 2 CO_2 Standards for Model Year (MY) 2027 and Later Class 7 and Class 8 Tractors (g/ton-mile)

Subcategory	Phase 2 MY 2027+
Class 7 Low-Roof (all cab styles)	96.2
Class 7 Mid-Roof (all cab styles)	103.4
Class 7 High-Roof (all cab styles)	100.0
Class 8 Low-Roof Day Cab	73.4
Class 8 Low-Roof Sleeper Cab	64.1
Class 8 Mid-Roof Day Cab	78.0
Class 8 Mid-Roof Sleeper Cab	69.6
Class 8 High-Roof Day Cab	75.7
Class 8 High-Roof Sleeper Cab	64.3
Heavy-Haul Tractors	48.3

The vehicle manufacturers that certified to EPA standards for MY 2022 are those listed in Table 1-8. The manufacturer names with '*' indicate that they have EPA certifications for BEVs. The manufacturer names with '^' indicate they have certifications for FCEVs.

Table 1-8 Vehicle Manufacturers Certified to EPA HDV Emission Standards in MY 2024[65]

Alexander Dennis Limited	Ford Motor Co	PACCAR Inc*^
An Yuan Bus Manufacture Co.*	General Motors LLC	Proterra Operating Company, Inc*
ARBOC Specialty Vehicles, LLC	Gillig LLC*	REE Automotive*
Autocar, LLC*	Global Environment Product Inc*	Rosenbauer Motors LLC
Battle Motors, Inc.*	Greenpower Motor Co.*	SEA Electric*
Blue Bird Body Company*	Grove US LLC	Seagrave Fire Apparatus LLC
BYD Auto Industry Company Ltd*	Hino Motors, Ltd	Spartan Fire LLC
Cenntro Automotive*	HME Inc	Temsa Skoda Sabanci Ulasim Araclari A.S.*
Chanje*	Hyundai Motor Co.^	Tesla*
CHTC	Irizar Sociedad Coop.	Terex Corporation
Daimler Coaches North America	Isuzu Motors Limited	The Shyft Group*
Daimler Truck North America LLC*	Kovatch Mobile Equipment Corp.	Tiffon Motor Homes Inc
Dennis Eagle Inc	Lion Electric Co*	Unique Electric Sol.*
Distinctive Services, Inc.	Mitsubishi Fuso Truck and Bus	Van Hool N.V.*
e-Roll*	Motor Coach Industries*	Vicinity Motor (Bus) Corp*
Eldorado National-California Inc*^	Navistar, Inc*	Volvo Group Trucks, Technology, Powertrain Engineering, a Division of Mack Trucks*
Envirotech Drive Systems Inc*	New Flyer of America, Inc*^	Workhorse*
E-One Inc	Newell Coach	XOS, Inc*
EVO Bus GmbH*	Nikola Corporation*^	Zeus Electric Chassis, Inc*
FCA US LLC	Nova Bus*	
Ferrara Fire Apparatus Inc*	Oshkosh Corporation*	

The CO_2 engine standards are divided by the type of vehicle where the engine will be installed—tractor or vocational vehicles—and then further divided by engine category. The engine standards for engines used in tractors and vocational vehicles are found in 40 CFR 1036.108 and the MY 2027 standards are shown in Table 1-9 and Table 1-10. The standards for engines installed in tractors decrease 3.4% between MY 2021 and MY 2027. The standards for engines installed in vocational vehicles decrease between 1.8–2% from MY 2021 to MY 2027.

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[65] U.S. Environmental Protection Agency. “Annual Certification Data for Vehicles, Engines, and Equipment”. Available online: https://www.epa.gov/compliance-and-fuel-economy-data/annual-certification-data-vehicles-engines-and-equipment.

Table 1-9 MY 2027 Engine CO_2 Emission Standards for Engines Installed in Tractors (SET cycle)

Engine Category	CO_2 Emissions Standard (g/bhp-hr)
Medium HD	457
Heavy HD	432

Table 1-10 MY 2027 Engine CO_2 Emission Standards for Heavy-Duty Engines Installed in Vocational Vehicles (FTP cycle)

Engine Category	CO_2 Emissions (g/bhp-hr)
Light HD	552
Medium HD	535
Heavy HD	503
HD Spark Ignition	627

The engine manufacturers that currently certify to EPA standards are listed in Table 1-11. These certifications are for compression ignition and spark ignition engines.

Table 1-11 Engine Manufacturers Certified to EPA HDE Emission Standards in MY 2024[65]

AGA Systems, LLC	FPT Industrial S.p.A	PACCAR Inc
Agility Powertrain Systems LLC	General Motors, LLC	PARNELL USA, Inc
Bi-Phase technologies, LLC	Greenkraft, Inc	Power Solutions International, Inc
Blossman Services, Inc	Hino Motors, Ltd	Powertrain Integration LLC
Clean Fuel USA, Inc	Icom North America LLC	Roush Industries Inc
Cummins, Inc.	IMPCO Technologies, Inc	Team Quality Services, Inc
Detroit Diesel Corporation	Isuzu Motors Limited	Volvo Group Trucks, Technologies, Powertrain Engineering, a Division of Mack Trucks
Encore TEC LLC	Landi Renzo USA Corp	Wing Power Systems
FCA US LLC	Navistar, Inc	
Ford Motor Company	NGV Motori USA, LLC	

1.3.2 Bipartisan Infrastructure Law (BIL) and Inflation Reduction Act (IRA)

1.3.2.1 BIL

The BIL[66] was enacted on November 15, 2021, and contains provisions to support the deployment of low- and zero-emission transit buses, school buses, and trucks that service ports, as well as electric vehicle charging infrastructure and hydrogen. These provisions include Section 71101 establishing EPA's Clean School Bus Program,[67] with $5 billion to fund the replacement of ICE school buses with clean and zero-emission buses over five years. In its first

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[66] United States, Congress. Public Law 117-58. Infrastructure Investment and Jobs Act of 2021. Congress.gov, www.congress.gov/bill/117th-congress/house-bill/3684/text. 117th Congress, House Resolution 3684, passed 15 Nov. 2021.

[67] U.S. Environmental Protection Agency. "2022 Clean School Bus (CSB) Rebates Program Guide," EPA-420-B-22-025, May 2022. Available online: https://nepis.epa.gov/Exe/ZyPDF.cgi/P1014WNH.PDF?Dockey=P1014WNH.PDF.

phase of funding for the Clean School Bus Program, EPA awarded nearly $1 billion in rebates (up to a maximum of $375,000 per bus, depending on the bus fuel type, bus class size, and school district prioritization status)[68] for approximately 2,400 replacement clean and zero-emission buses and associated infrastructure costs.[69,70] Nearly 95% of the replacement buses are BEVs. In January 2024, EPA awarded nearly $1 billion in competitive grant funding to purchase new school buses and eligible infrastructure (up to $395,000 per bus with charging infrastructure).[71,72,73] EPA also anticipates awarding at least $500 million through a second phase of rebates (up to a maximum of $345,000 per bus with charging infrastructure).[74,75] The application period for the rebate program closed in January 2024 and will be awarded in April or May 2024.[76] Recipients of both the grant and second rebate funding opportunity can determine the split between funding for the bus and supporting infrastructure.[77]

The BIL also includes funding for DOT's Federal Transit Administration (FTA) Low or No Emission competitive grant program,[78] with over $5.5 billion over five years to support the purchase of zero- or low-emission transit buses and associated infrastructure.[79] Grants were awarded to state and local government authorities for $1.66 billion in FY 2022 and $1.7 billion

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[68] U.S. Environmental Protection Agency. "2022 Clean School Bus (CSB) Rebates Program Guide". May 2022. Available online: https://nepis.epa.gov/Exe/ZyPDF.cgi/P1014WNH.PDF?Dockey=P1014WNH.PDF.

[69] Some recipients are able to claim up to $20,000 per bus for charging infrastructure.

[70] U.S. Environmental Protection Agency, "EPA Clean School Bus Program Second Report to Congress Fiscal Year 2022," EPA-420-R-23-002, February 2023. Available online: https://www.epa.gov/system/files/documents/2023-02/420r23002.pdf.

[71] Funding levels are dependent on the bus fuel type, class size, and school district prioritization status. Selectees may also be eligible for IRA tax credits applicable to their bus and infrastructure purchases such as the Commercial Clean Vehicle Credit and the Alternative Fuel Vehicle Purchasing Property Credit.

[72] U.S. Environmental Protection Agency. "2023 Clean School Bus (CSB) Grant Program: Notice of Funding Opportunity (NOFO): EPA-OAR-OATQ-23-06". Available online: https://www.epa.gov/system/files/documents/2023-04/2023-csb-grant-nofo-4-20-23.pdf.

[73] U.S. Environmental Protection Agency. "Biden-Harris Administration announces nearly $1B in awards for clean school buses across the nation as part of Investing in America Agenda". January 8, 2024. Available online: https://www.epa.gov/newsreleases/biden-harris-administration-announces-nearly-1b-awards-clean-school-buses-across#:~:text=In%20April%202023%2C%20EPA%20announced,and%20low%2Demission%20school%20buses.

[74] Funding levels are dependent on the bus fuel type, class size, and school district prioritization status.

[75] U.S. Environmental Protection Agency, Office of Transportation and Air Quality. "2023 Clean School Bus Rebates Program Guide". September 2023. Available online: https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P1018JIT.pdf.

[76] U.S. Environmental Protection Agency, Office of Transportation and Air Quality. "2023 Clean School Bus Rebates Program Guide". September 2023. Available online: https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P1018JIT.pdf.

[77] U.S. Environmental Protection Agency, Office of Transportation and Air Quality. "2023 Clean School Bus Rebates Program Guide". September 2023. Available online: https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P1018JIT.pdf.

[78] U.S. Department of Transportation, Federal Transit Administration. "Low or No Emission Vehicle Program – 5339(c)". Available online: https://www.transit.dot.gov/lowno.

[79] U.S. Department of Transportation, Federal Transit Administration. "Bipartisan Infrastructure Law Fact Sheet: Grants for Buses and Bus Facilities". Available online: https://www.transit.dot.gov/funding/grants/fact-sheet-buses-and-bus-facilities-program.

in FY 2023, contributing to the purchase of more than 1,800 ZEV transit buses so far over two years.[80,81]

The BIL includes up to $7.5 billion to help build out a national network of EV charging and hydrogen fueling administered by DOT's Federal Highway Administration (FHWA) with support from the Joint Office of Energy and Transportation (JOET). This includes $5 billion for the National Electric Vehicle Infrastructure (NEVI) Formula Program (under Division J, Title VIII).[82] In September 2022, the FHWA approved the first set of plans for the NEVI program covering all 50 states, Washington, D.C., and Puerto Rico. The approved plans provide $1.5 billion in funding for fiscal years (FY) 2022 and 2023 to expand charging on over 75,000 miles of highway.[83] In November 2023, the FHWA completed NEVI plan approvals for FY 2024.[84] Ohio was the first state to open a NEVI-funded station near Columbus in December 2023.[85] New York and Pennsylvania followed with stations in Kingston and Pittstown, respectively.[86,87] Another 30 states have released solicitations with some already awarding contracts and installing charging stations.[88] Over $600 million was awarded for state plans for FY 2024[89,90] One of the

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[80] U.S. Department of Transportation, Federal Transit Administration. "Biden-Haris Administration Announces Over $1.6 Billion in Bipartisan Infrastructure Law Funding to Nearly Double the Number of Clean Transit Buses on America's Roads". August 16, 2022. Available online: https://www.transit.dot.gov/1800buses.

[81] U.S. Department of Transportation, Federal Transit Administration. "Biden-Harris Announces Nearly $1.7 Billion to Help Put Better, Cleaner Buses on the Roads in Communities Across the Country". June 26, 2023. Available online: https://www.transit.dot.gov/about/news/biden-harris-administration-announces-nearly-17-billion-help-put-better-cleaner-buses.

[82] U.S. Department of Transportation, Federal Highway Administration. "Memorandum: National Electric Vehicle Infrastructure Formula Program (Update)". June 2, 2023. Available online: https://www.fhwa.dot.gov/environment/nevi/formula_prog_guid/90d_nevi_formula_program_guidance.pdf.

[83] U.S. Department of Transportation. "Historic Step: All Fifty States Plus D.C. and Puerto Rico Greenlit to Move EV Charging Networks Forward, Covering 75,000 miles of Highway." September 27, 2022. Available online: https://www.transportation.gov/briefing-room/historic-step-all-fifty-states-plus-dc-and-puerto-rico-greenlit-move-ev-charging.

[84] U.S. Department of Transportation. "Biden-Harris Administration Announces Grants to Upgrade Almost 4,500 Public Electric Vehicle Chargers". January 18, 2024. Available online: https://www.transportation.gov/briefing-room/biden-harris-administration-announces-grants-upgrade-almost-4500-public-electric#:~:text=In%20November%202023%2C%20FHWA%20approved,funding%20to%20implement%20those%20plans.

[85] Joint Office of Energy and Transportation. "First Public EV Charging Station Funded by NEVI Open in America". December 13, 2023. Accessed December 18, 2023, at: *https://driveelectric.gov/news/first-nevi*-funded-*stations-open*.

[86] Joint Office of Energy and Transportation. "New York Continues NEVI Charging Station Momentum". December 15, 2023. Accessed December 18, 2023, at: *https://driveelectric.gov/news/new-york-NEVI-charging-station-momentum*.

[87] Joint Office of Energy and Transportation. "Pennsylvania Continues Shift Toward Thriving Electric Transportation Sector". January 23, 2024. Accessed February 24, 2024, at https://driveelectric.gov/news/new-pennsylvania-nevi-station.

[88] Joint Office of Energy and Transportation. " 2024 Q1 NEVI Progress Update," February 16, 2024. Accessed February 24, 2024, at: https://driveelectric.gov/news/nevi-update-q1.

[89] U.S. Department of Transportation. "Biden-Harris Administration Announces Grants to Upgrade Almost 4,500 Public Electric Vehicle Chargers". January 18, 2024. Available online: https://www.transportation.gov/briefing-room/biden-harris-administration-announces-grants-upgrade-almost-4500-public-electric#:~:text=In%20November%202023%2C%20FHWA%20approved,funding%20to%20implement%20those%20plans.

[90] Joint Office of Energy and Transportation. "State Plans for Electric Vehicle Charging". Available online: https://driveelectric.gov/state-plans/.

stated goals of this infrastructure funding is to support equitable access to charging across the country.[91] Accordingly, FHWA instructed states to incorporate public engagement in their NEVI Formula Program planning process, including reaching out to Tribes, and rural, underserved, and disadvantaged communities among other stakeholders. While jurisdictions are not required to build stations specifically for heavy-duty vehicles, FHWA's guidance encourages states to consider station designs and power levels that could support heavy-duty vehicles.[92]

In September 2023, JOET announced that up to $100 million in NEVI funding would be available to increase reliability of the existing charging infrastructure network with funds going to repair or replace charging equipment.[93] This will complement efforts of the National Charging Experience Consortium (ChargeX Consortium). Launched in May 2023 by JOET and led by U.S. DOE labs, the ChargeX Consortium will develop solutions and identify best practices for common problems related to the consumer experience, e.g., payment processing and user interface, vehicle-charger communication, and diagnostic data sharing.[94] Relatedly, in January 2024, JOET announced $46.5 million in federal funding to support 30 projects to increase charging access, reliability, resiliency, and workforce development. This includes projects to increase the commercial capacity for testing and certification of high-power electric vehicle chargers, which will accelerate the deployment of interoperable, safe, and efficient electric vehicle and charger systems.[95]

The remaining $2.5 billion administered by FHWA is for the Charging and Fueling Infrastructure (CFI) Discretionary Grant Program (under Section 11401).[96] In January 2024, over $600 million in grants under the CFI Program (for FY 2022 to 2023) was announced to deploy BEV charging and alternative fueling infrastructure projects in communities and along corridors in 22 states and Puerto Rico. This first round of CFI grants is expected to fund the construction of about 7,500 EVSE charging ports.[97,98] Table 1-12 includes an example of projects awarded specifically for the corridor portion of the program. To support these programs, in February

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[91] U.S. Department of Transportation, Federal Highway Administration. “Memorandum: National Electric Vehicle Infrastructure Formula Program Guidance (Update)”. June 2, 2023. Available online: https://www.fhwa.dot.gov/environment/nevi/formula_prog_guid/90d_nevi_formula_program_guidance.pdf

[92] U.S. Department of Transportation, Federal Highway Administration. “Memorandum: National Electric Vehicle Infrastructure Formula Program Guidance (Update)”. June 2, 2023. Available online: https://www.fhwa.dot.gov/environment/nevi/formula_prog_guid/90d_nevi_formula_program_guidance.pdf

[93] Joint Office of Energy and Transportation. “Biden-Harris Administration to Invest $100 Million for EV Charger Reliability.” September 13, 2023. Available online: https://driveelectric.gov/news/ev-reliability-funding-opportunity.

[94] Joint Office of Energy and Transportation. “Joint Office Announces National Charging Experience Consortium”. May 18, 2023. Available online: https://driveelectric.gov/news/chargex-consortium.

[95] Joint Office of Energy and Transportation. “New Funding Enhances EV Charging Resiliency, Reliability, Equity, and Workforce Development”. January 19, 2024. Accessed February 24, 2024, at: https://driveelectric.gov/news/workforce-development-ev-projects.

[96] U.S. Department of Transportation, Federal Highway Administration. “Memorandum: National Electric Vehicle Infrastructure Formula Program Guidance (Update)”. June 2, 2023. Available online: https://www.fhwa.dot.gov/environment/nevi/formula_prog_guid/90d_nevi_formula_program_guidance.pdf.

[97] Joint Office of Energy and Transportation. "Biden-Harris Administration Bolsters Electric Vehicle Future with More than $600 Million in New Funding". January 11, 2024, https://driveelectric.gov/news/new-cfi-funding.

[98] U.S. Department of Transportation. “Biden-Harris Administration Announces $623 Million in Grants to Continue Building Out Electric Vehicle Charging Network”. January 11, 2024. Available online: https://highways.dot.gov/newsroom/biden-harris-administration-announces-623-million-grants-continue-building-out-electric.

2023, DOE announced $7.4 million in funding to develop seven medium- and heavy-duty BEV charging and hydrogen corridor infrastructure plans: from Georgia to New Jersey (along I-95), Indiana to Ohio (along I-80), Houston to Los Angeles (along I-10), and around Los Angeles (I-710 Corridor), the Northeast (New Jersey to Maine), San Francisco Bay Area, and the Greater Salt Lake City Region.[99]

Table 1-12 CFI Corridor Program Grant Recipients[100]

Lead Applicant State: Project Name	Amount	CFI Program
CA: City of Blythe WattEV I–10 Truck Charging Terminal	$19,635,156	EV Charging
CA: FY 2023 San Joaquin Valley I–5 Electric Freight Corridor (Valley EFC) Project	$56,008,096	EV Charging
CA: Workforce and Renewable Hydrogen for Light – to Heavy –Duty ZEV Fueling in DAC	$7,156,982	Hydrogen
CO: Colorado with Hydrogen Refueling Infrastructure on the I–25 Corridor (Hy–25)	$8,977,947	Hydrogen
ID: City of Idaho Falls Corridor Charging Infrastructure	$3,002,856	EV Charging
NC: Empower Durham: Equitable EV Charging in the City of Durham, NC – Corridor Component	$4,864,000	EV Charging
NM: New Mexico Clean Fuel Build–out Project for Medium – and Heavy–duty Electric Corridors along Interstate 10 Unincorporated Hidalgo and Dona Ana Counties	$63,898,809	EV Charging
NY: Urban Area Strategies to Electrify Light – to Heavy – duty Mobility in NYC – Corridor Component	$15,000,000	EV Charging
PR: Puerto Rico Corridors: Alternative Charging and Fueling Infrastructure for All, PR–2, PR–22, and PR–52	$51,480,000	EV Charging
TX: Charging and Fueling Infrastructure (CFI) Corridor Program for the Texas Hydrogen and Electric Freight Infrastructure (Tx–HEFTI) Project	$70,000,000	Hydrogen
WA: Port Angeles	$2,103,611	EV Charging
WA: Catalyzing Zero–Emission Drayage Trucking Infrastructure & Opportunities in the Seattle–Tacoma Region	$12,000,000	EV Charging

The BIL funds other programs that could support HD vehicle electrification. For example, there is continued funding of the Congestion Mitigation and Air Quality (CMAQ) Improvement Program, with more than $2.5 billion authorized each year from FY 2022 through FY 2026. The BIL (Section 11115) amended the CMAQ Improvement Program to add, among other things, “the purchase of medium- or heavy-duty zero emission vehicles and related charging equipment”

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[99] U.S. Department of Energy. “Biden-Harris Administration Announces Funding for Zero-Emission Medium- and Heavy-Duty Vehicle Corridors, Expansion of EV Charging in Underserved Communities”. February 15, 2023. Available online: https://www.energy.gov/articles/biden-harris-administration-announces-funding-zero-emission-medium-and-heavy-duty-vehicle.

[100] U.S. Department of Transportation, Federal Highway Administration. “Charging and Fueling Infrastructure Program Grant Recipients: FY 2022- FY 2023 Grant Award Recipients”. Available online: https://highways.dot.gov/sites/fhwa.dot.gov/files/CFI%20Grant%20Awards%20Project%20Descriptions%20FY22-23.pdf.

to the list of activities eligible for funding. The BIL establishes a program under Section 11402 "Reduction of Truck Emissions at Port Facilities" that includes grants to be administered through FHWA aimed at reducing port emissions, including through electrification. In addition, the BIL includes funding for DOT's Maritime Administration (MARAD) Port Infrastructure Development Program[101] and DOT's Federal Highway Administration (FHWA) Carbon Reduction Program (Section 11403).[102]

The BIL also targets batteries used for BEVs and FCEVs. It funds DOE's Battery Materials Processing and Battery Manufacturing program,[103] which grants funds to promote U.S. processing and manufacturing of batteries for automotive and electric grid use through demonstration projects, the construction of new facilities, and the retooling, retrofitting, and expansion of existing facilities. This includes a total of $3 billion for battery material processing and $3 billion for battery manufacturing and recycling, with additional funding for a lithium-ion battery recycling prize competition, research and development activities in battery recycling, state and local programs, and the development of a collection system for used batteries. In addition, the BIL includes $200 million for the Electric Drive Vehicle Battery Recycling and Second-Life Application Program for research, development, and demonstration of battery recycling and second-life applications.

Hydrogen provisions of the BIL include $9.5 billion in funding for several programs to accelerate progress towards the Hydrogen Shot goal, launched on June 7, 2021, to reduce the cost of clean hydrogen[104] production by 80% to $1 for 1 kg in 1 decade[105] and jumpstart the hydrogen market in the United States. This includes a total of $8 billion for the Department of Energy's Regional Clean Hydrogen Hubs Program to establish networks of clean hydrogen producers, potential consumers, and connective infrastructure in close proximity. The BIL provisions establishing this program include several diversity requirements. For example, the program must fund at least one hub each that produces hydrogen using fossil fuels, renewable energy, and nuclear power; and a minimum of two hubs must be sited in natural gas-producing regions.[106,107] Additional provisions in the BIL include $1 billion for a Clean Hydrogen

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[101] U.S. Department of Transportation, Maritime Administration. "Bipartisan Infrastructure Law: Maritime Administration". Available online: https://www.maritime.dot.gov/about-us/bipartisan-infrastructure-law-maritime-administration.

[102] U.S. Department of Transportation, Federal Highway Administration. "Bipartisan Infrastructure Law, Fact Sheets: Carbon Reduction Program (CRP)". April 20, 2022. Available online: https://www.fhwa.dot.gov/bipartisan-infrastructure-law/crp_fact_sheet.cfm.

[103] U.S. Department of Energy. "Biden Administration Announces $3.16 Billion From Bipartisan Infrastructure Law to Boost Domestic Battery Manufacturing and Supply Chains". May 2, 2022. Available online: https://www.energy.gov/articles/biden-administration-announces-316-billion-bipartisan-infrastructure-law-boost-domestic.

[104] The BIL defines "clean hydrogen" as hydrogen produced in compliance with the GHG emissions standard established under 42 U.S. Code section 16166(a), including production from any energy source, where the standard developed shall define the term to mean hydrogen produced with a carbon intensity equal to or less than 2 kilograms of carbon dioxide-equivalent produced at the site of production per kilogram of hydrogen produced.

[105] Satyapal, Sunita. "2022 AMR Plenary Session". U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office. June 6, 2022. Available online: https://www.energy.gov/sites/default/files/2022-06/hfto-amr-plenary-satyapal-2022-1.pdf.

[106] U.S. Department of Energy, Office of Clean Energy Demonstrations. "Regional Clean Hydrogen Hubs". Available online: https://www.energy.gov/oced/regional-clean-hydrogen-hubs.

[107] 42 United States Code 16161a. "Regional clean hydrogen hubs". Effective on March 19, 2024. Available online: https://uscode.house.gov/view.xhtml?req=granuleid:USC-prelim-title42-section16161a&num=0&edition=prelim.

Electrolysis Program and $500 million for Clean Hydrogen Manufacturing and Recycling Initiatives.[108] More details about hydrogen initiatives launched by the BIL are in Chapter 1.8.3.

1.3.2.2 IRA Sections 13502 and 13403

The IRA,[109] which was enacted on August 16, 2022, contains several provisions relevant to vehicle electrification and the associated infrastructure via tax credits, grants, rebates, and loans through CY 2032, including two key provisions that provide a tax credit to reduce the cost of producing qualified batteries (battery tax credit) and to reduce the cost of purchasing qualified ZEVs (vehicle tax credit). The battery tax credit in "Advanced Manufacturing Production Credit" in IRA section 13502 and the "Qualified Commercial Clean Vehicles" vehicle tax credit in IRA section 13403 are included quantitatively in our analysis, including for our potential compliance pathway.

IRA section 13502, "Advanced Manufacturing Production Credit," provides tax credits for the production and sale of battery cells and modules of up to $45 per kilowatt-hour (kWh), and for 10 percent of the cost of producing applicable critical minerals (including those found in batteries and fuel cells, provided that the minerals meet certain specifications), when such components or minerals are produced in the United States. These credits begin in CY 2023 and phase down starting in CY 2030, ending after CY 2032. This tax credit has the potential to noticeably reduce the cost of qualifying batteries and by extension, the cost of BEVs and FCEVs with qualifying batteries. We did not include a detailed cost breakdown of fuel cells quantitatively in our analysis, but the potential impact on fuel cells may also be significant because platinum (an applicable critical mineral commonly used in fuel cells) is a contributor to the cost of fuel cells.[110]

We limited our assessment of this IRA section 13502 tax credit provision in our Chapter 2 analysis to the tax credits for battery cells and modules. Pursuant to the IRA, qualifying battery cells must have an energy density of not less than 100 watt-hours per liter, and we expect that batteries for heavy-duty BEVs, PHEVs and FCEVs will satisfy (indeed, surpass) this requirement as described in RIA Chapter 2.4.2.2. Qualifying battery cells must be capable of storing at least 12 watt-hours of energy and qualifying battery modules must have an aggregate capacity of not less than 7 kWh (or, for FCEVs, not less than 1 kWh); typical battery cells and modules for motor vehicles also satisfy (and surpass) these requirements.[111] Additionally, the ratio of the capacity of qualifying cells and modules to their maximum discharge amount shall not exceed 100:1. We expect that battery cells and modules in heavy-duty BEVs, PHEVs, and FCEVs will also meet this requirement because the high costs and weight of the batteries and the

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[108] U.S. Department of Energy. "DOE Establishes Bipartisan Infrastructure Law's $9.5 Billion Clean Hydrogen Initiatives". February 15, 2022. Available online: https://www.energy.gov/articles/doe-establishes-bipartisan-infrastructure-laws-95-billion-clean-hydrogen-initiatives.

[109] Inflation Reduction Act of 2022, Pub. L. No. 117-169, 136 Stat. 1818 (2022) ("Inflation Reduction Act" or "IRA"), *available at* https://www.congress.gov/117/bills/hr5376/BILLS-117hr5376enr.pdf.

[110] Leader, Alexandra & Gaustad, Gabrielle & Babbitt, Callie. (2019). The effect of critical material prices on the competitiveness of clean energy technologies. Materials for Renewable and Sustainable Energy. 8. 10.1007/s40243-019-0146-z.

[111] Islam, Ehsan Sabri, Ram Vijayagopal, Aymeric Rousseau. "A Comprehensive Simulation Study to Evaluate Future Vehicle Energy and Cost Reduction Potential", *Report to the U.S. Department of Energy, Contract ANL/ESD-22/6*, October 2022. Available online: https://anl.app.box.com/s/an4nx0v2xpudxtpsnkhd5peimzu4j1hk/file/1406494585829.

competitiveness of the heavy-duty industry will pressure manufacturers to allow as much of their batteries to be useable as possible. We did not consider the tax credits for critical minerals quantitatively in our analysis. However, we note that any applicability of the critical mineral tax credit may further reduce the costs of batteries.

We included this battery tax credit by reducing the direct manufacturing costs of batteries in BEVs and FCEVs, but not the associated indirect costs. See RIA 2.4.3. As discussed in Section II.D.2.ii.b of the preamble, our assessment of North American and worldwide battery and cell manufacturing capacity is that capacity is rapidly growing to accommodate demand. Thus, we have chosen to model this tax credit by assuming that HD BEV and FCEV manufacturers fully utilize the module tax credit (which provides $10 per kWh) and gradually increase their utilization of the cell tax credit (which provides $35 per kWh) for MY 2027–2029 until MY 2030 and beyond, when they earn 100 percent of the available cell and module tax credits. Further discussion of this battery tax credit and our battery costs can be found in RIA Chapter 2.4.3.1.

IRA section 13403, “Qualified Commercial Clean Vehicles,” creates a tax credit of up to $40,000 per Class 4 through 8 HD vehicles above 14,000 pounds GVWR with a battery capacity of at least 15 kWh (up to $7,500 for vehicles under 14,000 pounds GVWR with a battery capacity of at least seven kWh, such as Class 2b or 3 vehicles) that are acquired for use or lease of a qualified commercial clean vehicle. This tax credit is available from CY 2023 through CY 2032 and is based on the lesser of the incremental cost of the clean vehicle over a comparable ICE vehicle or the specified percentage of the basis of the clean vehicle, up to the maximum $40,000 limitation. By effectively reducing the price a vehicle owner must pay for a HD ZEV and the incremental difference in cost between it and a comparable ICE vehicle—by $40,000 in many cases—more vehicle purchasers will be poised to take advantage of the cost savings anticipated from total cost of ownership, including operational cost savings from fuel and maintenance and repair compared with ICE vehicles. Among other specifications, these vehicles must be on-road vehicles (or mobile machinery) that are propelled to a significant extent by a battery-powered electric motor or are qualified fuel cell motor vehicles (also known as fuel cell electric vehicles, FCEVs). For the former, the battery must have a capacity of at least 15 kWh (or 7 kWh if it has a gross vehicle weight rating of less than 14,000 pounds (Class 3 or below)) and must be rechargeable from an external source of electricity. This limits the qualified vehicles to BEVs and plug-in hybrid electric vehicles (PHEVs), in addition to FCEVs. Since this tax credit overlaps with the model years for which we are finalizing standards (MYs 2027 through 2032), we included it in our calculations for each of those years in our analysis to develop our potential compliance pathway’s technology packages to support the feasibility of for our final standards (see Chapter 2).

For BEVs and FCEVs, the per-vehicle tax credit is equal to the lesser of the following, up to the cap limitation: (A) 30 percent of the BEV or FCEV cost, or (B) the incremental cost of the BEV or FCEV when compared to a comparable (in size and use) ICE vehicle. The limitation on this tax credit is $40,000 for vehicles with a gross vehicle weight rating of equal to or greater than 14,000 pounds (Class 4–8 commercial vehicles) and $7,500 for vehicles with a gross vehicle weight rating of less than 14,000 pounds (commercial vehicles Class 3 and below). For example, if a BEV with a gross vehicle weight rating equal to or greater than 14,000 pounds costs $350,000 and a comparable ICE vehicle costs $150,000,[112] the tax credit would be the lesser of the following, subject to the limitation: (A) 30 percent × $350,000 = $105,000 or (B) $350,000 – $150,000 = $200,000. (A) is less than (B), but (A) exceeds the limit of $40,000, so the tax credit would be $40,000. For PHEVs, the per-vehicle tax credit follows the same calculation and cap limitation as for BEVs and FCEVs except that (A) is 15 percent of the PHEV cost.

For details on how we estimated the impact of the tax credit in our feasibility analysis see Chapters 2.4.3.5 (BEVs), 2.5.2.3 (FCEVs), and 2.11.5 (PHEVs). In the final rule, PHEVs are not included in our modeled potential compliance pathway's technology packages but are included in our additional example potential compliance pathways that are provided as another example of the many ways that manufacturers may choose to comply with the final standards; this tax credit would also serve to effectively reduce the price a vehicle owner must pay for a HD PHEV for any incremental difference in cost between it and a comparable ICE vehicle. The tax credit amounts for each vehicle type included in our analysis for the modeled potential compliance pathway in MYs 2027 and 2032 are shown in RIA Chapter 2.9.2.

We project that the impact of the IRA vehicle tax credit will be significant, as shown in RIA Chapter 2.8.2. In many cases, the incremental cost (with the tax credit) of a BEV compared to an ICE vehicle is eliminated, leaving only the state and federal taxes and the cost of the electric vehicle supply equipment (if applicable) as an added upfront cost to the BEV owner. Similarly, in some cases, the tax credit eliminates the upfront cost of a FCEV compared to an ICE vehicle, leaving only state and federal taxes.

1.3.2.3 IRA Sections 13404

Section 13404, "Alternative Fuel Refueling Property Credit," modifies an existing tax credit that applies to alternative fuel refueling property (e.g., electric vehicle charging equipment and hydrogen fueling stations) and extends the tax credit through CY 2032. The credit also applies to refueling property that stores or dispenses specified clean-burning fuels, including at least 85 percent hydrogen, into the fuel tank of a motor vehicle. Starting in CY 2023, this provision provides a tax credit of up to 30 percent of the cost of the qualified alternative fuel refueling property (e.g., HD BEV charging and hydrogen refueling equipment), up to $100,000 per item when located in low-income or non-urban area census tracts and certain other requirements are met. We expect that many HD BEV owners will need charging equipment installed in their depots for overnight or other off-shift charging, and this tax credit will effectively reduce the costs of installing charging infrastructure and, in turn, further effectively reduce the total costs associated with owning a BEV for many HD vehicle owners. Additionally, this tax credit will offset some of the costs of installing high-powered public and private charging equipment that may be necessary to charge HD BEVs with minimal downtime during the day. Similarly, we expect that this tax credit will reduce the costs associated with refueling heavy-duty FCEVs, whose owners may rely on public hydrogen refueling stations or those installed in their depots. We expect this tax credit will help incentivize the build out of the charging and hydrogen

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[112] Sharpe, B., Basma, H. "A meta-study of purchase costs for zero-emission trucks." International Council on Clean Transportation. February 17, 2022. Available online: https://theicct.org/wp-content/uploads/2022/02/purchase-cost-ze-trucks-feb22-1.pdf

refueling infrastructure necessary for high BEV and FCEV adoption, which will further support increased BEV and FCEV uptake.

For the final rule, we have quantified the impact of this tax credit in our analysis by estimating that 60% of the EVSE installations will qualify for the tax credit, including for our potential compliance pathway. See RIA Chapter 2.6.2.1.2.

1.3.2.4 Other IRA Provisions

There are many other provisions of the IRA that we expect will support application of BEV and FCEV technologies in the heavy-duty fleet. Due to the complexity of analyzing the combined potential impact of these provisions, we did not quantify their potential impact in our assessment of costs and feasibility, but we note that they are expected to help to reduce many obstacles to application of BEV and FCEV technologies in HD vehicles and may further support ZEV adoption rates at the levels we currently project in the potential compliance pathway's technology packages for the final program.

Section 60101, "Clean Heavy-Duty Vehicles," amends the CAA to add new section 132 (42 U.S.C. 7432) and appropriates $1 billion to the Administrator, including $600 million for carrying out this new requirement generally and $400 million to specifically make awards to eligible recipients/contractors that propose to replace eligible vehicles to serve one or more communities located in an air quality area designated pursuant to CAA section 107 as nonattainment for any air pollutant. This section requires the Administrator to implement a program to make awards of grants and rebates to eligible recipients (defined as States, municipalities, Indian tribes, and nonprofit school transportation associations), and to make awards of contracts to eligible contractors for providing rebates, for up to 100 percent of costs for: 1) the incremental costs of replacing a Class 6 or Class 7 heavy-duty vehicle that is not a zero-emission vehicle with a zero-emission vehicle (as determined by the Administrator based on the market value of the vehicles); 2) purchasing, installing, operating, and maintaining infrastructure needed to charge, fuel, or maintain zero-emission vehicles; 3) workforce development and training to support the maintenance, charging, fueling, and operation of zero-emission vehicles; and 4) planning and technical activities to support the adoption and deployment of zero-emission vehicles. A Technical Request for Information was issued in 2023 to collect information to inform the development of the Clean Heavy-Duty Vehicles and the Clean Ports Program, described next.[113] A notice of funding opportunity is expected in spring 2024.

Section 60102, "Grants to Reduce Air Pollution at Ports," amends the CAA to add a new section 133 (42 U.S.C. 7433) and appropriates $3 billion, $750 million of which is for projects located in areas of nonattainment for any air pollutant, to reduce air pollution at ports. In February 2024, EPA released a Notice of Funding Opportunity to solicit applications in anticipation of awarding up to $2.79 billion for zero-emission port equipment and infrastructure at U.S. ports. The competitive grant program funding can be used to purchase new eligible battery-electric and hydrogen fuel cell vehicles, vessels, powertrains, and other mobile

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[113] U.S. Environmental Protection Agency. "Clean Heavy-Duty Vehicle Program". Available online: https://www.epa.gov/inflation-reduction-act/clean-heavy-duty-vehicle-program.

equipment and related infrastructure to be used for eligible equipment directly serving a port, as well as support expenses related to deployment.[114]

Section 60103, "Greenhouse Gas Reduction Fund," amends the CAA to add a new section 134 (42 U.S.C. 7434) and appropriates $27 billion, $15 billion of which is for low-income and disadvantaged communities, in FY 2022 and available through FY 2024, for a greenhouse gas reduction grant program. The program supports direct investments in qualified projects at the national, regional, State, and local levels, and indirect investments to establish new or support existing public, quasi-public, not-for-profit, or nonprofit entities that provide financial assistance to qualified projects. The program focuses on the rapid deployment of low- and zero-emission products, technologies, and services to reduce or avoid GHG emissions and other forms of air pollution.

Section 60104, "Diesel Emissions Reductions," appropriates $60 million (2 percent of which must be reserved for administrative costs necessary to carry out the section's provisions), in FY 2022 and available through FY 2031, for grants, rebates, and loans under section 792 of the Energy Policy Act of 2005 (42 U.S.C. 16132) to identify and reduce diesel emissions resulting from goods movement facilities and vehicles servicing goods movement facilities in low-income and disadvantaged communities to address the health impacts of such emissions on such communities.

Section 70002 appropriates $3 billion in FY 2022 and available through FY 2031 for the United States Postal Service to purchase ZEVs ($1.29 billion) and to purchase, design, and install infrastructure to support zero-emission delivery vehicles at facilities that the United States Postal Service owns or leases from non-Federal entities ($1.71 billion).

Section 13501, "Extension of the Advanced Energy Project Credit," under section 48C(e) of the Internal Revenue Code allocates $10 billion in tax credits for facilities to domestically manufacture advanced energy technologies, subject to certain application and other requirements and limitations. Qualifying properties now include light-, medium-, or heavy-duty electric or fuel cell vehicles along with the technologies, components, or materials for such vehicles and the associated charging or refueling infrastructure. They also include hybrid vehicles with a gross vehicle weight rating of not less than 14,000 pounds along with the technologies, components, or materials for them.

Sections 50142, 50143, 50144, 50145, 50151, 50152, and 50153 collectively appropriate nearly $13 billion to support low- and zero-emission vehicle manufacturing and energy infrastructure. These provisions are intended to help accelerate the ability for industry to meet the demands spurred by the previously mentioned IRA sections, both for manufacturing vehicles, including BEVs and FCEVs, and for energy infrastructure.

Section 13204, "Clean Hydrogen," amends section 45V of the Internal Revenue Code (i.e., Title 26) to offer a tax credit to produce qualified clean hydrogen at a qualifying clean hydrogen production facility that use a process that results in a lifecycle GHG emissions rate of not greater than 4 kg of CO2e per kg of hydrogen. This hydrogen production tax credit is eligible for

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[114] U.S. Environmental Protection Agency, Office of Transportation and Air Quality. "Clean Ports Program: Zero-Emission Technology Deployment Competition". February 2024. Available online: https://www.epa.gov/system/files/documents/2024-02/2024-clean-ports-ze-tech-deploymt-competition-2024-02.pdf.

qualified clean hydrogen production facilities whose construction begins before January 1, 2033, and is available during the 10-year period beginning on the date such facility was originally placed in service. The credit increases to a maximum of $3 per kilogram produced as the lifecycle GHG emissions rate is reduced to less than 0.45 kg of CO2e per kg of hydrogen. Facilities that received credit for the construction of carbon capture and direct air capture equipment or facilities (i.e., under 45Q) do not qualify, and prevailing wage and apprenticeship requirements apply. Section 60113, "Methane Emissions Reduction Program," amends the CAA by adding Section 136 and appropriates $850 million to EPA to support methane mitigation and monitoring, plus authorizes a new fee of $900 per ton on "waste" methane emissions that escalates after two years to $1,500 per ton. These combined incentives promote the production of hydrogen in a manner that minimizes its potential greenhouse gas implications.

While there are challenges facing greater adoption of heavy-duty ZEV technologies, the IRA provides many financial incentives to overcome these challenges and thus provides support for the utilization of HD vehicle technologies with the potential for large reductions in greenhouse gas emissions during the MYs at issue in this rulemaking, which in turn supports our final rule. We expect IRA sections 13502, 13403 and 13404 to support the adoption of HD ZEV technologies in the market, as detailed in our assessment of the appropriate GHG standards we are finalizing. Additionally, we expect IRA sections 60101–60104, 70002, 13501, 50142–50145, 50151–50153, and 13204 to further accelerate ZEV adoption, but we are not including them quantitatively in our analyses. Furthermore, our upstream modeling of electricity generation unit (EGU) and refinery emissions, as described in RIA Chapter 4.3.3, also quantitatively reflects the following tax credit provisions of the IRA that affect power sector operations: the Clean Electricity Investment and Production Tax Credits (sections 13702 and 13701), the credit for Carbon Capture and Sequestration (section 13104), the Zero-Emission Nuclear Power Production Credit (section 13105), the Credit for the Production of Clean Hydrogen (section 13204), and the Advanced Manufacturing Production Tax Credit (13502).

1.3.3 California Advanced Clean Trucks Regulation and Other State's Efforts to Increase Adoption of ZEVs

HD vehicle sales and on-road vehicle populations are significant in the state of California. Approximately ten percent of U.S. HD ICE vehicles in 2016 were registered in California.[115] The California Air Resources Board (CARB) adopted the Advanced Clean Trucks (ACT) Regulation on March 15, 2021.[116] EPA granted the ACT rule waiver requested by California under CAA section 209(b) on March 30, 2023.

The ACT Regulation requires manufacturers who certify Class 2b through 8 chassis or complete vehicles with combustion engines to sell zero-emission trucks as an increasing percentage of their annual state sales from MY 2024 to MY 2035. The ACT Regulation is applicable for all vehicles sold in California with gross vehicle weight rating greater than 8,500 pounds.

The ACT Regulation requires a specified percentage of heavy-duty ZEVs each model year with increasing percentages for each subsequent model year, as reflected in Table 1-13. The

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[115] FHWA. U.S. Highway Statistics. Available online at: *https://www.fhwa.dot.gov/policyinformation/statistics.cfm*.
[116] California Air Resources Board, Final Regulation Order – Advanced Clean Trucks Regulation. Filed March 15, 2021. Available at: https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2019/act2019/fro2.pdf.

percentages are categorized by Class 2b–3 vehicles, Class 4–8 vocational vehicles, and Class 7–8 tractors. Major program milestones include MYs 2030 and 2035, which require 30 percent and 55 percent of Class 2b–3 vehicles, 50 percent and 75 percent of Class 4–8 vocational vehicles, and 30 percent and 40 percent of Class 7–8 tractors that are produced to be ZEVs for those model years, respectively.

Table 1-13 California Air Resource Board ACT Regulation ZEV Sales Percentage Schedule

Model Year	Class 2b-3 Group	Class 4-8 Group	Class 7-8 Tractors Group
2024	5%	9%	5%
2025	7%	11%	7%
2026	10%	13%	10%
2027	15%	20%	15%
2028	20%	30%	20%
2029	25%	40%	25%
2030	30%	50%	30%
2031	35%	55%	35%
2032	40%	60%	40%
2033	45%	65%	40%
2034	50%	70%	40%
2035 and beyond	55%	75%	40%

ACT includes a credit program that allows credits generated for each ZEV and near zero-emission vehicle (NZEV)[117] to offset deficits generated from the production and sale in California of vehicles and tractors. Credits may be banked, traded, sold and otherwise transferred between manufacturers. Table 1-14 describes the multipliers for credits and deficits by vehicle class. Credits for NZEVs may only be generated through MY 2035. The generated credits have a set time frame for expiration based on the model year in which the credits were generated. Credits generated by certifying ZEVs between MY 2021 through MY 2023 expire in MY 2030 and credits accumulated during MY 2024 and later model years expire after five model years.

Table 1-14 CARB Weight Class Modifiers

	Vehicles in the Class 2b-3	Class 4-5 Vehicles in the Class 4-8 Group	Class 6-7 Vehicles in the Class 4-8 Group	Class 8 Vehicles in the Class 4-8 Group	Vehicles in the Class 7 and 8 Tractor Group
Weight Class Modifier	0.8	1	1.5	2	2.5

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[117] NZEV is an on-road hybrid electric vehicle that has the capability to charge the battery from an off- vehicle conductive or inductive electric source and achieves minimum all-electric range per CARB. See, e.g., footnote 1 at https://ww2.arb.ca.gov/resources/fact-sheets/advanced-clean-trucks-credit-summary-through-2022-model-year#_ftn1.

The ACT Regulation also has a provision for hybrid vehicles being sold in MYs 2030 and beyond, which requires that a hybrid have an all-electric 75-mile range.[116]

Outside of California, a number of states have signaled interest in greater adoption of HD ZEV technologies and/or establishing specific goals to increase the HD electric vehicle market. For example, ACT had been proposed or adopted by other states (Colorado[118], Maryland[119], Massachusetts[120], New Mexico[121], New York[122], New Jersey[123], Oregon[124], Rhode Island[125], Vermont[126], and Washington[127]) under CAA section 177 as of February 2024.[128] As another example, the Memorandum of Understanding (MOU), "Multi-State Medium- and Heavy-Duty Zero Emission Vehicle," (Multi-State MOU) organized by Northeast States for Coordinated Air Use Management (NESCAUM), sets targets "to make all sales of new medium- and heavy-duty vehicles [in the jurisdictions of the signatory states and the District of Columbia] zero emission vehicles by no later than 2050" with an interim goal of 30 percent of all sales of new medium- and heavy-duty vehicles being zero emission vehicles no later than 2030.[129] The Multi-State MOU was signed by the governors of 17 states including California, Colorado, Connecticut, Hawaii, Maine, Maryland, Massachusetts, New Jersey, New York, North Carolina, Nevada, Oregon, Pennsylvania, Rhode Island, Vermont, Virginia, and Washington, as well as the mayor of the District of Columbia. The Multi-State MOU outlines these jurisdictions' more specific commitments to move toward ZEVs through the Multi-State ZEV Task Force and provides an action plan for zero-emission medium- and heavy-duty vehicles with measurable sales targets and a focus on overburdened and underserved communities. Several states that signed the Multi-

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[118] Colorado Clean Trucks. Available online: https://cdphe.colorado.gov/cleantrucking

[119] Maryland Md. Code Regs. 26.11.43.04. Available online: https://www.law.cornell.edu/regulations/maryland/COMAR-26-11-43-04

[120] Final Advanced Clean Truck Amendments, 1461 Mass. Reg. 29 (Jan. 21, 2022). Available online: https://www.mass.gov/doc/310-cmr-740-advanced-clean-truck-amendments/download

[121] New Mexico Advanced Clean Trucks. Available online: https://cloud.env.nm.gov/air/resources/_translator.php/NoP4Wd1EyorPC~sl~BWz~sl~H2+PXdCQEKefUZ7Ou8Vgq~sl~x2ZYzqa1zexRjWPJMkpMtY7aK2mnJ9Ao0IZEOEbuZDv5gjdz5ZLJvJUhgZUY7TTUnFGi~sl~XBzQ4GPo+3bjoke7jG9.pdf

[122] Medium- and Heavy-Duty (MHD) Zero Emission Truck Annual Sales Requirements and Large Entity Reporting, 44 N.Y. Reg. 8 (Jan. 19, 2022), *available at* https://dos.ny.gov/system/files/documents/2022/01/011922.pdf.

[123] Advanced Clean Trucks Program and Fleet Reporting Requirements, 53 N.J.R. 2148(a) (Dec. 20, 2021), *available at* https://www.nj.gov/dep/rules/adoptions/adopt_20211220a.pdf (pre-publication version).

[124] Clean Trucks Rule 2021, DEQ-17-2021 (Nov. 17, 2021), *available at* http://records.sos.state.or.us/ORSOSWebDrawer/Recordhtml/8581405.

[125] Rhode Island Advanced Clean Trucks. Available online: https://dem.ri.gov/environmental-protection-bureau/air-resources/advanced-clean-cars-ii-advanced-clean-trucks

[126] Vermont Low Emission Vehicle and Zero Emission Vehicle Rules. Available online: https://dec.vermont.gov/sites/dec/files/aqc/laws-regs/documents/Chapter_40_LEV_ZEV_rule_adopted.pdf.

[127] Low emission vehicles, Wash. Admin. Code. § 173-423-070 (2021), *available at* https://app.leg.wa.gov/wac/default.aspx?cite=173-423-070

[128] Oregon, Washington, New York, New Jersey, and Massachusetts adopted ACT in 2021 beginning in MY 2025 while Vermont and New Mexico adopted ACT beginning in MY 2026 and Colorado in MY 2027.

[129] Northeast States for Coordinated Air Use Management (NESCAUM), Multi-state Medium- and Heavy-duty Zero Emission Vehicle Memorandum of Understanding, available at *https://www.nescaum.org/documents/mhdv-zev-mou-20220329.pdf/* (hereinafter "Multi-State MOU").

State MOU have since adopted California's ACT program, pursuant to CAA section 177, and we anticipate more jurisdictions will follow with similar proposals.[130]

1.4 GHG-Reducing Technologies for ICE-Powered Vehicles

The CO_2 emissions of HD vehicles vary depending on the configuration of the vehicle. Many aspects of the vehicle impact its emissions performance, including the engine, transmission, drive axle, aerodynamics, and rolling resistance.

The technologies we considered for tractors include technologies that we analyzed in Phase 2 such as improved aerodynamics; low rolling resistance tires; tire inflation systems; efficient engines, engines fueled with natural gas, transmissions, drivetrains, and accessories; and extended idle reduction for sleeper cabs. We analyzed the overall effectiveness of the technology packages using EPA's Greenhouse Gas Emissions Model (GEM), which was used for analyzing the technology packages that support the Phase 2 vehicle CO_2 emission standards and is used by manufacturers to demonstrate compliance with the Phase 2 standards. EPA's GEM model simulates road load power requirements over various duty cycles to estimate the energy required per mile for HD vehicles. The inputs for the individual technologies that make up the fleet average technology package that meets the Phase 2 MY 2027 CO_2 tractor emission standards are shown in Table 1-15.[131] The comparable table for vocational vehicles is shown in Table 1-16.[132] The technology package for vocational vehicles include technologies such as low rolling resistance tires; tire inflation systems; efficient engines, transmissions, and drivetrains; weight reduction; and idle reduction technologies. Note that the HD GHG Phase 2 standards (like the Phase 1 and 3 standards) are performance-based; EPA does not require this specific technology mix, rather the technologies shown in Table 1-15 and Table 1-16 are potential pathways for compliance.

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[130] *See, e.g.*, Final Advanced Clean Truck Amendments, 1461 Mass. Reg. 29 (Jan. 21, 2022) (Massachusetts). Medium- and Heavy-Duty (MHD) Zero Emission Truck Annual Sales Requirements and Large Entity Reporting, 44 N.Y. Reg. 8 (Jan. 19, 2022) (New York), available at *https://dos.ny.gov/system/files/documents/2022/01/011922.pdf*. Advanced Clean Trucks Program and Fleet Reporting Requirements, 53 N.J.R. 2148(a) (Dec. 20, 2021) (New Jersey), available at *https://www.nj.gov/dep/rules/adoptions/adopt_20211220a.pdf* (pre-publication version). Clean Trucks Rule 2021, DEQ-17-2021 (Nov. 17, 2021), available at *http://records.sos.state.or.us/ORSOSWebDrawer/Recordhtml/8581405* (Oregon). Low emission vehicles, Wash. Admin. Code. § 173-423-070 (2021), available at *https://app.leg.wa.gov/wac/default.aspx?cite=173-423-070*; 2021 Wash. Reg. 587356 (Dec. 15, 2021); Wash. Reg. 21-24-059 (Nov. 29, 2021) (amending Wash. Admin. Code. §§ 173-423 and 173-400), available at *https://lawfilesext.leg.wa.gov/law/wsrpdf/2021/24/21-24-059.pdf* (Washington).

[131] 81 FR at 73616, October 25, 2016.

[132] 81 FR at 73714, October 25, 2016.

Table 1-15 GEM Inputs for Vehicles Meeting the Phase 2 MY 2027 Tractor CO_2 Emission Standards

Class 7			**Class 8**					
Day Cab			**Day Cab**			**Sleeper Cab**		
Low Roof	**Mid Roof**	**High Roof**	**Low Roof**	**Mid Roof**	**High Roof**	**Low Roof**	**Mid Roof**	**High Roof**
Engine Fuel Map								
2027MY 11L Engine 350 HP	2027MY 11L Engine 350 HP	2027MY 11L Engine 350 HP	2027MY 15L Engine 455 HP	2027MY 15L Engine 455 HP	2027MY 15L Engine 455 HP	2027MY 15L Engine 455 HP	2027MY 15L Engine 455 HP	2027MY 15L Engine 455 HP
Aerodynamics (C_dA in m^2)								
5.12	6.21	5.67	5.12	6.21	5.67	5.08	6.21	5.26
Steer Tire Rolling Resistance (CRR in kg/metric ton)								
5.8	5.8	5.6	5.8	5.8	5.6	5.8	5.8	5.6
Drive Tire Rolling Resistance (CRR in kg/metric ton)								
6.2	6.2	5.8	6.2	6.2	5.8	6.2	6.2	5.8
Extended Idle Reduction Weighted Effectiveness								
N/A	N/A	N/A	N/A	N/A	N/A	3%	3%	3%
Transmission = 10 speed Manual Transmission Gear Ratios = 12.8, 9.25, 6.76, 4.90, 3.58, 2.61, 1.89, 1.38, 1.00, 0.73								
Drive Axle Ratio = 3.21 for day cabs, 3.16 for sleeper cabs								
6x2 Axle Weighted Effectiveness								
N/A	N/A	N/A	0.6%	0.6%	0.6%	0.6%	0.6%	0.6%
Transmission Type Weighted Effectiveness = 1.6%								
Neutral Idle Weighted Effectiveness								
0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.03%	0.03%	0.03%
Direct Drive Weighted Effectiveness = 1.0%								
Transmission Efficiency Weighted Effectiveness = 0.7%								
Axle Efficiency Improvement = 1.6%								
Air Conditioner Efficiency Improvements = 0.3%								
Accessory Improvements = 0.2%								
Predictive Cruise Control =0.8%								
Automatic Tire Inflation Systems = 0.4%								
Tire Pressure Monitoring System = 0.7%								

Table 1-16 GEM Inputs for Vehicles Meeting the Phase 2 MY 2027 Vocational Vehicle CO_2 Emission Standards

LHD (Class 2b-5)			MHD (Class 6-7)			HHD (Class 8)		
Urban	**Multi-Purpose**	**Regional**	**Urban**	**Multi-Purpose**	**Regional**	**Urban**	**Multi-Purpose**	**Regional**
SI Engine Fuel Map								
2018 MY 6.8L, 300 hp engine								
CI Engine Fuel Map								
2027 MY 7L, 200 hp Engine			2027 MY 7L, 270 hp Engine			2027 MY 11L, 350 hp Engine	2027 MY 11L, 350 hp Engine and 2027 MY 15L 455hp Engine	
Torque Converter Lockup in 1st Gear (adoption rate)								
50%	50%	50%	50%	50%	50%	30%	30%	0%
6x2 Disconnect Axle (adoption rate)								
0%	0%	0%	0%	0%	0%	0%	25%	30%
Automatic Engine Shutdown (adoption rate)								
70%	70%	90%	70%	70%	90%	70%	70%	90%
Stop-Start (adoption rate)								
30%	30%	0%	30%	30%	0%	20%	20%	0%
Neutral Idle (adoption rate)								
60%	60%	0%	60%	60%	0%	70%	70%	0%
Steer Tire Rolling Resistance (CRR kg/metric ton)								
6.8	6.2	6.2	6.7	6.2	6.2	6.2	6.2	6.2
Drive Tire Rolling Resistance (CRR kg/metric ton)								
6.9	6.9	6.9	7.5	6.9	6.9	7.5	6.9	6.9
Weight Reduction (pounds)								
75	75	75	75	75	75	125	125	125

Technologies exist today and continue to evolve to improve the efficiency of the engine, transmission, drivetrain, aerodynamics, and tire rolling resistance in HD vehicles and therefore reduce their CO_2 emissions. As shown here in Table 1-15 and Table 1-16, there are a variety of such technologies. We also discussed many of these technologies when we promulgated the HD GHG Phase 2 program.[133] In developing the Phase 2 CO_2 emission standards, we developed technology packages that were premised on a mix of projected technologies and potential technology adoption rates of less than 100 percent. As discussed in Section II.F.4, there is an opportunity for further improvements and increased adoption through MY 2032 for many of these technologies. Furthermore, we also considered additional technologies such as H2-ICE, hybrids, and natural gas engines. Each of these technologies is discussed in this section and RIA Chapter 1.4.

1.4.1 Aerodynamics

We evaluated the potential for additional GHG performance gains from aerodynamic improvements. Up to 25 percent of the fuel consumed by a sleeper cab tractor traveling at highway speeds is used to overcome aerodynamic drag forces, making aerodynamic drag a

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[133] See 71 FR 73478 (October 25, 2016) and Regulatory Impact Analysis Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles - Phase 2. Chapter 2. EPA-420-R-16-900. August 2016

significant contributor to a Class 7 or 8 tractor's GHG emissions and fuel consumption.[134] Because aerodynamic drag varies by the square of the vehicle speed, small changes in the tractor aerodynamics can have a large impact on the GHG emissions of a tractor. With much of their driving at highway speed, the GHG emission reductions of reduced aerodynamic drag for Class 7 or 8 tractors can be significant.[135]

Improving the vehicle shape may include revising the fore components of the vehicle such as rearward canting/raking or smoothing/rounding the edges of the front end components (e.g., bumper, headlights, windshield, hood, cab, mirrors) or integrating the components at key interfaces (e.g., windshield/glass to sheet metal) to alleviate fore vehicle drag. Finally, improvements may include redirecting the air to prevent areas of low pressure and slow moving air (thus, eliminating areas where air builds creating turbulent vortices and increasing drag). Techniques such as blocking gaps in the sheet metal, ducting of components, shaping or extending sheet metal to reduce flow separation and turbulence are methods being considered by manufacturers to direct air from areas of high drag (e.g., underbody and tractor-trailer gap).

As discussed in the Phase 2 RIA, the National Research Council of Canada performed an assessment of the aerodynamic drag effect of various tractor components.[136] Based on the results, there is the potential to improve tractor aerodynamics by 0.206 wind averaged coefficient of drag area (C_dA) with the addition of wheel covers, drive axle wrap around splash guards, and roof fairing rear edge filler. Up to 0.460 C_dA improvement is possible if the side and fender mirrors are replaced with a camera system, as suggested by the study, and combined with the wheel covers, drive axle wrap around splash guards, and roof fairing rear edge filler. In our Phase 2 analysis, considering the wind average drag performance of heavy-duty tractors at the time, this study demonstrated the possibility to improve tractors an additional ~1 percent with some simple changes.

In Phase 2, the tractor aerodynamic performance was evaluated using the wind averaged coefficient of drag area results measured during aerodynamic testing as prescribed in 40 CFR 1037.525. The results of the aerodynamic testing were used to determine the aerodynamic bin and C_dA input value for GEM, as prescribed in 40 CFR 1037.520 and shown in Table 1-17Table 1-17.

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134 Assumes travel on level road at 65 MPH. (21st Century Truck Partnership Roadmap and Technical White Papers, December 2006. U.S. Department of Energy, Energy Efficiency and Renewable Energy Program. 21CTP-003. p.36.

135 Reducing Heavy-Duty Long Haul Combination Truck Fuel Consumption and CO2 Emissions, ICCT, October 2009.

[136] Jason Leuschen and Kevin R. Cooper (National Research Council of Canada), Society of Automotive Engineer (SAE) Paper #2006-01-3456: "Full-Scale Wind Tunnel Tests of Production and Prototype, Second-Generation Aerodynamic Drag-Reducing Devices for Tractor-Trailers.," November 2, 2006.

Table 1-17 GEM Inputs for Tractor Aerodynamic Bins (C_dA in m^2)

	Class 7			Class 8					
	Day Cab			Day Cab	Sleeper Cab				
Low Roof	Mid Roof	High Roof	Low Roof	Mid Roof	High Roof	Low Roof	Mid Roof	High Roof	Low Roof
Bin I	6.00	7.00	7.45	6.00	7.00	7.45	6.00	7.00	7.15
Bin II	5.60	6.65	6.85	5.60	6.65	6.85	5.60	6.65	6.55
Bin III	5.15	6.25	6.25	5.15	6.25	6.25	5.15	6.25	5.95
Bin IV	4.75	5.85	5.70	4.75	5.85	5.70	4.75	5.85	5.40
Bin V	4.40	5.50	5.20	4.40	5.50	5.20	4.40	5.50	4.90
Bin VI	4.10	5.20	4.70	4.10	5.20	4.70	4.10	5.20	4.40
Bin VII	3.80	4.90	4.20	3.80	4.90	4.20	3.80	4.90	3.90

EPA conducted aerodynamic testing for the Phase 2 final rule.[137] As shown in Phase 2 RIA Chapter 3.2.1.2, the most aerodynamic high roof sleeper cabs tested had a CdA of approximately 5.4 m^2, which is a Bin IV tractor. Therefore, we concluded that prior to 2016 manufacturers were producing high roof sleeper cabs that range in aerodynamic performance between Bins I and IV. Bin V is achievable through the addition of aerodynamic features that improve the aerodynamics on the best pre-2016 sleeper cabs tested by at least 0.3 m^2 CdA. The features that could be added include technologies such as wheel covers, drive axle wrap around splash guards, and roof fairing rear edge filler, and active grill shutters. In addition, manufacturers continue to improve the aerodynamic designs of the front bumper, grill, hood, and windshield.

Our analysis of high roof day cabs is similar to our assessment of high roof sleeper cabs. Also, as shown in Phase 2 RIA Chapter 3.2.1.2, the most aerodynamic high roof day cab tested by EPA achieved Bin IV. Our assessment is that the same types of additional technologies that could be applied to high roof sleeper cabs could also be applied to high roof day cabs to achieve Bin V aerodynamic performance. Finally, because the manufacturers have the ability to determine the aerodynamic bin of low and mid roof tractors from the equivalent high roof tractor, this assessment also applies to low and mid roof tractors.

For our modeled potential compliance pathway in Phase 3 tractors’ technology packages, the vehicles with ICE portion of the technology package for the MY 2027 high roof sleeper cab tractor includes 20 percent Bin III, 30 percent Bin IV, and 50 percent Bin V reflecting our assessment of the fraction of high roof sleeper cab tractors. We continue to project, as we projected in the Phase 2 rulemaking, that manufacturers could successfully apply these aerodynamic packages by MY 2027. The weighted average for tractors of this set of adoption rates is equivalent to a tractor aerodynamic performance near the border between Bin IV and Bin V.

The Phase 2 standards for vocational vehicles were not projected to be met with the use of aerodynamic improvements.

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[137] US EPA. Regulatory Impact Analysis Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles - Phase 2. Chapter 3. EPA-420-R-16-900. August 2016.

1.4.2 Tire Rolling Resistance

Energy loss associated with tires is mainly due to deformation of the tires under the load of the vehicle, known as hysteresis, but smaller losses result from aerodynamic drag, and other friction forces between the tire and road surface and the tire and wheel rim. Collectively the forces that result in energy loss from the tires are referred to as rolling resistance. Tires with higher rolling resistance lose more energy, thus using more fuel and producing more CO_2 emissions in operation, while tires with lower rolling resistance lose less energy, and use less fuel, producing less CO_2 emissions in operation.

A tire's rolling resistance is a factor considered in the design of the tire and is affected by the tread and casing compound materials, the architecture of the casing, tread design, and the tire manufacturing process. It is estimated that 35 to 50 percent of a tire's rolling resistance is from the tread and the other 50 to 65 percent is from the casing.[138] Tire inflation can also impact rolling resistance in that under-inflated tires can result in increased deformation and contact with the road surface.

In Phase 2, we developed four levels of tire rolling resistance, as shown in Table 1-18Table 1-18. The levels included the baseline (average) from 2010, Level I and Level 2 from Phase 1, and Level 3 that achieves an additional 25 percent improvement over Level 2. The Level 2 threshold represents an incremental step for improvements beyond today's SmartWay level and represents the best in class rolling resistance of the tires we tested for Phase 1.[139] The Level 3 values represented the long-term rolling resistance value that EPA projected could be achieved in the MY 2025 timeframe. Given the multiple year phase-in of the Phase 2 standards, EPA expected that tire manufacturers will continue to respond to demand for more efficient tires and will offer increasing numbers of tire models with rolling resistance values significantly better than the typical low rolling resistance tires offered in 2016.

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[138] "Tires & Truck Fuel Economy," A New Perspective. Bridgestone Firestone, North American Tire, LLC, Special Edition Four, 2008.

[139] U.S. EPA. SmartWay Verified Low Rolling Resistance Tires Performance Requirements. Available online: https://www.epa.gov/sites/default/files/2016-02/documents/420f12024.pdf

Table 1-18 Phase 2 Tire Rolling Resistance Technologies

	Class 7			**Class 8**					
	Day Cab			**Day Cab**			**Sleeper Cab**		
	Low Roof	Mid Roof	High Roof	Low Roof	Mid Roof	High Roof	Low Roof	Mid Roof	High Roof
Steer Tires (CRR in kg/metric ton)									
Base	7.8	7.8	7.8	7.8	7.8	7.8	7.8	7.8	7.8
Level 1	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6
Level 2	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7
Level 3	4.9	4.9	4.9	4.9	4.9	4.9	4.9	4.9	4.9
Drive Tires (CRR in kg/metric ton)									
Base	8.1	8.1	8.1	8.1	8.1	8.1	8.1	8.1	8.1
Level 1	6.9	6.9	6.9	6.9	6.9	6.9	6.9	6.9	6.9
Level 2	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0
Level 3	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0

In the modeled compliance pathway for the Phase 3 tractors' technology packages, the vehicles with ICE portion of the technology package for the MY 2027 included steer and drive tires that on average performed at a Level 2 rolling resistance. We continue to project, as we projected in the Phase 2 rulemaking, that manufacturers could successfully apply tires that on average perform at this level by MY 2027.

1.4.3 Natural Gas Engines

Natural-gas powered heavy-duty vehicles are very similar to gasoline and diesel fueled ICE-powered vehicles. The engine functions the same as a gasoline or diesel fueled ICE. Two key differences are the fuel storage and delivery systems. The fuel delivery system delivers high-pressure natural gas from the fuel tank to the fuel injectors located on the engine. Similar to gasoline or diesel fuel, natural gas is stored in a fuel tank, or cylinder, but requires the ability to store the fuel under high pressure.

There are different ways that heavy-duty engines can be configured to use natural gas as a fuel. The first is a spark-ignition natural gas engine. An Otto cycle SI heavy-duty engine uses a spark plug for ignition and burns the fuel stoichiometrically. Due to this, the engine-out emissions require use of a three-way catalyst to control criteria pollutant emissions. The second is a direct injection natural gas that utilizes a compression-ignition (CI) cycle. The CI engine uses a small quantity of diesel fuel (pilot injection) as an ignition source along with a high compression ratio engine design. The engine operates lean of stoichiometric operation, which leads to engine-out emissions that require aftertreatment systems similar to diesel ICEs, such as diesel oxidation catalysts, selective catalytic reduction systems, and diesel particulate filters. The CNG CI engine is more costly than a diesel CI engine because of the special natural gas/diesel fuel injection system. The NG SI engine and aftertreatment system is less costly than a NG CI engine and aftertreatment system but is less fuel efficient than a NG CI engine because of the lower compression ratio.

In addition to differences in engine architecture, the natural gas fuel can be stored two ways – compressed (CNG) or liquified (LNG). A CNG tank stores pressurized gaseous natural gas and the system includes a pressure regulator. An LNG tank stores liquified natural gas that is cryogenically cooled but stored at a lower pressure than CNG. The LNG tanks often are double-walled to help maintain the temperature of the fuel, and include a gasification system to turn the fuel from a liquid to a gas before injecting the fuel into the engine. An important advantage of LNG is the increased energy density compared to CNG. Because of its higher energy density, LNG can be more suitable for applications such as long-haul applications.

Natural gas engines are a mature technology. Cummins manufactures natural gas engines that cover the complete range of heavy-duty vehicle applications, with engine displacements ranging from 6.7L to 12L. Heavy-duty CNG and LNG vehicles are available today in the fleet. EIA estimates that approximately 4,400 CNG and LNG heavy-duty vehicles were sold in 2022 and approximately 50,000 CNG and LNG vehicles are in the U.S. heavy-duty fleet.[140] Manufacturers are producing CNG and LNG vehicles in all of the vocational and tractor categories, especially buses, refuse hauler, street sweeper, and tractor applications, as shown in Table 1-19.[141]

Table 1-19 MY 2024 CNG, LNG and Propane Powered Heavy-Duty Vehicle Models

Manufacturer	Model	Category	Fuel	Power System
Autocar	ACMD	Refuse	LNG CNG	Cummins L9N 8.9L Near Zero
Autocar	ACMD	Vocational Cab Chassis	CNG LNG	Cummins L9N 8.9L Near Zero
Autocar	ACTT Severe Duty Terminal Tractor	Tractor	LNG CNG	Cummins B6.7N Near Zero
Autocar	ACX	Vocational Cab Chassis	CNG LNG	Cummins L9N 8.9L Near Zero Cummins ISX12N 11.9L Near Zero
Autocar	ACX	Refuse	LNG CNG	Cummins ISX12N 11.9L Near Zero Cummins L9N 8.9L Near Zero
Autocar	DC-64	Vocational Cab Chassis	LNG CNG	Cummins ISX12N 11.9L Near Zero
Autocar	DC-64R	Refuse	CNG LNG	Cummins ISX12N 11.9L Near Zero
Battle Motors	LOW ENTRY TILT 2	Vocational Cab Chassis	CNG	Cummins L9N 8.9L Near Zero Cummins B6.7N Near Zero
Battle Motors	LOW NARROW TILT	Vocational Cab Chassis	CNG	Cummins L9N 8.9L Near Zero Cummins B6.7N Near Zero
Blue Bird	All American Activity	Passenger Van Shuttle Bus	CNG	Cummins L9N 8.9L Near Zero
Blue Bird	All American Rear Engine - Class 7	School Bus	CNG	Cummins L9N 8.9L Near Zero
Blue Bird	Micro Bird 5G Activity	Passenger Van Shuttle Bus	Propane	Ford 7.3L V8
Blue Bird	Micro Bird G5 - Class 3	School Bus	Propane	Ford 7.3L V8
Blue Bird	Vision - Class 7	School Bus	Propane	Ford 7.3L V8
Blue Bird	Vision Activity	Passenger Van Shuttle Bus	Propane	Ford 7.3L V8
Elgin	Broom Bear	Street Sweeper	CNG	Cummins L9N 8.9L Near Zero
Elgin	Crosswind1	Street Sweeper	CNG	Cummins L9N 8.9L Near Zero
Elgin	Pelican	Street Sweeper	CNG	Cummins B6.7N Near Zero

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[140] EIA. Annual Energy Outlook 2023. Table 49. Available Online: https://www.eia.gov/outlooks/aeo/data/browser/#/?id=58-AEO2023&cases=ref2023&sourcekey=0

[141] Department of Energy Alternative Fuels Data Center. Available Online: https://afdc.energy.gov/vehicles/search/results?manufacturer_id=67,205,117,394,415,201,113,5,408,481,9,13,11,458,81,435,474,57,416,141,197,417,121,475,53,397,418,85,414,17,21,143,476,492,23,484,398,27,477,399,31,207,396,489,107,465,487,193,460,35,459,115,37,147,480,199

ENC	AXESS 32'	Transit Bus	LNG CNG	Cummins L9N 8.9L Near Zero Allison Transmission hybrid drive
ENC	AXESS 35'	Transit Bus	LNG CNG	Cummins L9N 8.9L Near Zero
ENC	AXESS 40'	Transit Bus	LNG CNG	Cummins L9N 8.9L Near Zero
ENC	E-Z RIDER II 30'	Transit Bus	CNG LNG	Cummins L9N 8.9L Near Zero
ENC	E-Z RIDER II 32'	Transit Bus	CNG LNG	Cummins L9N 8.9L Near Zero
ENC	E-Z RIDER II 35'	Transit Bus	CNG LNG	Cummins L9N 8.9L Near Zero
Ford	F-59 Stripped Chassis	Vocational Cab Chassis	CNG E85/Hybrid Electric CNG - Bi-fuel Propane - Bi-fuel Propane	Ford 7.3L V8
Freightliner	114SD NG - Class 8	Vocational Cab Chassis	LNG CNG	Cummins L9N 8.9L Near Zero Cummins ISX12N 11.9L Near Zero
Freightliner	Cascadia Natural Gas	Tractor	CNG LNG	Cummins ISX12N 11.9L Near Zero
Freightliner	M2 112 NG	Vocational Cab ChassisTractor	CNG LNG	Cummins L9N 8.9L Near Zero
Gillig	BRT, BRT Plus, Commuter	Transit Bus	CNG	Cummins L9N 8.9L Near Zero
Gillig	Low Floor, Low Floor Plus	Transit Bus	CNG	Cummins L9N 8.9L Near Zero
Gillig	Trolley	Transit Bus	CNG	Cummins L9N 8.9L Near Zero
Global	M4 M4HSD CNG	Street Sweeper	CNG	Cummins B6.7N Near Zero
Heil Environmental	Front Loader: Half Pack (incl Automated), Half Pack Sierra, Half Pack LowRider (incl Automated)	Refuse	CNG	Cummins L9N 8.9L Near Zero
Heil Environmental	Rear Loader: PT1100, PowerTrak Commercial, DuraPack 5000, DuraPack 4060 Split Body, PT1000	Refuse	CNG	Cummins L9N 8.9L Near Zero
Heil Environmental	Side Loader: DuraPack Python, DuraPack Rapid Rail, Liberty, Rapid Rail	Refuse	CNG	Cummins L9N 8.9L Near Zero
Hometown Manufacturing	Carriage	Passenger Van Shuttle Bus	CNG Propane	Ford 7.3L V8
Hometown Manufacturing	Commuter	Transit Bus	CNG	Cummins L9N 8.9L Near Zero
Hometown Manufacturing	Low-Floor Urban	Transit Bus	CNG	Cummins L9N 8.9L Near Zero
Hometown Manufacturing	Mainstreet	Passenger Van Shuttle Bus	CNG	Cummins L9N 8.9L Near Zero
Hometown Manufacturing	Streetcar	Passenger Van Shuttle Bus	CNG	Cummins L9N 8.9L Near Zero
Hometown Manufacturing	View	Transit Bus	Propane CNG	Ford 7.3L V8
Hometown Manufacturing	Villager	Passenger Van Shuttle Bus	CNG Propane	Ford 7.3L V8
Kenworth	T180 T280	Vocational Cab Chassis	CNG LNG	Cummins L9N 8.9L Near Zero
Kenworth	T380 T480	Vocational Cab Chassis	CNG LNG	Cummins L9N 8.9L Near Zero
Mack	Anthem - Class 8	Tractor	CNG LNG	Cummins ISX12N 11.9L Near Zero

Mack	Granite	Vocational Cab Chassis	CNG LNG	Cummins L9N 8.9L Near Zero
Mack	LR	Refuse	LNG CNG	Cummins L9N 8.9L Near Zero
Mack	LR	Vocational Cab Chassis	LNG CNG	Cummins L9N 8.9L Near Zero
Mack	TerraPro Cab Over	Vocational Cab Chassis	LNG CNG	Cummins L9N 8.9L Near Zero
Mack	TerraPro Cab Over	Refuse	LNG CNG	Cummins L9N 8.9L Near Zero
MCI	D4000 Commuter Coach	Transit Bus	CNG	Cummins ISX12N 11.9L Near Zero
MCI	D4500 Commuter Coach	Transit Bus	CNG	Cummins ISX12N 11.9L Near Zero
McNeilus	Atlantic Front Loader - Class 8	Refuse	CNG	Cummins L9N 8.9L Near Zero Cummins ISX12N 11.9L Near Zero
McNeilus	Rear Loader: Standard, Heavy-Duty, Extra Compaction,Tag Axle, Split Body, M2 - Class 8	Refuse	CNG	Cummins ISX12N 11.9L Near Zero Cummins L9N 8.9L Near Zero
McNeilus	Side Loader: AutoReach, Manual Automated, Zero Radius - Class 8	Refuse	CNG	Cummins L9N 8.9L Near Zero Cummins ISX12N 11.9L Near Zero
McNeilus	Standard, Bridgemaster, Oshkosh S-Series - Class 8	Vocational Cab Chassis	CNG	Cummins ISX12N 11.9L Near Zero Cummins L9N 8.9L Near Zero
New Flyer	Xcelsior CNG 35'	Transit Bus	CNG	Cummins L9N 8.9L Near Zero
New Flyer	Xcelsior CNG 40'	Transit Bus	CNG	Cummins L9N 8.9L Near Zero
New Flyer	Xcelsior CNG 60'	Transit Bus	CNG	Cummins L9N 8.9L Near Zero
Nitehawk	Osprey II sweeper	Street Sweeper	Propane - Bi-fuel	GMC 6.0L V8
Nitehawk	Raptor II sweeper	Street Sweeper	CNG Propane - Bi-fuel	GMC 6.0L V8
Nova Bus	LFS CNG - Class 8	Transit Bus	CNG	Cummins L9N 8.9L Near Zero
Peterbilt	365 - Class 6	Vocational Cab Chassis	CNG LNG	Cummins B6.7N Near Zero Cummins L9N 8.9L Near Zero
Peterbilt	520	Vocational Cab Chassis	CNG	Cummins L9N 8.9L Near Zero Cummins ISX12N 11.9L Near Zero
Peterbilt	535 - Class 5	Vocational Cab Chassis	CNG LNG	Cummins B6.7N Near Zero
Peterbilt	536 - Class 6	Vocational Cab Chassis	LNG CNG	Cummins B6.7N Near Zero Cummins L9N 8.9L Near Zero
Peterbilt	537 - Class 7	Vocational Cab Chassis	LNG CNG	Cummins L9N 8.9L Near Zero Cummins B6.7N Near Zero
Peterbilt	548 - Class 8	Vocational Cab Chassis	LNG CNG	Cummins B6.7N Near Zero Cummins L9N 8.9L Near Zero
Peterbilt	567 - Class 8	TractorVocational Cab Chassis	CNG LNG	Cummins L9N 8.9L Near Zero Cummins ISX12N 11.9L Near Zero
Peterbilt	579	TractorVocational Cab Chassis	CNG LNG	Cummins ISX12N 11.9L Near Zero
Schwarze Industries	A7 Tornado sweeper - Class 6	Street Sweeper	CNG	
Schwarze Industries	A7 Zephyr sweeper - Class 6	Street Sweeper	CNG	
Schwarze Industries	M6 Avalanche	Street Sweeper	CNG	
TICO	Pro Spotter	Tractor	CNG LNG	Cummins B6.7N Near Zero

TYMCO	500x	Street Sweeper	CNG	Cummins L9N 8.9L Near Zero
TYMCO	600	Street Sweeper	CNG	Cummins L9N 8.9L Near Zero
TYMCO	HSP	Street Sweeper	CNG	Cummins L9N 8.9L Near Zero

1.4.4 Hydrogen-Fueled Internal Combustion Engines

Currently, hydrogen fueled internal combustion engines (H2-ICE) are in the demonstration stage. H2-ICE is a technology that provides nearly zero tailpipe emissions for hydrocarbons, carbon monoxide, and carbon dioxide. H2-ICE require less exhaust aftertreatment. These systems may not require the particulate filter (DPF) components. However, NOx emissions are still formed during the H2-ICE combustion process and therefore a selective catalytic reduction (SCR) system and diesel oxidation catalyst (DOC) would be required, though it may be smaller in size than that used in a comparable diesel-fueled ICE. The use of lean air-fuel ratios, and not exhaust gas recirculation (EGR), is the most effective way to control NO_x in a H2-ICE, as EGR is less effective with H2 due to the absence of CO_2 in the exhaust gas.

H2-ICE can be developed using an OEM’s existing tooling, manufacturing processes, and engine design expertise. H2-ICE engines are very similar to existing ICEs and can leverage the extensive technical expertise manufacturers have developed with existing products. Similarly, H2-ICE products can be built on the same assembly lines as other ICE vehicles, by the same workers and with many of the same component suppliers.

H2-ICE incorporate several differences from their diesel baseline. Components such as the cylinder head, valves, seals, piston, and piston rings would be unique to the H2-ICE to control H2 leakage during engine operation. Another difference between a diesel-fueled ICE and a H2-ICE is the fuel storage tanks. The hydrogen storage tanks are more expensive than today’s diesel fuel tanks. The fuel tanks likely to be used by H2-ICE are identical to those used by a fuel cell electric vehicle (FCEV) and they may utilize either compressed storage (350 or 700 Bar pressure) or cryogenic storage (temperatures as low as -253 Celsius). Please refer to Chapter 1.7.2 of this document for the discussion regarding H2 fuel storage tanks.

H2-ICE may hasten the development of hydrogen infrastructure because they do not require as pure of hydrogen as FCEVs. Hydrogen infrastructure exists in limited quantities in some parts of the country for applications such as forklifts, buses, and LDVs and HDVs at ports. Federal funds are being used to support the development of additional hubs and other hydrogen related infrastructure items through the BIL and IRA, as described in more detail in Chapter 1.8.

Since neat hydrogen fuel does not contain any carbon, H2-ICE fueled with neat hydrogen produce zero HC, CH_4, CO, and CO_2 engine-out emissions.[142] However, as explained in Section III.C.2.xviii, we recognize that, like CI ICE, there may be negligible, but non-zero, CO_2 emissions at the tailpipe of H2-ICE that use SCR and are fueled with neat hydrogen due to contributions from the aftertreatment system from urea decomposition; thus, for purposes of 40 CFR 1036 we are finalizing an engine testing default CO_2 emission value (3 g/hp-hr) option (though manufacturers may instead conduct testing to demonstrate that the CO_2 emissions for their engine is below 3 g/hp-hr). Under this final rule, consistent with treatments of such

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[142] Note, NOx and PM emission testing is required under existing 40 CFR part 1036 for engines fueled with neat hydrogen.

contributions from the aftertreatment system from urea decomposition for diesel ICE vehicles, we are not including such contributions as vehicle emissions for H2-ICE vehicles.[143] Thus, H2-ICE technologies that run on neat hydrogen, as defined in 40 CFR 1037.150(f) and discussed in Section III.C.3.ii of the preamble, have HD vehicle CO_2 emissions that are deemed to be zero for purposes of 40 CFR 1037. Therefore, the technology effectiveness (in other words CO_2 emission reduction) for the vehicles that are powered by this technology is 100 percent.

1.4.5 Hybrid and Plug-in Hybrid Powertrains

The heavy-duty industry has also been developing hybrid powertrains, as shown in Table 1-20. Hybrid powertrains consist of an ICE as well as an electric drivetrain. The ICE uses a consumable fuel (e.g., diesel) to produce power which can either propel the vehicle directly or charge the traction battery from which the electric motor draws its energy. These two sources of power can be used in combination to do work and move the vehicle, or they may operate individually, switching between the two sources. Plug-in hybrid electric vehicles (PHEVs) are a combination of ICE and electric vehicles, so they have an ICE and a battery, an electric motor, and a fuel tank, and plug-in to the electric grid to recharge the battery. PHEVs use both gasoline or diesel and electricity as fuel sources.

Table 1-20 Heavy-Duty Hybrid Vehicle Examples[144]

Manufacturer	Model	Category	Fuel	Transmission Make	Heavy-Duty Power System
Elgin	Broom Bear CNG Hybrid	Street Sweeper	Plug-in Hybrid Electric|CNG - Compressed Natural Gas		Cummins L9N 8.9L Near Zero
Elgin	Broom Bear Plug-In Hybrid	Street Sweeper	Diesel/Hybrid Electric|Plug-in Hybrid Electric		Cummins ISL 9L
ENC	AXESS 32'	Transit Bus	Diesel/Hybrid Electric	Allison, Voith, ZF	Cummins ISL 9L|Allison Transmission hybrid drive
ENC	AXESS 35'	Transit Bus	Diesel/Hybrid Electric	Allison, Voith, ZF	Cummins ISL 9L|Allison Transmission hybrid drive
ENC	AXESS 40'	Transit Bus	Diesel/Hybrid Electric	Allison, Voith, ZF	Cummins ISL 9L|Allison Transmission hybrid drive
ENC	E-Z RIDER II 30'	Transit Bus	Diesel/Hybrid Electric	Allison, Voith, ZF	Cummins ISL 9L|Cummins

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[143] The results from the fuel mapping test procedures prescribed in 40 CFR 1036.535 are fuel consumption values, therefore the CO_2 emissions from urea decomposition is not included in the results.

[144] Department of Energy Alternative Fuels Data Center. Available Online: https://afdc.energy.gov/vehicles/search/results?view_mode=grid&search_field=vehicle&search_dir=desc&per_page=8&current=true&display_length=25&model_year=2024&fuel_id=57,45,61,-1&all_categories=y&manufacturer_id=67,205,117,394,415,201,113,5,408,481,9,13,11,458,81,435,474,57,416,141,197,417,121,475,53,397,418,85,414,17,21,143,476,492,23,484,398,27,477,399,31,207,396,489,107,465,487,193,460,35,459,115,37,147,480,199,-1

					ISB6.7|Allison Transmission hybrid drive|BAE Systems HybriDrive
ENC	E-Z RIDER II 32'	Transit Bus	Diesel/Hybrid Electric	Allison, Voith, ZF	Cummins ISL 9L|Cummins ISB6.7|Allison Transmission hybrid drive|BAE Systems HybriDrive
ENC	E-Z RIDER II 35'	Transit Bus	Diesel/Hybrid Electric	Allison, Voith, ZF	Cummins ISB6.7|Cummins ISL 9L|BAE Systems HybriDrive|Allison Transmission hybrid drive
Gillig	BRT, BRT Plus, Commuter	Transit Bus	Diesel/Hybrid Electric	Voith, Allison, ZF	Cummins ISB6.7|Cummins ISL 9L
Gillig	Low Floor, Low Floor Plus	Transit Bus	Diesel/Hybrid Electric		
Global	M4 Hybrid	Street Sweeper	Diesel/Hybrid Electric	Global	Cummins ISB6.7
Hometown Manufacturing	Streetcar	Passenger Van/Shuttle Bus	Diesel/Hybrid Electric	Allison B300, B400	Cummins ISB6.7
MCI	D4000 Commuter Coach	Transit Bus	Diesel/Hybrid Electric	Allison	Cummins ISL 9L
MCI	D4500 Commuter Coach	Transit Bus	Diesel/Hybrid Electric	Allison	Cummins ISL 9L
New Flyer	Xcelsior Hybrid 35'	Transit Bus	Diesel/Hybrid Electric	Allison, BAE	Cummins ISB6.7|Allison Transmission hybrid drive|BAE Systems HybriDrive
New Flyer	Xcelsior Hybrid 40'	Transit Bus	Diesel/Hybrid Electric	Allison, BAE	Cummins ISB6.7|Allison Transmission hybrid drive|BAE Systems HybriDrive
New Flyer	Xcelsior Hybrid 60'	Transit Bus	Diesel/Hybrid Electric	Allison, BAE	Cummins ISL 9L|BAE Systems HybriDrive|Allison Transmission hybrid drive
Nova Bus	LFS Artic HEV - Class 8	Transit Bus	Diesel/Hybrid Electric	Allison, BAE	Cummins ISL 9L|Allison Transmission H 50 EP|BAE Systems HDS300
Nova Bus	LFS HEV - Class 8	Transit Bus	Diesel/Hybrid Electric	Allison, BAE	Cummins ISB6.7

Hybrid powered vehicles can provide CO_2 emission reductions from splitting or blending of ICE and electric operation. Hybrid vehicles reduce CO_2 emissions through four primary mechanisms:

- In a series hybrid powertrain, the ICE operates as a generator to create electricity for the battery. Series hybrids can be optimized through downsizing, modifying the operating cycle, or other control techniques to operate at or near its most efficient engine speed-load conditions more often than is possible with a conventional engine-transmission driveline. Power loss due to engine downsizing can be mitigated by employing power assist from the secondary, electric driveline.
- Hybrid vehicles typically include regenerative braking systems that capture some of the energy normally lost while braking and store it in the traction battery for later use. That stored energy is typically used to provide additional torque upon initial acceleration from stop or additional power for moving the vehicle up a steep incline.
- Hybrid powertrains allow the engine to be turned off when it is not needed, such as when the vehicle is coasting or when the vehicle is stopped. Furthermore, some vehicle systems such as cabin comfort and power steering can be electrified if a 48V or higher battery system is incorporated into the vehicle. The electrical systems are more efficient than their conventional counterparts which utilize an accessory drive belt on a running engine. When the engine is stopped these accessory loads are supported by the traction battery.
- Plug-in hybrid vehicles can further reduce CO_2 emissions by increasing the battery storage capacity and adding the ability to connect to the electrical power grid to fully charge the battery when the vehicle is not in service, which can significantly expand the amount of all-electric operation.

Hybrid vehicles can utilize a combination of some or all of these mechanisms to reduce fuel consumption and CO_2 emissions. The magnitude of the CO_2 reduction achieved depends on the utilization/optimization of the above mechanisms and the powertrain design decisions made by the manufacturer.

Hybrid technology is well established in the U.S. light-duty market, where some manufacturers have been producing light-duty hybrid models for several decades and others are looking to develop hybrid models in the future. Hybrid powertrains are available today in a number of heavy-duty vocational vehicles including passenger van/shuttle bus, transit bus, street sweeper, refuse hauler, and delivery truck applications. Hybrid transit buses have been purchased for use in cities including Philadelphia, PA and Toronto, Canada. Heavy-duty hybrid vehicles may include a power takeoff (PTO) system that is used to operate auxiliary equipment, such as the boom/bucket on a utility truck or the water pump on a fire truck. Utility trucks with electric PTOs where the electricity to power the auxiliary equipment can be provided by the battery have been sold.

Plug-in hybrid electric vehicles run on both electricity and fuel. Many PHEV models are available today in the light-duty market.[145] Today there is a limited number of PHEV heavy-duty models. Light-duty manufacturers that also produce heavy-duty vehicle could bring PHEVs to market in the LHD and MHD segments in less time than for the HHD and tractor segments. The utility factor is the fraction of miles the vehicle travels in electric mode relative to the total miles traveled. The percent CO_2 emission reduction is directly related to the utility factor. The greater the utility factor, the lower the tailpipe CO_2 emissions from the vehicle. The utility factor depends on the size of the battery and the operator's driving habits.

1.5 Battery Electric Vehicle Technologies

The application of battery electric vehicle technologies primarily results in the effective replacement of the ICE powertrain with a battery electric propulsion system. The battery electric propulsion system includes a battery pack that provides the power to the motor to move the vehicle.

Battery technology improvements are being widely researched in industry and academia with goals to lengthen vehicle range and increase battery life. Examples of battery technologies that would result in a significant jump in battery performance include semi-solid state and solid-state designs. Improvements in charging strategies can also increase a battery's operational life and have been demonstrated in transit bus applications.

1.5.1 Batteries

The batteries used for today's BEVs are highly advanced; however, the fundamental theory of the battery continues to include two half-cell electrodes separated by a membrane separator that is submerged in a conductive electrolyte. These half-cells, together, make up a battery cell. During charge and discharge cycles, a chemical reaction takes place at each of the electrodes when ions, such as lithium, move through a conductive medium between the electrodes. Here, an electron is either released or consumed, in turn generating an electric current. This electricity is used to perform work-- converting the electric current into mechanical work using an electric motor. While some heat is generated during the chemical process, all reactions are contained within the cell and no emissions are produced from the battery cell itself on-board the vehicle.

1.5.1.1 Battery Design Parameters

Battery design involves balancing considerations of cost[146] and performance parameters including specific energy[147] and power, energy density[148], temperature impact on performance,

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[145] US Department of Energy. Fueleconomy.gov. Available online: https://fueleconomy.gov/feg/PowerSearch.do?action=alts&path=3&year=2024&vtype=Plug-in+Hybrid&srchtyp=yearAfv&rowLimit=50&pageno=1

[146] Cost, here, is associated with cost of the battery design produced at scale instead of the decrease in cost of batteries from high volume production. This cost may be associated with using more expensive minerals (nickel and cobalt instead of iron phosphate). Alternatively, some battery cell components may be more expensive for the same chemistry. For example, power battery cells are more expensive to manufacture than energy battery cells because these cells require thinner electrodes which are more complex to produce.

[147] Battery specific energy (also referred to as gravimetric energy density) is a measure of battery energy per unit of mass.

[148] Battery energy density (also referred to as volumetric energy density) is a measure of battery energy per unit of volume.

durability, and safety. These parameters typically vary based on the battery chemistry of the cathode and anode materials, and the conductive electrolyte medium at the cell level. Different battery chemistries have different intrinsic values. External factors such as ambient temperature can also affect the performance of the battery. There are extensive bodies of work within each of these areas that are beyond the scope of this document. Nonetheless, because of the novel nature of these technologies for HD application, we provide a brief overview of the different energy and power capacities of batteries depending on their battery chemistries.

Design choices about the different energy and power capacities to emphasize in a battery can depend on its battery chemistry. Common battery chemistries today include nickel-manganese-cobalt (NMC), nickel-cobalt-aluminum (NCA), and iron-phosphate (LFP) based-chemistries. Nickel-based chemistries typically have higher gravimetric and volumetric energy densities than iron phosphate-based chemistries. Batteries have a nested design: a group of cells are typically placed inside a module and a group of modules are placed inside a pack. While the modules and packs provide design simplicity and structure support, energy or power is only housed at the chemistry level. Therefore, any additional mass such as the cell, module, and pack casings will only add to the weight of the battery without increasing the energy of the overall system. In recent years, some pack producers have eliminated the module in favor of a "cell-to-pack" design.[149] Here, the module is eliminated where cells are placed directly into battery packs without the intermediate module component; the purpose is to reduce both weight and volume of the battery pack and thus increase the specific energy and energy density of the pack, respectively.

Specific energy and power and energy density are a function of how much energy or power can be stored per unit mass or volume; these values typically have units of Watt-hour per kilogram (Wh/kg), Watt per kilogram (W/kg) or Watt-hour per liter (Wh/L), respectively. Therefore, for a given battery weight, the energy (in kilowatt-hour or kWh) can be calculated. A battery chemistry with high specific energy and a lower weight may yield the same amount of energy as a battery chemistry with a lower specific energy and higher weight. An example of this can be found in Table 1-21.

Table 1-21 Battery weight and volume to meet vehicle requirement for two different chemistries

Battery Chemistry	Vehicle Energy Requirement (kWh)	Specific Energy (Wh/kg)	Weight of Battery (kg)	Energy Density (Wh/L)	Volume of Battery (L)
A	100	200	500	400	250
B	100	100	1,000	200	500

External factors, especially temperature, can have a strong influence on the performance of the battery; for example, lower temperatures typically result in lower useable energy. For more efficient operation, batteries are maintained at a particular operating temperature range; this is commonly referred to as conditioning of the battery. Heavy-duty BEVs today include thermal management systems to keep the battery operating within a desired temperature range. If the battery is plugged in overnight, the manufacturer may allow for grid energy to maintain this temperature range. Generally, this is referred to as pre-conditioning. However, during vehicle

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[149] BYD's "blade" cells are an example of cell-to-pack technology.

operation, the energy will have to come from the energy stored within the battery itself without the ability to rely on grid energy. Therefore, additional energy for battery conditioning will be required for vehicles operating in hot and cold climates.[150] Cold temperatures, in particular, can result in reduced useable energy as a result of reduced mobility of the lithium ions in the liquid electrolyte; for the driver, this may mean lower range. Battery thermal management is also used during hot ambient temperatures to keep the battery from overheating.

Another important battery design consideration is the durability of the battery. Durability is frequently associated with cycle life, where cycle life is the number of times a battery can fully charge and discharge before the battery is no longer usable for its original purpose. In 2015 the United Nations Economic Commission for Europe (UN ECE) began studying the need for a Global Technical Regulation (GTR) governing battery durability in light-duty vehicles. In 2021 it finalized United Nations Global Technical Regulation No. 22, "In-Vehicle Battery Durability for Electrified Vehicles,"[151] or GTR No. 22, which provides a regulatory structure for contracting parties to set standards for battery durability in light-duty BEVs and PHEVs. Likewise, although not finalized, the UN ECE GTR working group began drafting language for HD BEVs and PHEVs. Loss of electric range could lead to a loss of utility, meaning electric vehicles are driven less and therefore displace less distance travelled that might otherwise be driven in conventional vehicles. Furthermore, a loss in utility could also dampen purchaser sentiment.

For batteries that are used in HD BEVs, the state-of-health (SOH) is an important design factor.[152] The environmental performance of electrified vehicles may be affected by excess degradation of the battery system over time. However, the durability of a battery is not limited to the cycling of a battery; there are many phenomena that can impact the duration of usability of a battery. As a battery goes through charge and discharge cycles, the SOH of the battery decreases. Capacity fade, increase in internal resistance, and voltage loss, for example, are other common metrics to measure the SOH of a battery. These parameters together help better determine and define the longevity or durability of the battery. The SOH and, in turn, the cycle life of the battery is determined by both the chemistry of the battery as well as external factors including temperature. The rate at which the battery is discharged as well as the rate at which it is charged will also impact the SOH of the battery. Lastly, calendar aging, or degradation of the battery while not in use, can also contribute to the deterioration of the battery.

There are a number of ways to improve and prolong the battery life in a vehicle. We included additional energy for conditioning the battery in our analysis for sizing the batteries and for operating costs. Furthermore, we considered the impact of deterioration on battery size. This is discussed in Chapter 2.4.1.

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[150] AAA Report. “AAA Electric Vehicle Range Testing: AAA proprietary research into the effect of ambient temperature and HVAC use on driving range and MPGe”. Available on: https://www.aaa.com/AAA/common/AAR/files/AAA-Electric-Vehicle-Range-Testing-Report.pdf

[151] United Nations Economic Commission for Europe, Addendum 22: United Nations Global Technical Regulation No. 22, United Nations Global Technical Regulation on In-vehicle Battery Durability for Electrified Vehicles, April 14, 2022. Available at: https://unece.org/sites/default/files/2022-04/ECE_TRANS_180a22e.pdf

[152] See Section III.B of the preamble for information on the durability monitoring requirements we are finalizing.

1.5.1.2 Critical Minerals and Battery Market

In Section II.D.2.ii.c of the Preamble and RTC section 17.2, we provide a thorough analysis of recent events in the growth of U.S. and global battery manufacturing capacity, review the role and importance of critical minerals, and considered the outlook for availability of both the critical minerals themselves, and their related supply chains. Citations for the content in this section can be found in Preamble Section II.D.2.ii.c, except where cited here. We show there that of the four minerals considered critical for battery manufacture (lithium, cobalt, nickel, and graphite), domestic lithium supply and refining capacity plus capacity available from Free Trade Agreement (FTA) countries appears to be largely sufficient to accommodate domestic lithium-ion battery demand in the mid- and long-term, and that the U.S. could be one of the worldwide leaders in production by 2035. The three remaining critical minerals, are unlikely to be sourced domestically within the rule's timeframe, but can be adequately sourced by supplies from FTA and Mineral Security Partnership (MSP) countries, and (for cobalt and graphite in particular) from other countries with which the U.S. has strong ties as well (for example through defense treaties or other agreements or partnerships). In this regard, we discuss the bilateral and multi-lateral agreements with various non-FTA/MSP countries that help provide an assurance of supply. We also discuss availability of manganese, which is important to battery manufacture but is not classified as a critical mineral, and examine pathways to securing manganese supply. The focus on lithium, cobalt, nickel, manganese, and graphite, stems from the fact that their increased use is unique to BEVs compared with ICE vehicles (Figure 1-5 below)

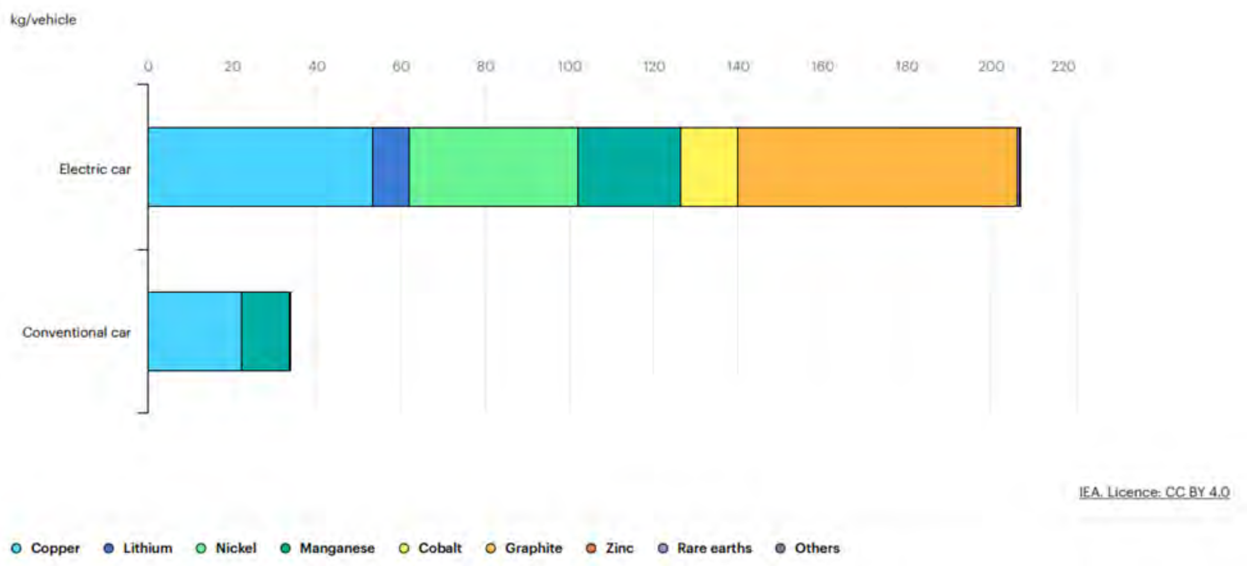

Figure 1-5 Minerals used in electric cars compared to conventional cars

In those same Preamble and RTC discussions, we show that there is sufficient battery cell production capacity to satisfy demand from the heavy-duty sector. We further discuss availability of supply for battery components, including cathode and anode active materials.

We also note that further development of a secure, diversified mineral supply chain is already being accelerated by the provisions of the Inflation Reduction Act (IRA) and the Bipartisan Infrastructure Law (BIL), as well as ongoing efforts by the Executive Branch:

- The IRA offers sizeable tax incentives for domestic production of batteries and critical minerals, including production tax credits that apply to domestically produced cells, modules, and packs, electrode active materials, and critical minerals, that can reduce battery manufacturing cost by thirty percent or more.
- The BIL provides $7.9 billion to support development of the domestic supply chain for battery manufacturing, recycling, and critical minerals. Provisions extend across critical minerals mining and recycling research, USGS energy and minerals research, rare earth elements extraction and separation research and demonstration, and expansion of DOE loan programs in critical minerals and recycling.
- Through these provisions, DOE is actively working to prioritize points in the domestic supply chain to target with accelerated development, and rapidly funding those areas through numerous programs and funding opportunities.
- With BIL funding and heavy private investment[153], more than half of the capital investment that the Department of Energy's Li-Bridge alliance considers necessary for supply chain investment to 2030 has already been committed.

- The White House announced the IPEF Critical Minerals Dialogue, an initiative to support U.S. expansion and development of the critical mineral supply chain. IPEF is the Indo-Pacific Economic Framework for Prosperity (IPEF), a partnership between Australia, Brunei, Fiji, India, Indonesia, Japan, Republic of Korea, Malaysia, New Zealand, the Philippines, Singapore, Thailand, and Viet Nam[154].More broadly, the IPEF’s pillars spanning trade, supply chains, clean economy, and fair economy form a foundation to ensure tangible benefits that fuel economic activity and investment, promote sustainable and inclusive economic growth, and benefit workers and consumers across the region.[155] The IPEF Supply Chain Agreement entered into force on February 24, 2024.[156]

- The State Department also sent delegations to Chile, the Philippines, and South Korea, led by Under Secretary Jose W. Fernandez, to strengthen cooperation around critical mineral supply chains. [157]

- The State Department launched the Minerals Investment Network for Vital Energy Security and Transition, or MINVEST, in 2023: a public-private partnership between the

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[153] Automotive News. “Private companies fund most EV battery manufacturing investment, DOE says”. Available online: https://www.autonews.com/suppliers/us-ev-battery-manufacturing-investment-led-private-companies-doe-says

[154] The White House. “FACT SHEET: In San Francisco, President Biden and 13 Partners Announce Key Outcomes to Fuel Inclusive, Sustainable Growth as Part of the Indo-Pacific Economic Framework for Prosperity”. November 16, 2023. Available online: https://www.whitehouse.gov/briefing-room/statements-releases/2023/11/16/fact-sheet-in-san-francisco-president-biden-and-13-partners-announce-key-outcomes-to-fuel-inclusive-sustainable-growth-as-part-of-the-indo-pacific-economic-framework-for-prosperity/

[155] UD Department of Commerce. “Indo-Pacific Economic Framework. Accessed March 11, 2024. Available online: https://www.commerce.gov/ipef

[156] U.S. Department of Commerce. “U.S. Department of Commerce Announces Upcoming Entry into Force of the IPEF Supply Chain Agreement”. Available online: https://www.commerce.gov/news/press-releases/2024/01/us-department-commerce-announces-upcoming-entry-force-ipef-supply-chain

[157] U. S. Department of State. “Under Secretary Fernandez’s Travel to Vietnam, the Philippines, and the Republic of Korea”. January 19, 2024. Available online: https://www.state.gov/under-secretary-fernandezs-travel-to-vietnam-the-philippines-and-the-republic-of-korea/

U.S. Department of State and SAFE Center for Critical Minerals Strategy to spur investment in mining, processing, and recycling opportunities.[158] The State Department's ambassadors and commercial experts also connect U.S. companies with mining and opportunities internationally through the Direct Line for American Business program.[159]

- The White House and the European Union together announced support for the Lobito Corridor, which connects the Democratic Republic of the Congo and Northwest Zambia to regional and global trade through the Port of Lobito in Angola. The corridor will reduce transport time, lower costs, and reduce the carbon footprint of metals exports from the region. The United States and the E.U. also intend to support sustainable economic development in the three countries, including clean energy projects and supporting diversified investment in critical minerals and clean energy supply chains.[160] In February 2024, the MSP announced the signing of an MOU between DRC's state mining company, Gecamines, and the Japan Organization for Metals and Energy Security (JOGMEC), to collaborate on exploration, production, and processing of critical minerals in the DRC.[161]Shortly thereafter, Gecamines announced the transfer of exclusive mining rights for five mining areas to its subsidiary Entreprise Generale du Cobalt (EGC); EGC Chairman describes this action as "the beginning of the standardization of artisanal cobalt mining," which has been linked to human rights violations.[162]

- The U.S. Trade Representative facilitated an agreement between the U.S. and India to develop a roadmap on critical minerals and supply chains to increase cooperation and achieve economically meaningful outcomes.[163]

- The USGS collaborated with the federal geological surveys of Canada and Australia to release a compilation of minerals resource datasets.[164]

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[158] U. S. Department of State. "MINVEST: Minerals Investment Network for Vital Energy Security and Transition". Available online: https://www.state.gov/minvest

[159] U.S. Department of State. "Direct Line for American Business". Available online: https://www.state.gov/direct-line-for-americanbusiness/

[160] The White House. "Joint Statement from the United States and the European Union on Support for Angola, Zambia and the Democratic Republic of the Congo's commitment to Further Develop the Lobito Corridor and the U.S.-EU Launch of a Greenfield Rail Line Feasibility Study". September 9, 2023. Available online: https://www.whitehouse.gov/briefing-room/statements-releases/2023/09/09/joint-statement-from-the-united-states-and-the-european-union-on-support-for-angola-zambia-and-the-democratic-republic-of-the-congos-commitment-to-further-develop-the-lobito-corridor-and-the/

[161] U.S. Department of State. "The Minerals Security Partnership Announces Collaboration in Minerals Exploration, Production, and Processing Between GECAMINES in the Democratic Republic of the Congo and JOGMEC in Japan". February 5, 2024. Available online: https://www.state.gov/the-minerals-security-partnership-announces-collaboration-in-minerals-exploration-production-and-processing-between-gecamines-in-the-democratic-republic-of-the-congo-and-jogmec-in-japan/

[162] Reuters. "Congo's Gecamines and Entreprise Generale du Cobalt sign mining deal". February 7, 2024. Available online: https://www.reuters.com/markets/commodities/congos-gecamines-entreprise-generale-du-cobalt-sign-mining-deal-2024-02-07/

[163] Office of the United States Trade Representative. "Joint Statement on the United States-India Trade Policy Forum". January 12, 2024. Available online: https://ustr.gov/about-us/policy-offices/press-office/press-releases/2024/january/joint-statement-united-states-india-trade-policy-forum

[164] U.S. Geological Survey. "Australia, Canada and US Unify Critical Minerals Data. August 17, 2023. Available online: https://www.usgs.gov/news/technical-announcement/australia-canada-and-us-unify-critical-minerals-data

- USAID granted funds through the Just Energy Transition Green Minerals Challenge to 11 partners across 15 countries throughout Africa, Asia, and Latin America, to combat corruption and increase transparency and integrity in global critical minerals supply chains.[165]
- DOI, through its International Technical Assistance Program, is working with partners around the world to advance technical capacity and improve governance for clean energy minerals projects. Recent work includes working with Argentina to build capacity for sustainable lithium development.[166]
- USAID, in collaboration with the U.S. Commercial Service, formalized a $5 million technical assistance program to develop the Philippines' critical minerals sector.[167]
- In September 2023, President Biden met with the presidents of Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan (C5+1), launching the C5+1 Critical Minerals Dialogue and committing to principles of partnership. The Dialogue aims to strengthen economic cooperation, support sustainable development, and advance the development of a robust minerals industry in the region.[168]
- The U.S. Trade and Development Agency (USTDA), which advances economic development and U.S. export opportunities abroad, recently accepted proposals for a contractor to assess potential critical minerals projects in Sub-Saharan Africa.[169]

EPA recognizes that the global minerals industry and battery supply chain are already anticipating and preparing for accelerated growth in demand for critical minerals resulting from already-existing expectations of greatly increased global ZEV production and sales in the future, as well as expectations of growing demand for these materials in other areas of clean energy and decarbonization. Thus, in the context of evaluating the impact of the final standards on demand for critical minerals and development of the domestic supply chain, EPA recognizes that much of the anticipated growth in global mineral demand stems not from the incremental effect of the final standards but from these ongoing forces that are already driving the global industry to increase mineral production. While the U.S. will need imports to bolster supply for most key minerals, these imports can come from friendly nations, and is also bolstered by growing domestic supply, especially for lithium. The analysis also finds that, with the appropriate policies and enabling approaches in place, the U.S. is capable of securing the minerals it needs by relying on domestic production as well as trade relationships with allies and partners (Figure 1-6).

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[165] United States Agency for International Development. "Powering a Just Energy Transition Green Minerals Challenge". Available online: https://www.usaid.gov/anti-corruption/document/powering-just-energy-transition-green-minerals-challenge

[166] U.S. Department of the Interior. "Energy and Minerals". Available online: https://www.doi.gov/itap/energy-and-minerals

[167] U.S. Embassy in the Philippines. "Partnership Launched To Implement U.S.-Funded Php280 Million Program For Philippine Critical Minerals Sector

[168] The White House. "C5+1 Leaders' Joint Statement". September 21, 2023. Available online: https://www.whitehouse.gov/briefing-room/statements-releases/2023/09/21/c51-leaders-joint-statement/

[169] U.S. Trade and Development Corporation. "Clean Energy and Critical Minerals Desk Study: Sub-Saharan Africa". Available online: https://www.ustda.gov/business_opp_ustda/clean-energy-and-critical-minerals-desk-study-sub-saharan-africa/

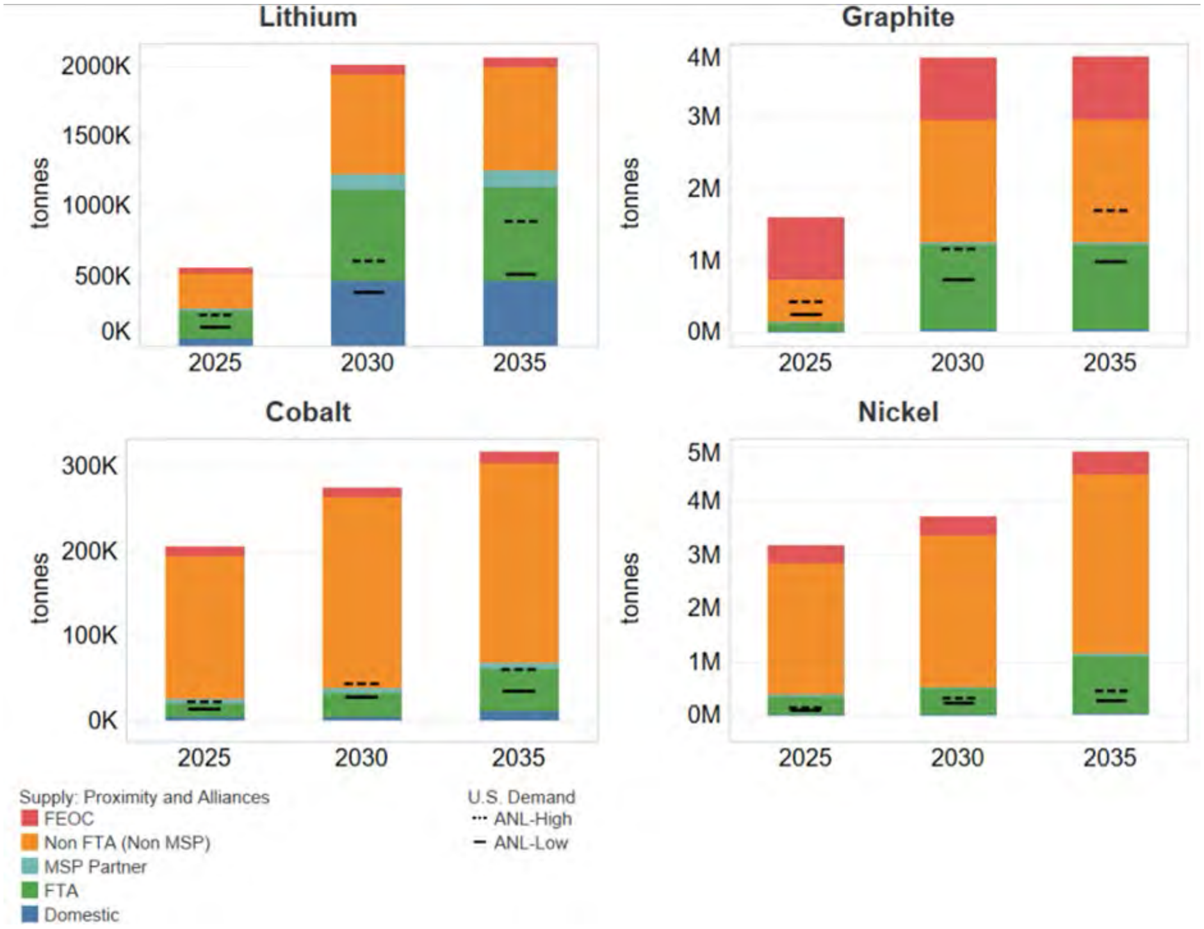

Figure 1-6 Potential upstream mined critical materials supply, tonnes/year, grouped by location of mine production

Relatedly, EPA notes that the IRA, the BIL, and ongoing activity on the part of Executive Branch agencies are actively addressing the need for further development of the domestic supply chain to supply growing demand for critical minerals. The provisions of the IRA and BIL were in fact developed with the intent of growing the domestic supply chain for critical minerals and related products and to achieve mineral security as the industry pursues clean energy technology. Accordingly, EPA expects that the BIL and IRA will prove instrumental in meeting incremental needs of the supply chain under the final standards, and that the ongoing efforts to build and strengthen partnerships with friendly countries are in process to fill any supply gaps that cannot be met domestically.

1.5.1.3 Additional Information on Critical Mineral Supply Chain Development

This section provides additional detailed evidence of recent developments in the growth of the critical mineral supply chain, and other specific topics relevant to this topic. Citations for all of the examples listed in this section may be found in a Memo to the Docket titled "DOE Communication to EPA Regarding Critical Mineral Projects." We then go on to discuss further developments and analysis since proposal (and see preamble section II.D.2.c. ii and RTC section 17.2 for additional information.)

A number of additional U.S. government efforts are underway to accelerate lithium and critical minerals production:

- In February 2023, President Biden signed a presidential waiver of some statutory requirements (Waiver) authorizing the use of the Defense Production Act (DPA) to allow the Department of Defense (DoD) to more aggressively build the resiliency of America's defense industrial base and secure its supply chains including for critical minerals and energy storage. Since many of the investments needed in areas like mining and processing of critical minerals can be very costly and take several years, the Waiver permits the DoD to leverage DPA Title III incentives against critical vulnerabilities, and removes the statutory spending limitation for aggregate action against a single shortfall exceeding $50 million. This in turn allows the DoD to make more substantial, longer-term investments.[170]
- In December 2022, the Blue Ribbon Commission on Lithium Extraction in California issued a report detailing actions to support the further develop geothermal power with the potential co-benefit lithium recovery from existing and new geothermal facilities in the Salton Sea geothermal resource area. The three owners developing projects in California may produce 600 kt/y LCE from geothermal brines around 2030.[171]
- In June 2022, the United States formed the Minerals Security Partnership (MSP),[172] whose goal is to ensure that critical minerals are produced, processed, and recycled in a manner that supports the ability of countries to realize the full economic development benefit of their geological endowments. The MSP will help catalyze investment from governments and the private sector for strategic opportunities — across the full value chain —that adhere to the highest environmental, social, and governance standards.[173] In November 2023, the United States announced a similar further initiative, the Minerals Investment Network for Vital Energy Security and Transition (MINVEST), a new public private partnership with the nonprofit SAFE's Center for Critical Minerals Strategy. The MINVEST Partnership will promote public-private dialogue and spur investment in strategic mining, processing, and recycling

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[170] U.S. Department of Defense. "President Biden Signs Presidential Waiver of Statutory Requirements for Supply Chain Resilience". February 28, 2023. Available online: https://www.defense.gov/News/Releases/Release/Article/3312486/president-biden-signs-presidential-waiver-of-statutory-requirements-for-supply/.

[171] "Report of the Blue Ribbon Commission on Lithium Extraction in California". Available online: https://efiling.energy.ca.gov/GetDocument.aspx?tn=247861. See also the extended discussion and analysis of domestic lithium availability in the report of Argonne National Laboratory discussed in detail in preamble section II.D.2.c.ii and TRC section 17.2.

[172] MSP partners include Australia, Canada, Finland, France, Germany, Japan, the Republic of Korea, Sweden, the United Kingdom, the United States, and the European Commission.

[173] Stark, Vicky. "Italy Joins US-Led Mineral Security Partnership for Ethical Mining". February 6, 2023. Available online: https://www.voanews.com/a/italy-joins-us-led-mineral-security-partnership-for-ethical-mining/6950081.html.

opportunities that adhere to high environmental, social, and governance (ESG) standards.[174]

Preamble II.D.1.ii mentioned $3.4 billion in DOE Loan Program projects that were recently awarded to aid in the extraction, processing and recycling of lithium and other critical minerals to support continued market growth. Details on these projects are provided below.

- A $50M BIL grant to Lilac plans to build out domestic manufacturing capacity for the company's patented ion-exchange technology to increase production of lithium from brine resources with minimal environmental impact and streamlined project development timelines and develop domestic lithium projects.[175]
- A $141.7M BIL grant to Piedmont Lithium plans to accelerate the construction of the Tennessee Lithium project in McMinn County as a world-class lithium hydroxide operation, which is expected to more than double the domestic production of battery-grade lithium hydroxide. The project is being designed to produce lithium hydroxide from spodumene concentrate using the innovative Metso:Outotec process flow sheet, enabling lower emissions and carbon intensity as well as improved capital and operating costs relative to incumbent operations.[176]
- A $150M BIL grant to Albemarle plans to support a portion of the cost to construct a new, commercial-scale U.S.-based lithium concentrator facility at Albemarle's Kings Mountain North Carolina location. Albemarle's "mega-flex" conversion facility would be capable of accommodating multiple feedstocks, including spodumene from the proposed reopening of the company's hard rock mine in Kings Mountain; its existing lithium brine resources in Silver Peak, Nevada, and other global resources; as well as potential recycled lithium materials from existing batteries. The facility is expected to eventually produce up to 100,000 metric tons of battery-grade lithium per year to support domestic manufacturing of up to 1.6 million EVs per year.[177]
- A $700 million DOE loan to Ioneer Rhyolite Ridge LLC plans to help develop domestic processing capabilities of lithium carbonate for nearly 400,000 EV batteries from the Rhyolite Ridge Lithium-Boron Project in Esmeralda County, Nevada.[178]

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[174] U.S. Department of State. "MINVEST: Minerals Investment Network for Vital Energy Security and Transition". Available online: https://www.state.gov/minvest.

[175] Lilac Solutions. "Lilac Solutions Selected by U.S. Department of Energy for $50 Million Award to Unlock U.S. Lithium Production". October 19, 2022. Available online: https://lilacsolutions.com/2022/10/lilac-solutions-selected-by-u-s-department-of-energy-for-50-million-award-to-unlock-u-s-lithium-production/.

[176] Piedmont Lithium. "Piedmont Lithium Selected for $141.7 Million Grant by United States Department of Energy for Tennessee Lithium Project". October 19. 2022. Available online: https://www.businesswire.com/news/home/20221019005681/en/Piedmont-Lithium-Selected-for-141.7-Million-Grant-by-United-States-Department-of-Energy-for-Tennessee-Lithium-Project.

[177] Albemarle Corporation. "Albemarle Secures DOE Grant for U.S.-Based Lithium Facility to Support Domestic EV Supply Chain". PR Newswire. October 19, 2022. Available online: https://www.prnewswire.com/news-releases/albemarle-secures-doe-grant-for-us-based-lithium-facility-to-support-domestic-ev-supply-chain-301653808.html.

[178] U.S. Department of Energy, Loan Programs Office. "LPO Announces Conditional Commitment to Ioneer Rhyolite Ridge to Advance Domestic Production of Lithium and Boron, Boost U.S. Battery Supply Chain". January 13, 2023. Available online: https://www.energy.gov/lpo/articles/lpo-announces-conditional-commitment-ioneer-rhyolite-ridge-advance-domestic-production.

- A $2 billion DOE loan to Redwood Materials plans to construct and expand its battery materials recycling campus in McCarran, Nevada. It would be the first U.S. facility to support production of anode copper foil and cathode active materials in a fully closed-loop lithium-ion battery manufacturing process by recycling end-of-life battery and production scrap and remanufacturing that feedstock into critical materials, supporting EV production of more than 1 million per year. Redwood Materials will use both new and recycled feedstocks—comprised of critical materials like lithium, nickel, and cobalt—to produce approximately 36,000 metric tons per year of ultra-thin battery-grade copper foil for use as the anode current collector, and approximately 100,000 metric tons per year of cathode active materials.[179]
- A $375 million DOE loan to Li-Cycle plans to help finance a high efficiency, low-emission resource recovery facility for batteries in Rochester, New York. The Li-Cycle project will use hydrometallurgical recycling to efficiently recover battery-grade lithium carbonate, cobalt sulfate, nickel sulfate, and other critical materials from manufacturing scrap materials and used batteries to enable a circular economy.[180]

ANL assesses that domestic lithium production is currently limited, but the next decade could see a surge from promising projects that are already underway, potentially satisfying domestic demand and allowing the U.S. to become a global leading producer of lithium depending in part on the progress of permitting and other contingencies common to any new mining operations. As described in Preamble section II.D.2.c.ii.c, the U.S. government is actively working through various programs to streamline U.S. mining as well as promote and pursue partnerships and resource development opportunities in FTA countries, MSP countries, and allies. ANL also notes that in both the near and medium term, a significant portion of domestic lithium demand can be met by lithium in the U.S and in FTA countries, with several MSP partners likely to add capacity. ANL identifies several potential mitigation approaches for any remaining risk, including collaborative efforts with FTA and MSP partners to ensure mining project success in the U.S, FTA and non-FTA countries, pursuing offtake agreements for stockpiling lithium from U.S producers to alleviate downward price pressure that could discourage development of new sources, and strengthening recycling in the U.S. and ally nations.

Regarding lithium, DOE finds that there are significant efforts to scale lithium supply both domestically and also in the FTA countries. The majority of early stage and exploration projects are in Australia, Canada, and the U.S. DOE assesses that the U.S. is well positioned in securing lithium materials domestically, particularly if all projects underway (particularly later stage projects) are successful. Global lithium mining supply is anticipated to more than double in the next five years. In fact, if lithium demand does not match this supply, it could lead to oversupply and create downward price pressure. Several U.S. projects are in the construction stage,

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[179] U.S. Department of Energy, Loan Programs Office. “LPO Offers Conditional Commitment to Redwood Materials to Produce Critical Electric Vehicle Battery Components From Recycled Materials”. February 9, 2023. Available online: https://www.energy.gov/lpo/articles/lpo-offers-conditional-commitment-redwood-materials-produce-critical-electric-vehicle.

[180] U.S. Department of Energy, Loan Programs Office. “LPO Announces a Conditional Commitment for Loan to Li-Cycle’s U.S. Battery Resource Recovery Facility to Recover Critical Electric Vehicle Battery Materials”. February 27, 2023. Available online: https://www.energy.gov/lpo/articles/lpo-announces-conditional-commitment-loan-li-cycles-us-battery-resource-recovery.

including at Fort Cady, Thacker Pass, Rhyolite Ridge, and King Mountains, with others undergoing prefeasibility or feasibility studies, e.g., Great Salt Lake. Through such projects the U.S. lithium supply is expected to more than double by 2025, and the U.S. is poised to become a global key player in lithium industry if all ongoing projects come to fruition and can overtake current key players such as Australia, Argentina and Chile. The majority of U.S. lithium production is likely to come from brines, which are relatively cheaper to produce compared to lithium from spodumene deposits. Both in the near term and the medium term a significant portion of lithium will be available domestically and in FTA countries, likely enough to meet domestic demand. Several FTA and MSP partners, such as Canada and Germany, are likely to add capacity over the medium term, further strengthening U.S. lithium availability. DOE assesses that the U.S. largely has sufficient lithium supply to meet domestic demand of battery manufacturers under a number of reasonable demand scenarios. Only in the near term will the U.S. likely depend on imported lithium, and sufficient additional capacity exists in FTA countries to meet this import demand. Specifically, international trade will continue to be important in the next three years as the U.S. scales domestic production; from 2025, if all U.S. projects currently underway commence production and scale as expected, the U.S. may have sufficient lithium to meet domestic manufacturer demand with an opportunity to be a net exporter of lithium. See generally, ANL at pp. 33-36.

Although currently there is no alternative to lithium in manufacturing on-road BEV batteries, several alternatives are under development that may provide an alternative, either in on-road batteries, or in non-road applications whose use of these alternatives would reduce competition for lithium in on-road applications. Citations for these examples may be found in a memo to the docket.[181]

- BNEF estimates that sodium-ion batteries are scaling for use in applications that do not require the high-performance capabilities of large EV batteries, including stationary energy storage and 2- and 3-wheeled vehicles. Substitution from lithium to alternative chemistries could alleviate price pressures as soon as 2026.[182]
- A new PNNL molten salt battery design, which uses Earth-abundant and low-cost materials, has demonstrated superior charge/discharge capabilities at lower operating temperatures while maintaining high energy storage capacity compared to conventional sodium batteries.[183]
- NASA's Solid-state Architecture Batteries for Enhanced Rechargeability and Safety (SABERS) research for aerospace applications will likely have spin-off benefits for the automotive sector. As lithium-ion based liquid electrolytes are not suitable for aircraft, the development of a scalable, solid state battery that is safer, more energy

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[181] Safoutin, Michael. Memorandum to docket EPA-HQ_OAR-2022-0985. "DOE Communication to EPA Regarding Critical Mineral Projects". April 2023.

[182] BloombergNEF. "Top 10 Energy Storage Trends in 2023". January 11, 2023. Available online: https://about.bnef.com/blog/top-10-energy-storage-trends-in-2023/.

[183] Hede, Karyn. "New Sodium, Aluminum Battery Aims to Integrate Renewables for Grid Resiliency". February 7, 2023. Pacific Northwest National Laboratory. Available online: https://www.pnnl.gov/news-media/new-sodium-aluminum-battery-aims-integrate-renewables-grid-resiliency?utm_campaign=News%20Releases&utm_medium=email&_hsmi=244877345&_hsenc=p2ANqtz-9mA8d2QBIt1O8ZzPiHk_CqrKoJr8IjLhfsBtyTJmoYJmXQbQ7tGvdsdVcg2W4j7c5_LLSmXmd0YZPyV4vMOQX5VcTydQ&utm_content=244877345&utm_source=hs_email.

dense, and capable of faster charging has high commercialization potential in on-road vehicles applications, and can reduce lithium demand.[184,185]

Finally, a large amount of research and development is taking place to increase circularity and effective use of lithium and other critical minerals. Beyond commercial technologies, continued research and development with industry and academia through the United States Advanced Battery Consortium (USABC), Critical Minerals Institute (CMI), and ARPA-E will expand the recycling and recovery of lithium to help expand the use of unconventional supplies to help pace the growing demand for EVs:

- A $2M USABC grant to American Battery Technology Company (ABTC) in Fernley, Nevada will help develop a recycling development program to demonstrate a scaled, fully-domestic, integrated processing cycle for the universal recycling of large format Li-ion batteries in coordination with partners in the battery supply chain.[186]
- The CMI's EC-LEACH project successfully demonstrated a 10x scale-up of electrochemical leaching for lithium-ion batteries black mass, e-waste comprised of crushed and shredded battery cells, with a capacity up to 500 g/day, achieving over 96% leaching efficiency for all metals. The scale up demonstrated leaching under higher voltage while maintaining lower currents and used conventional power electronics.[187,188]
- $39 million in ARPA-E funding for the Mining Innovations for Negative Emissions Resource Recovery (MINER) program will help develop market-ready technologies that will increase domestic supplies of critical elements, including copper, nickel, lithium, cobalt, rare earth elements, that are required for the clean energy transition. The MINER program will fund research that increases the mineral yield while decreasing the required energy, and subsequent emissions, to mine and extract energy-relevant minerals.[189]

EPA has carefully considered the substantive and detailed comments offered by the various commenters regarding battery manufacturing. In light of additional information that EPA has collected through continued research and the public comments, the evidence continues to support our previous assessment that domestic and global battery manufacturing is well positioned to deliver sufficient battery production to allow manufacturers to meet the standards.

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[184] Gould, John. "NASA Seeks to Create a Better Battery with SABERS". NASA. April 7, 2021. Available online: https://www.nasa.gov/feature/nasa-seeks-to-create-a-better-battery-with-sabers.

[185] Clancy, Ryan. "NASA battery for electric aircraft ready to take-off". February 19, 2023. Available online: https://electronics360.globalspec.com/article/19317/nasa-battery-for-electric-aircraft-ready-to-take-off.

[186] Advanced Battery Technology Company. "US Advanced Battery Consortium". Available online: https://americanbatterytechnology.com/projects/usabc-project/.

[187] AMES National Laboratory. "CMI Project 2.1.11: Lithium, cobalt & platinum group metals recovery from lithium-ion batteries & e-waste". Available online: https://www.ameslab.gov/index.php/cmi/cmi-project-3111-li-co-pgm-recovery-li-ion-batteries-and-e-waste.

[188] AMES National Laboratory. "Scale-up of electrochemical leaching". March 1, 2021. Available online: https://www.ameslab.gov/index.php/cmi/research-highlights/scale-up-of-electrochemical-leaching-cell.

[189] ARPA-E. "MINER—Miner Innovations for Negative Emissions Resource Recovery". Available online: https://arpa-e.energy.gov/sites/default/files/documents/files/MINER_Final%20Project%20Descriptions.pdf.

Based on announced investments in battery cells production, companies have announced over 1,300 GWh/year in battery production in North America by 2030 (Figure 1-7).

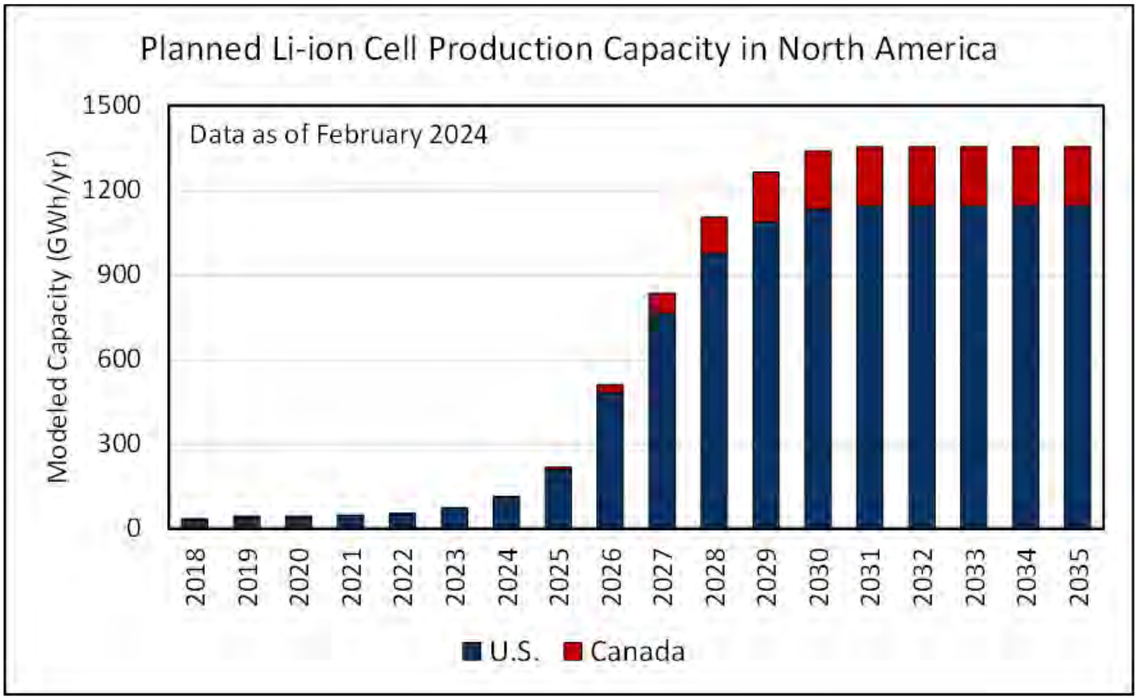

Figure 1-7 Modeled lithium-ion cell production capacity in North America from 2018 to 2035 by country

EPA finds that there is sufficient North American battery production capacity for HDVs within the rule's timeframe, and ANL projects at least 45 GWh of announced cell production will be dedicated to HDV BEVs by 2030 (Figure 1-8). See ANL, "Quantification of Commercially Planned Battery Component Supply in North American Through 2035" (ANL-24/14) (March 2024) at 23. Moreover, end use for some battery cell manufacturing facilities has not been announced, and it is likely that this North American capacity can service HDV applications in greater than announced amounts.

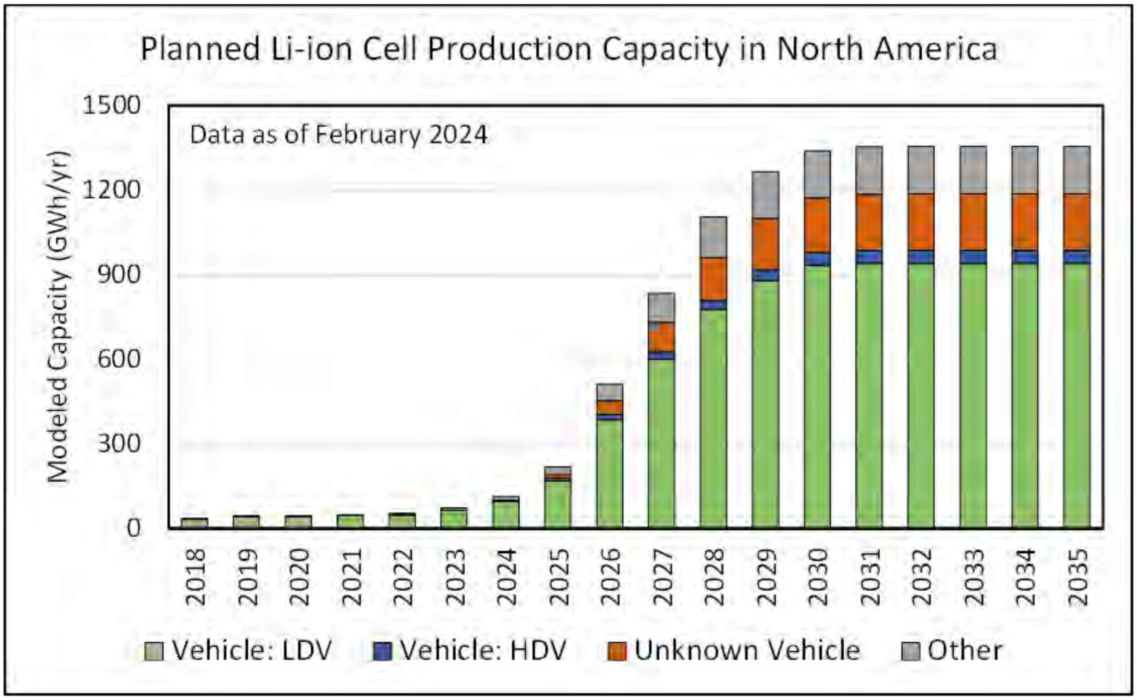

Figure 1-8 Modeled lithium-ion cell production capacity in North America from 2018 to 2035 by transportation sector

The three most recent projections of capacity (from BNEF, Roland Berger, and S&P Global in 2020-2021) that were collected by ANL at that time exceeded the corresponding projections of demand by a significant margin in every year for which they were projected, suggesting that global battery manufacturing capacity is responding strongly to increasing demand. The updated ANL supports the continuation of this trend. Figure 1-9 shows projected battery cell production in MSP countries through 2035: the sum of announced battery cell production capacity in MSP countries (outside North America) exceeds the sum in North America, with both reaching 1,300 GWh/year by 2030.

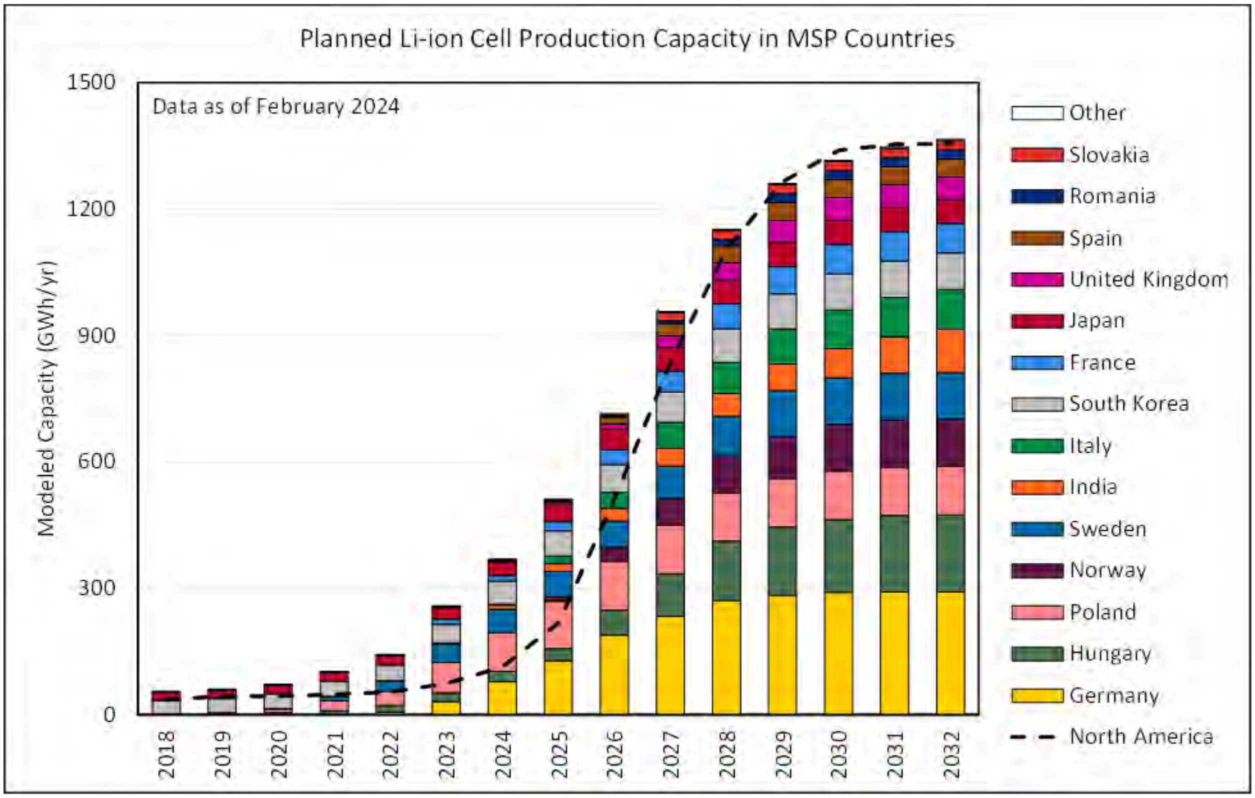

Figure 1-9 Modeled MSP lithium-ion battery cell production capacity through 2035

In consideration of this updated information on battery component and cell manufacturing, it continues to be our assessment that the industry is well positioned to support the battery and cell demand that is projected under the modeled potential compliance pathway supporting the feasibility of the final standards, including taking into consideration uncertainties that generally accompany forward-looking projections.

1.5.2 BEV Safety Considerations

EPA assessed potential safety issues associated with BEV technologies and FCEV technologies, noting potential safety issues and means of securely managing those issues. EPA has been in communication with NHTSA[190] to ascertain the latest status on risks associated with; mass of BEV and the impact of that mass on crash outcomes, BEV shock risk especially as it pertains to mechanics and first responders, BEV and FCEV fire and explosion risk, FCEV explosion risk in enclosed structures like tunnels.[191] Updates from NHTSA are included in the appropriate sections below. FCEV, HEV, and PHEV technologies all include use of batteries with significant energy levels and voltages high enough to cause harm if not handled safely. Battery safety associated with BEVs are discussed below. These same battery safety considerations apply to FCEV, HEV, and PHEV. FCEV safety will be covered in section 1.7.4 and will focus on hydrogen as the battery aspects are covered with BEV below. The ICE safety aspects of HEV and PHEV are aligned with current ICE technologies, and are well understood

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[190] Landgraf, Michael. Memorandum to docket EPA-HQ-OAR-2022-0985. Summary of NHTSA Safety Communications. February 14, 2024.

[191] Kuppa, Shashi. “HD safety for BEV and H2 FCV” email reply October 24, 2023.

and managed with today's technology and its use. HEV and PHEV will not be separately discussed as the battery aspect of safety is covered with our discussion of BEV safety while ICE considerations do not require discourse.

BEVs receive, store, and utilize large amounts of electrical energy. The stored electrical energy resides as chemical energy in the battery. This electrical and chemical energy must be safely controlled during charging, while held by the battery and other high voltage components, and when providing vehicle power. The electrical energy must be isolated from humans to prevent shock. The electrical energy also needs isolation so that a short does not allow harmful amounts of electricity to leak to and through other components, causing damage. Finally, the chemical energy held in the battery must be managed so it is not allowed to generate excessive heat that could harm surrounding components or cause a thermal event.

Both LD and HD BEVs are progressing beyond 400V systems with some LD BEVs at 800V and Tesla considering 800V for their HD tractor.[192] Systems of 400V up to 800V are clearly high voltage and carry high voltage risk, as high voltage is considered to be 60V DC up to 1,500V DC.[193] The safety of a HD BEV benefits from the significant work conducted in the LD BEV sector addressing the BEV risk factors. Risk factors related to battery capacity will generally be greater for HD BEVs, as they often, though not always, need to be larger and do more work than the LD BEV.

HD BEV systems must always maintain safe operation. As with any on-road vehicle, they must be robust during temperature extremes as well as rain and snow. The systems must be designed for reasonable levels of immersion, including immersion in salt water or brackish water. BEV systems must be designed to be crashworthy and limit damage that compromises safety. If the structure is compromised by a severe impact, the systems must provide first responders with a way to safely conduct their work at an accident scene. The HD BEV systems must be designed to ensure the safety of users, occupants, and the general public in their vicinity. As shown in section 1.5.5, almost 180 BEV vehicle models are available in MY 2023 while over 180 are expected in MY 2024 (per literature review) suggesting that many manufactures are meeting safety standards over a wide range of HD BEVs.

1.5.2.1 Charging Safety

Charging involves electricity flowing into the vehicle at power levels that are capable of harming people and equipment. To ensure safety, the vehicle and charging system must:[194]

- Isolate individuals from the high voltage electricity that is present in the vehicle and charger. (High voltage must not be present within 1 second of charger disconnect.);
- Establish and monitor a ground path;

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[192] Randall, Chris. "Tesla considers using 800-volt architecture for trucks". Electrive. Updated on November 7, 2023. https://www.electrive.com/2022/04/22/tesla-considers-using-800-volt-architecture-for-trucks/

[193] Global Technical Regulation No. 20 page 20 https://unece.org/fileadmin/DAM/trans/main/wp29/wp29wgs/wp29gen/wp29registry/ECE-TRANS-180a20e.pdf

[194] Part 571305 - Federal Motor Vehicle Safety Standards – Electric Powered Vehicles https://www.govinfo.gov/content/pkg/CFR-2017-title49-vol6/xml/CFR-2017-title49-vol6-part571.xml#seqnum571.305

- Monitor the process for isolation faults and shorts;
- Exchange information;
- Indicate if the vehicle is in active drive mode; and
- Notify the operator if action is required to complete charging safely.

Complexities with the battery design and reactions occurring in the battery cells drive the need for feedback from the battery to the charging system. This charge management is handled within the vehicle with AC chargers or within the DC charging equipment that is external to the vehicle. The safety of HD vehicle charging systems has benefitted from the more extensive LD vehicle development and deployment. Some of the industry codes and standards that guide safe deployment of BEV charging systems are:

- Society of Automotive Engineers (SAE) J-1772, conductive charging
- SAE J-2954/2, inductive charging
- SAE J-3072, grid support from the EV
- SAE J-3271, megawatt charging system (up to 1500V/3000A) requirements

Other related standards have been developed by NHTSA,[195] International Electrotechnical Commission (IEC), National Electric Code (NEC), and Underwriters Laboratories (UL). These standards ensure safety in various ways. Using J-1772 as an example, mechanical features are prescribed that ensure electricity is flowing only when the connecter is safely coupled and the electricity is separated from the user. Likewise, as the connecter is disconnected after charging, power flow is stopped before any high voltage parts are exposed to the user. Continuing with the J-1772 example, it contains signaling features that allow communication between the vehicle and charger to ensure charging is only taking place when safe to do so.

1.5.2.2 Battery Safety

BEV batteries receive, store, and discharge electrical power. BEV batteries require both the proper physical design and the proper controls (or battery management system) to allow them to safely accept and deliver power throughout the life of the vehicle. The battery design must provide external short circuit protection, over and under charge protection, and over temperature protection. NHTSA has a rulemaking proposal to address EV battery fire risk with planned publication in 2024. Some of the design and controls standards that ensure BEV can accept and deliver power robustly, without overheating or failing, are shown below.

- SAE J2464-202108, safety and abuse testing at the component level. This guide describes a body of tests which may be used as needed for abuse testing of electric or hybrid electric vehicle rechargeable energy storage systems (RESS) to determine the response of such electrical energy storage and control systems to conditions or events which are beyond their normal operating range.

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[195] For example, “DC and AC Charging Safety Evaluation Procedure Development, Validation, and Assessment”. Published Date : 2019-07-01 Report Number : DOT HS 812 778 Available online: https://rosap.ntl.bts.gov/view/dot/41933

- SAE J2929-201102, safety standard for lithium-based cells. This SAE Standard defines a minimum set of acceptable safety criteria for a lithium-based rechargeable battery system to be considered for use in a vehicle propulsion application as an energy storage system connected to a high voltage power train.
- NHTSA DOT 49 CFR 571.305 EV Safety is adding battery requirements per RIN: 2127-AM43

Other related standards have been developed by IEC, International Standards Organization (ISO) and UL.

1.5.2.3 Battery Protection from the Environment, Road Hazards, and Immersion

The BEV battery must be designed to handle external challenges. A HD BEV and its battery will be exposed to vibration, temperature extremes, temperature cycling, water, and mechanical impact from items such as road debris. The water may arrive as rain, snow, and/or soaking rains that later freeze. The vehicle may drive through or be exposed to water with varying levels of salt that will be a much better conductor of electricity and can be corrosive over time. The batteries must hold up to impact from foreseeable types of road debris. The standards that address these conditions are SAE J2464, safety and abuse testing, and others from IEC and ISO.

1.5.2.4 BEV Safety Regarding Crash and Maintenance

The crash test performance of today's LD electric vehicles shows that they are at least as safe as ICE vehicles.[196] This conclusion is based on a 2021 report and assessment of LDV by the Insurance Institute for Highway Safety (IIHS). IIHS found that driver and passenger injury claims from 2011 to 2019 were 40% lower for electric vehicles versus "identical" conventional vehicles.[197] As explained earlier in this section, we coordinated with NHTSA to assess any potential safety concerns, including due to vehicle weight and crash safety. NHTSA has shared that they are not aware of differences in crash outcomes between electric and non-electric vehicles. They confirmed they are monitoring this topic closely and are conducting extensive research on the differences between ICE and electric vehicles. Their research includes investigating size- and weight-related compatibility implications relative to overall road safety. Additionally, NHTSA's CAFE proposal[198], issued on July 28, 2023 for all light passenger vehicles, includes estimates of the safety impacts of EV weight. NHTSA reports that, "Change in vehicle mass affects the prevalence of injuries and fatalities on roadways. Increases in vehicle mass might confer additional safety to vehicle occupants while also reducing safety for pedestrians, cyclists, and other vulnerable road users, as well as for road users with lower mass vehicles". But this light passenger vehicle Preliminary RIA goes on to say, "Across all alternatives, mass changes relative to the baseline result in small reductions in overall fatalities,

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[196] Bartlett, Jeff. "Ford and Volvo Earn Top Safety Picks as Insurance Study Shows Electric Cars Are Safe". Consumer Reports published on April 22, 2021. https://www.consumerreports.org/car-safety/electric-cars-prove-safe-in-iihs-crash-tests-and-insurance-claims-a2640558822/

[197] Insurance Institute for Highway Safety. "With more electric vehicles comes more proof of safety". Published on April 22, 2021. https://www.iihs.org/news/detail/with-more-electric-vehicles-comes-more-proof-of-safety

[198] US Department of Transportation, National Highway Traffic Safety Administration. "Preliminary Regulatory Impact Analysis. Corporate Average Fuel Economy Standards for Passenger Cars and Light Trucks for Model Years 2027 and Beyond and Fuel Efficiency Standards for Heavy-Duty Pickup Trucks and Vans for Model Years 2030 and Beyond. July, 2023. Available online: https://www.nhtsa.gov/sites/nhtsa.gov/files/2023-08/NHTSA-2127-AM55-PRIA-tag.pdf

injuries, and property damage. These results may seem counterintuitive given the agency's previous analyses. This outcome amounts to noise around zero." Regarding HD BEV weight, it is important to acknowledge that current HD ICE vehicles have much more weight the LD vehicles. Even a large SUV at 6,000 lbs is dwarfed by a Class 8 loaded truck at 80,000 pounds. Although the HD BEV Class 8 could go to 82,000 pounds, the weight ratio increase of 13.3X (80,000 / 6,000) to 13.7X (82,000 / 6,000) should prove insignificant. The Class 8 weight increase of 2,000 pounds is just an example for demonstration purposes, many HD BEV trucks, and especially those where significant early adoption is expected, have little to no weight gain.

For HD BEVs to uphold battery/electrical safety during and after a crash, they are designed to maintain high voltage isolation, prevent leakage of electrolyte and volatile gases, maintain internal battery integrity, and withstand external fire that could come from the BEV or other vehicle(s) involved in a crash. The internal battery integrity is important to prevent fire risk from developing within the battery over time. Standards driving design and process for optimizing crash and post-crash safety have been completed by IEC and ISO as well as:

- National Highway Traffic Safety Administration (NHTSA) FMVSS 305, electrolyte spillage and electrical shock protection
- NHTSA DOT HS 812 789, post-crash stranded energy tools and procedures
- SAE J1766, crash integrity testing. This SAE Recommended Practice is applicable to Electric, Fuel Cell and Hybrid vehicle designs that are comprised of at least one vehicle propulsion voltage bus with a nominal operating voltage greater than 60 and less than 1,500 VDC, or greater than 30 and less than 1,000 VAC. This Recommended Practice addresses post-crash electrical safety, retention of electrical propulsion components and electrolyte spillage.
- SAE J2990, first and second responder recommended practice. xEVs involved in incidents present unique hazards associated with the high voltage system (including the battery system). These hazards can be grouped into three categories: chemical, electrical, and thermal. The potential consequences can vary depending on the size, configuration, and specific battery chemistry. This RP aims to describe the potential consequences associated with hazards from xEVs and suggest common procedures to help protect emergency responders, tow and/or recovery, storage, repair, and salvage personnel after an incident has occurred with an electrified vehicle.

An important aspect of crash safety is knowledge and training for first responders and those handling crashed BEV vehicles. First responders must know how to locate and perform high voltage disconnects. They must also know to check for high voltage sources so they can avoid or disconnect or drain those energy sources. This is especially true if they are in contact with the vehicle to free an occupant. NHTSA is working on providing emergency response guides for each vehicle make and model which will be on NHTSA's website. BEV fire occurrence analysis shows that BEVs are less likely to catch fire than vehicles powered by internal combustion engines. Recent analysis combining car fire data from NTSB with sales data from the Bureau of Transportation Statistics shows gas vehicle fires occur in over 1,500 vehicles per 100,000 sales while BEV fires are just over 25 fires per 100,000 sales.[199] Although BEVs can behave differently in fires from ICE vehicles, emergency responders have been gaining experience in BEV fire response and there are protocols and guidance at the federal and private levels in support of first responders. Real world operation and testing has shown that large amounts of water (2,600 gallons for a 600 lbs. li-ion battery) are needed for BEV firefighting to cool the batteries and eliminate the risk of fire.[200] There has been considerable advancement in BEV firefighting, and additional work in this area is underway. For example, BEST (Battery Extinguishing System Technology) can pierce the battery case and apply water directly to the battery, extinguishing the fire with as little as 500 gallons in an hour[201]. Safe storage of crashed vehicles is critical as internal battery failure reactions may occur days after the crash and reignite. Recommendations for safe storage of damaged BEV include: ID and label the damaged vehicles, park the damaged vehicles in a safe zone (generally 50 feet away from buildings and combustible materials), create an EV fire response plan, conduct regular inspections.[202]

Protocols and guidance exist to mitigate shock risk to mechanics during maintenance and repair. Performing standard maintenance on BEVs leads to new or increased risk compared to ICE vehicles and requires corresponding safety training due to the following:[203]

- the presence of high voltage components and cabling capable of delivering a fatal electric shock;
- the storage of electrical energy with the potential to cause explosion or fire;
- components that may retain a dangerous voltage even when a vehicle is switched off;
- electric motors or the vehicle itself that may move unexpectedly due to magnetic forces within the motors;
- manual handling risks associated with battery replacement;
- the potential for the release of explosive gases and harmful liquids if batteries are damaged or incorrectly modified;
- the possibility of people being unaware of vehicles being in motion because when they are electrically driven they are silent in operation;

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[199] Wright, Justin. "Gas vs. Electric Car Fires [2024 Findings]". December 19, 2023. Available online: https://www.autoinsuranceez.com/gas-vs-electric-car-fires/

[200] Moore, Ron. "University of Extrication: Electric Vehicle Fire Suppression" Firehouse. Published on March 14, 2022. Available online: https://www.firehouse.com/operations-training/article/21255066/university-of-extrication-electric-vehicle-fire-suppression

[201] Margaretten, Emily. " New firefighting device helps Mountain View extinguish electric vehicle fires faster, using less water". Palo Alto online. January 4, 2024. Available online: https://www.paloaltoonline.com/news/2024/01/04/new-firefighting-device-helps-mountain-view-extinguish-electric-vehicle-fires-faster-using-less-water/

[202] O'Shaughnessy, Micah. "EV Hazards: Tips to Reduce Fire and Storage Hazards in Your Dealership". KPA. July 13, 2022. Available online: https://kpa.io/blog/ev-hazards-tips-to-reduce-fire-and-storage-hazards-in-your-dealership/

[203] Health and Safety Executive – Electric and Hybrid Vehicles https://www.hse.gov.uk/mvr/topics/electric-hybrid.htm Accessed February 2, 2023.

- the potential for the electrical systems on the vehicle to affect medical devices such as pacemakers.

While the systems have safety guards and checks, personnel must be able to verify that those systems are operating correctly. NHTSA confirmed that the current FMVSS No. 305 specifies protection systems to mitigate shock risk to mechanics and emergency responders. Maintenance personnel will need appropriate personal protective equipment (PPE), testing equipment, and manufacturer-specified service procedures on use. Review of literature by safety systems providers[204], state technology offices[205], and NHTSA[206] show consistent messaging on the need for proper equipment, PPE, training, disconnection or lock out and isolation of high energy systems.

In sum, the public and private sectors have been working diligently to address BEV safety considerations. While current standards are appropriate, optimization efforts will continue as the HD BEV industry matures. Heavy-duty BEVs can be and are designed and operated safely.

1.5.3 BEV System Integration

While both BEV and ICE vehicle technologies have some components in common, as described in Chapter 1 and 2, there are also many components that differ between the two vehicle types. The arrangement of a vehicle's components can have a significant impact on its energy efficiency, volumetric and gravimetric payload capacity, and cost. Currently, some BEVs are designed very similarly to comparable ICE vehicles, while other BEVs are designed more from a "ground-up" approach, allowing them to better take advantage of the characteristics unique to BEVs, such as the flexibility of placement in battery mass and the modularity of battery pack sizes.

HD vehicles fill a diverse set of requirements, necessitating different approaches to BEV component integration. This chapter gives a few examples of BEV systems and integration to illustrate the current state of HD BEV design and provides a projection of potential future evolution of the technology that we have assessed and determined is feasible during the time frame considered in this rulemaking.

1.5.3.1 Integration into Existing ICE Vehicle Design

Some HD vehicle outfitters take existing ICE vehicles and upgrade componentry;[207] this allows the vehicle owner to update a vehicle without purchasing an entirely new vehicle, saving cost. This has traditionally been done while maintaining the type of powertrain (e.g., compression ignition ICE), but may also be done to convert ICE vehicles to BEVs as Complete

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[204] "Electric And Hybrid Vehicle Risks". EINTAC. Accessed February 8, 2024. Available online: https://eintac.com/risks-working-electric-hybrid-vehicles/

[205] "High Voltage Safety with Hybrids and Electric Vehicles". Massachusetts Office of Technical Assistance. Accesssed on February 8, 2024. Available online: https://www.mass.gov/files/high_voltage_safety_with_hybrids_and_electric_vehicles.pdf

[206] "Electric and Hybrid Vehicles". US Department of Transportation. National Highway Traffic Administration. Accessed February 8, 2024. Available online: https://www.nhtsa.gov/vehicle-safety/electric-and-hybrid-vehicles#:~:text=Exposed%20electrical%20components%2C%20wires%2C%20and,or%20flammable%20gases%20and%20fire.

[207] This concept of replacement of ICE with BEV components can be applied to new vehicles without a complete vehicle re-design. Our standards would not apply to in-use products, so do not require repowering.

Coach Works does with buses, as shown in Figure 1-10. Additional outfitters taking this approach include Unique Electric Solutions (UES),[208] Revo Powertrains,[209] and Blue Bird.[210]

Figure 1-10 Complete Coach Works' process for repowering conventional buses to battery electric buses[211]

Complete Coach Works repowers buses by stripping the chassis down to the frame; removing all interior and exterior components; removing the diesel engine; installing a battery electric powertrain; installing light-weight flooring, seats, and windows and energy-efficient lighting; and conducting a final inspection. In the example shown in Figure 1-10, the bus was upgraded beyond a powertrain replacement by adding in lightweight and energy-efficient components to reduce the energy demands on the battery. Such an approach may have certain advantages and disadvantages. For example, the cost of such a bus conversion would likely be lower than the cost of purchasing a new battery electric bus, but the placement and size of the powertrain components would be constrained to the space that the diesel engine originally occupied. This latter consideration may be limiting for some of the components and specifications, e.g., the capacity of the battery packs.

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[208] UES. "EV Conversions for Commercial Vehicles - UES". https://www.uesmfg.com/. Accessed on October 5, 2022.

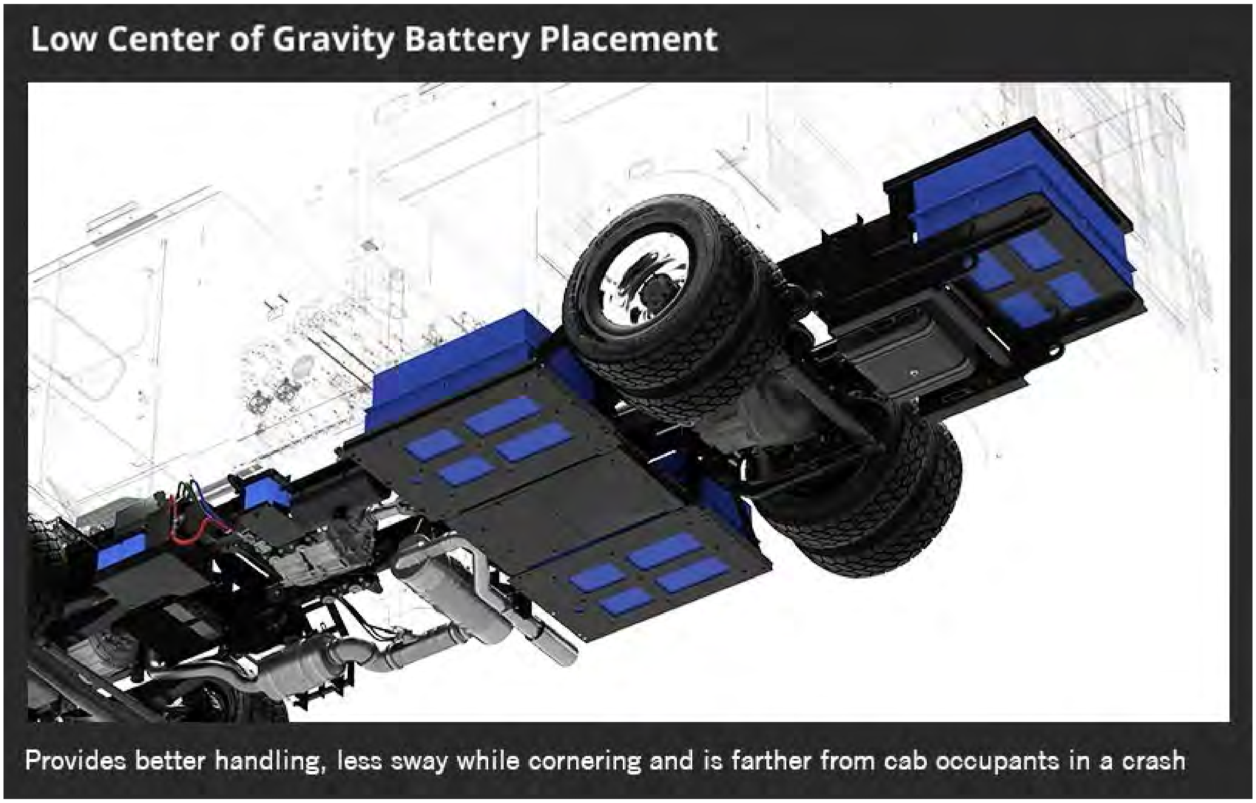
[209] Revo Powertrains. "Revo Electric Powertrains". https://www.revopowertrains.com/. Accessed on October 5, 2022.

[210] Barclay, J. "Blue Bird to Offer Electric Repower Option for Gasoline- and Propane-Powered School Buses". *Business Wire*. Published on August 3, 2022. https://www.businesswire.com/news/home/20220803005655/en/Blue-Bird-to-Offer-Electric-Repower-Option-for-Gasoline--and-Propane-Powered-School-Buses/. Accessed on October 5, 2022.

[211] Complete Coach Works. "Zero Emission Propulsion System". https://zepsdrive.com/. Accessed on September 18, 2022.

1.5.3.2 HD Vehicles with ICE and BEV Components

Spartan Emergency Response offers a fire truck called Vector, which the company purports to be an electric fire truck.[212] It is capable of all-electric operation for both driving and pumping water using its sizeable 327 kWh battery. The vehicle also comes with a range-extending option where the ICE that can recharge the battery at low charge; in this version, the vehicle functions similar to that of a series hybrid[213]. While this fire truck does not benefit from a fully electric vehicle's omission of an engine and associated components, the Vector fire truck was designed to take advantage of the battery's mass by placing them such that the truck has a lower center of gravity, which provides better handling and maneuverability, as shown in Figure 1-11. This design decision demonstrates one way that an electric vehicle could provide an advantage over a comparable ICE vehicle. Additional manufacturers of HD vehicles that include ICE components but may also operate in all-electric modes include Kenworth,[214] US Hybrid,[215] and Pierce Manufacturing.[216]



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[212] Spartan Fire, LLC. "Vector - Spartan Emergency Response". https://spartaner.com/products/vector/. Accessed on September 18, 2022.

[213] In a series hybrid, the engine is used to charge the battery which in turn powers the e-motor. The engine does not directly drive the powertrain using a transmission.

[214] Kenworth. "Kenworth Delivers Two Range-Extended Electric Prototype Trucks for Commercial Service". Published on February 17, 2021. https://www.kenworth.com/about-us/news/kenworth-delivers-two-range-extended-electric-prototype-trucks-for-commercial-service/. Accessed on October 5, 2022.

[215] US Hybrid. "Long Haul & Drayage - US Hybrid". https://www.ushybrid.com/applications/long-haul-drayage/. Accessed on October 5, 2022.

[216] Pierce Manufacturing, Inc. "Volterra™ Electric Fire Truck | Pierce Mfg". https://www.piercemfg.com/electric-fire-trucks/pierce-volterra. Accessed on January 8, 2023.

Figure 1-11 Spartan Emergency Response places the battery packs of their Vector fire truck strategically to improve handling

1.5.3.3 Integration into Vehicle Ladder Frame

Bollinger Motors approaches BEV design by constraining the battery packs and other BEV powertrain components to the ladder frame of their vehicles,[217] like trends in LD BEV design. This provides three advantages over an ICE vehicle, as illustrated in Figure 1-12. First, as shown in Figure 1-12(a), the relatively small size of the e-motor allows Bollinger Motors to bring the cab forward, which improves visibility and increases cargo space. Second, as depicted in Figure 1-12(b), this design provides a literal platform upon which to tailor the BEV to each customer's needs. Third, as shown in Figure 1-12(c), the battery capacity can be easily adjusted with the same general layout to accommodate different energy demands for a range of vehicles across duty cycles and gross weight vehicle rating (GVWR), which allows Bollinger Motors to reduce some of the engineering costs. Other manufacturers placing battery packs in the ladder frame of HD BEVs include Volvo,[218] Peterbilt,[219] Navistar,[220] and Xos.[221]

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[217] Bollinger Motors Inc. "TRUCKS - BOLLINGER MOTORS". https://bollingermotors.com/trucks/. Accessed on September 18, 2022.
Bollinger Motors Inc. "CLASS 3-6 FLEET-READY ELECTRIC TRUCKS - BOLLINGER MOTORS". https://bollingermotors.com/class-3-through-6-electric-truck-platforms/. Accessed on September 18, 2022.

[218] Howard, B. "Volvo Plans Big Electric Trucks for Local, Regional Hauls". *Extreme Tech*. Published on September 24, 2019. https://www.extremetech.com/extreme/298830-volvo-plans-big-electric-trucks-for-local-regional-hauls. Accessed on October 5, 2022.

[219] Peterbilt. "220EV". https://www.peterbilt.com/download/file/7696. Accessed on October 5, 2022.

[220] Green Car Congress. "Navistar launches new medium-duty electric International eMV Series; in production and available to order". *Green Car Congress*. Published on September 2, 2021. https://www.greencarcongress.com/2021/09/20210902-emv.html. Accessed on October 5, 2022.

[221] Xos. "Powertrain - Powered by Xos helps to electrify vehicles and equipment". https://xostrucks.com/powertrain/. Accessed on October 5, 2022.

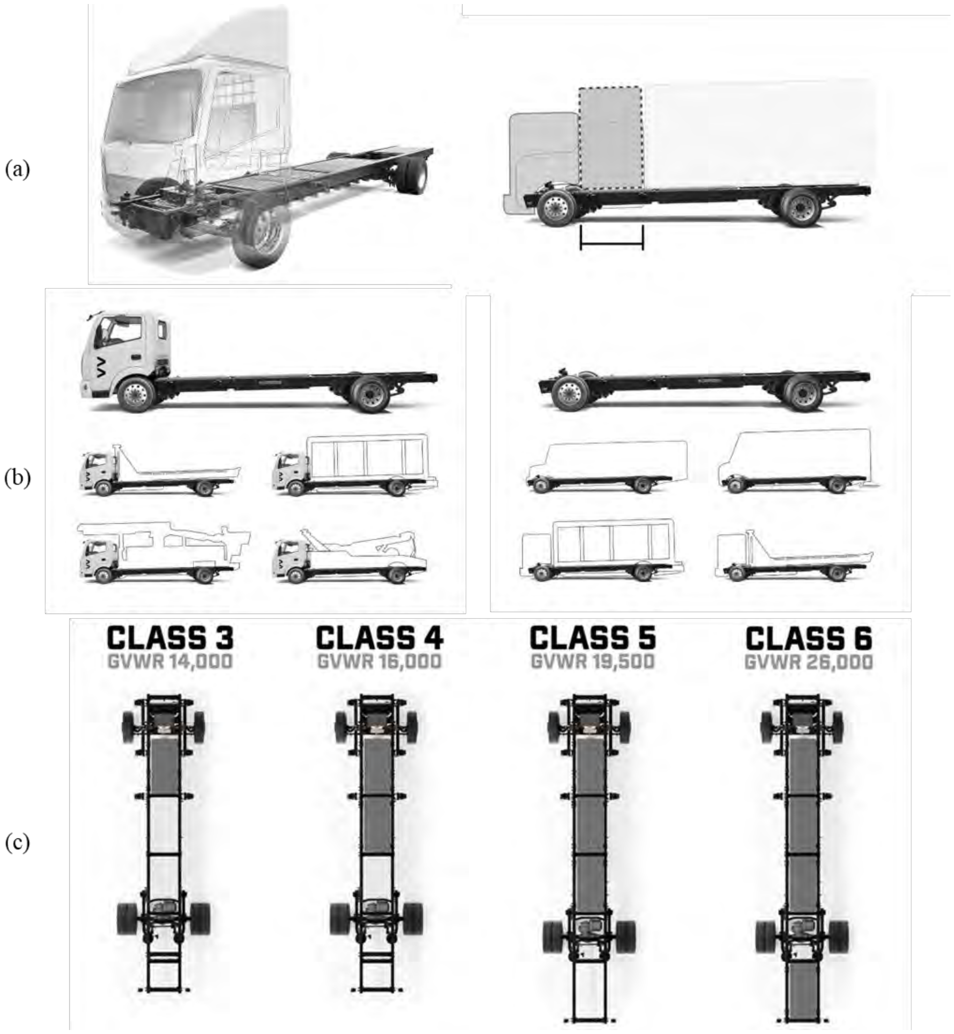

Figure 1-12 Bollinger Motors' commercial electric trucks. (a) Cab-forward design increases cargo space over conventional cabs. (b) Platform enables the trucks to be upfit to fill a wide variety of purposes. (c) Battery packs in the ladder frame are flexible enough

1.5.4 BEV Ancillary Systems

1.5.4.1 Heating, Ventilation, and Air Conditioning (HVAC)

The use of energy to heat or cool the cabin of the vehicle can require energy from a power source, typically the battery itself. As a result of the large interior cabins of some heavy-duty vehicles, such as a school bus, this may require a heat pump. Cabin heat can be provided by using a positive temperature coefficient (PTC) electric resistance heater. PTC electric heaters convert electrical energy into thermal energy. PTC energy conversion efficiency from electrical to thermal energy is 100 percent.

Heat pumps provide both heat and air conditioning (A/C) by utilizing a thermodynamic cycle to move thermal energy, rather than directly converting energy from another form. Heat pump system hardware and operation is fundamentally the same as a standard air conditioner. The addition of a reversing valve can change the direction in which thermal energy is moved. Heat pump heating efficiency is very high, normally exceeding 100 percent because they can move more thermal energy than the amount of electrical energy that is consumed to move it. Efficiency is dependent on ambient air temperature. Heat pump efficiency is described by the coefficient of performance (COP), a ratio of the useful thermal energy (heat) provided by the system, to the electrical energy that it consumed. Modern heat pumps achieve a COP ranging from 1.0, equal to 100 percent efficiency in very low ambient temperatures, to 4.0 or higher – 400 percent or higher efficiency, at moderate temperatures. In other sectors, heat pumps are currently and increasingly in use for water heating[222], industrial process heat[223], LD electric vehicles[224], and international market heavy-duty vehicles[225]. Rapid development of heat pumps in established and rising markets indicate both the appropriateness and heightened interest in adopting the technology. Heat pump manufacturers are developing and commercializing residential systems that operate with a minimum efficiency of 210 percent–240 percent at 5°F, and operating as low as -15°F (at 100 percent efficiency).[226] With a growing HD BEV market, we expect HVAC manufacturers will develop and expand their vehicle heat pump products.

Vehicles with a particularly high heating load or extended idle requirement may use auxiliary cabin heat systems. Fuel operated heaters (FOH), also known as direct fired heaters (DFH), are small standalone air or coolant heaters that combust diesel or gasoline solely as the source of heat. Emissions from combustion are directly exhausted outside the vehicle.

FOHs may be used in ZEV applications operating in extreme low temperatures, or where a reduction in driving range is unacceptable. Considering the applications most appropriate for electrification in MYs 2027 through 2032, the sustainability goals of both fleets and OEMs purchasing electric vehicles, and the high efficiency of heat pumps and sensitivities of FOH emissions, we believe that it is unlikely that FOH will be the primary solution for cabin heat.

1.5.4.2 Electric Power Take Off

Vehicles equipped today with an electric power take off (ePTO) are a small portion of the overall heavy-duty industry and are typically equipped on utility vehicles.[227] The ePTO's are powered by the batteries for a period of time, with the vehicle engine off, until the battery charge is depleted to the minimum allowable level. The vehicle's ICE then restarts to run the ePTO, charge the ePTO battery pack, or both. Some systems also have a plug-in option to recharge the

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[222] U.S. International Trade Commission. "Residential Heat Pump (Hybrid) Water Heater Market, Production, and Trade". *Executive Briefings on Trade, February 2022.* https://www.usitc.gov/publications/332/executive_briefings/ebot_residential_heat_pump_hybrid_water_heaters.pdf. Accessed January 24, 2023.

[223] Hockenos, P. "In Europe's Clean Energy Transition, Industry Turns to Heat Pumps". *Yale Environment 360*. Published January 19, 2023. https://e360.yale.edu/features/europe-industrial-heat-pumps. Accessed January 24, 2023.

[224] Osaka, S. "Why you might want a heat pump in your electric car". *Washington Post*. Published on January 7, 2023. https://www.washingtonpost.com/climate-solutions/2023/01/07/electric-vehicles-cold-winter-range/. Accessed January 24, 2023.

[225] Garry, M. "CO2 Heat Pumps Found to Outperform Electric Heaters in Electric Buses". *R744. (ATMOsphere)*. Published January 25, 2022. https://r744.com/co2-heat-pumps-found-to-outperform-electric-heaters-in-electric-buses/. Accessed January 24, 2023.

[226] U.S. Department of Energy. See www.energy.gov/sites/default/files/2022-02/bto-cchp-fact-sheet-021822.pdf

[227] PTO units are auxiliary power units used to power other work required by the HDV; these work units include lifting buckets in bucket trucks, lifting garbage cans or mixing cement.

batteries (plug-in hybrid). Three manufacturers offer these systems on a range of vocational vehicles. These vehicles are summarized in Table 1-22. Two all-electric vehicles with ePTOs are also listed – one for utility and one for refuse trucks.

Table 1-22 Current Electronic Power Take Off Market Offerings

Make	Model	Vehicle Type
Altec Industries	JEMS LE – plug-in/hybrid[228]	Utility, Digger Derricks, Service Body Trucks
Altec Industries	JEMS SE – plug-in/hybrid228	Utility, Digger Derricks, Service Body Trucks
Altec Industries	All Electric228	Utility
Odyne Systems, LLC	ePTO- plug-in/hybrid[229]	Utility, Compressors, Dump Trucks, Septic Trucks, etc.
Mack	LR Electric[230]	Refuse Trucks

1.5.5 BEV Market

Since 2012, manufacturers have developed a number of prototype and demonstration HD BEV projects establishing technological feasibility and durability of BEV technology for specific applications used for specific services.[231] In 2019, approximately 60 makes and models of HD BEVs were available for purchase, with additional product lines in prototype or other early development stages.[232,233,234] This market has been growing since MY 2018 and is projected to reach about 180 models of heavy-duty battery electric trucks by MY 2024 (see Section 1.5 in this chapter).[235]

Current production volumes of HD BEVs originally started increasing in the transit bus market, where electric bus sales grew from 300 to 650 in the United States between 2018 to

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[228] Altec. “JEMS Electrifying your MD/HD Fleet”. Available here https://www.altec.com/green-fleet-2/ Accessed on 3/13/2023.

[229] Odyne. “System Overview”. Available here: https://www.odyne.com/system-overview/. Accessed on 1/26/2023.

[230] https://www.macktrucks.com/trucks/lr-electric/

[231] NACFE (2019) “Guidance Report: Viable Class 7/8 Electric, Hybrid and Alternative Fuel Tractors”, available online at: *https://nacfe.org/downloads/viable-class-7-8-alternative-vehicles/.*

[232] Nadel, S. and Junga, E. (2020). “Electrifying Trucks: From Delivery Vans to Buses to 18-Wheelers.” American Council for an Energy-Efficient Economy White Paper, available at: https://aceee.org/white-paper/electrifying-trucks-delivery-vans-buses-18.

[233] The composition of all-electric truck models was: 36 buses, 10 vocational trucks, 9 step vans, 3 tractors, 2 street sweepers, and 1 refuse truck (Nadel and Junga (2020) citing AFDC (Alternative Fuels Data Center). 2018. “Average Annual Vehicle Miles Traveled by Major Vehicle Categories.” www.afdc.energy.gov/data/widgets/10309.

[234] Note that there are varying estimates of BEV and FCEV models in the market; NACFE (2019) “Guidance Report: Viable Class 7/8 Electric, Hybrid and Alternative Fuel Tractors”, available at: *https://nacfe.org/downloads/viable-class-7-8-alternative-vehicles*/. (NACFE 2019) provided slightly lower estimates than those included here from Nadel and Junga 2020. A recent NREL study suggests that there may be more models available, but it is unclear how many are no longer on the market since the inventory includes vehicles introduced and used in commerce starting in 2012 (Smith et al. 2019).

[235] Miller, Neil. Memorandum to docket EPA-HQ-OAR-2022-0985. “Heavy-Duty ZEV Models Available in the US through MY2024.” October 2023.

2019.[236,237] In 2020, the market continued to expand beyond transit, with approximately 900 HD BEVs sold in the United States and Canada combined, consisting of transit buses (54 percent), school buses (33 percent), and straight trucks (13 percent).[238] By 2021, M.J. Bradley's analysis of the HD BEV market found that 30 manufacturers had at least one BEV model for sale and an additional nine companies had made announcements to begin BEV production by 2025.[239] In April 2022, the Environmental Defense Fund (EDF) projected deployments and major orders of electric trucks and buses in the United States to rise to 54,000 by 2025 based on an analysis of formal statements and announcements by auto manufacturers, as well as analysis of the automotive press and data from financial and market analysis firms that regularly cover the auto industry.[240] Given the dynamic nature of the BEV market, the number and types of vehicles available are increasing fairly rapidly.[241]

EPA conducted an analysis of manufacturer-supplied end-of-year production reports provided to us as a requirement of the process to certify HD vehicles to our GHG emission standards.[242] Based on the end-of-year production reports for MY 2019, manufacturers produced approximately 350 certified HD BEVs. This is out of nearly 615,000 HD diesel ICE vehicles produced in MY 2019 and represents approximately 0.06 percent of the HD vehicles market. In MY 2020, 380 HD BEVs were certified, an increase of 30 BEVs from 2019. The BEVs were certified in a variety of the Phase 1 vehicle subcategories, including light, medium, and heavy heavy-duty vocational vehicles and vocational tractors. Out of the 380 HD BEVs certified in MY 2020, a total of 177 unique makes and models were available for purchase by 52 manufacturers in Classes 3–8. In MY 2021, EPA certified 1,163 heavy-duty BEVs, representing 0.2 percent of the HD vehicles. We note that these HD BEV certifications preceded implementation of incentives in the 2022 IRA, which we expect to increase adoption (and certification) of BEV and FCEV technology in the heavy-duty sector.

Based on current trends, manufacturer announcements, the 2021 BIL and 2022 IRA, and state-level actions, electrification of the HD market is expected to substantially increase over the next decade from current levels. The projected rate of growth in electrification of the HD vehicle sector currently varies widely. After passage of the IRA, EDF's September 2022 report update projected deployments and major orders of electric trucks and buses to rise to 166,000 by the end

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[236] Tigue, K. (2019) "U.S. Electric Bus Demand Outpaces Production as Cities Add to Their Fleets" Inside Climate News, November 14. https://insideclimatenews.org/news/14112019/electric-bus-cost-savings-health-fuel-charging.

[237] Note that ICCT (2020) estimates 440 electric buses were sold in the U.S. and Canada in 2019, with 10 of those products being FCEV pilots. The difference in estimates of number of electric buses available in the U.S. may lie in different sources looking at production vs. sales of units.

[238] International Council on Clean Transportation. "Fact Sheet: Zero-Emission Bus and Truck Market in the United States and Canada: A 2020 Update." Pages 3-4. May 2021.

[239] M.J. Bradley and Associates (2021) "Medium- and Heavy-Duty Vehicles: Market Structure, Environmental Impact, and EV Readiness." Page 21. July 2021.

[240] Environmental Defense Fund. "Electric Vehicle Market Update: Manufacturer Commitments and Public Policy Initiatives Supporting Electric Mobility in the U.S. and Worldwide". April 2022. Available online: *https://blogs.edf.org/climate411/files/2022/04/electric_vehicle_market_report_v6_april2022.pdf*.

[241] Union of Concerned Scientists (2019) "Ready for Work: Now Is the Time for Heavy-Duty Electric Vehicles," available at *www.ucsusa.org/resources/ready-work*.

[242] Memo to Docket. Heavy-Duty Greenhouse Gas Emissions Certification Data. March 2023. Docket EPA-HQ-OAR-2022-0985.

of 2022.[243] ERM updated an analysis for EDF that projected five scenarios that span a range of between 13 and 48 percent Class 4-8 ZEV sales in 2029, with an average of 29 percent.[244] The International Council for Clean Transportation (ICCT) and Energy Innovation conducted an analysis of the impact of the IRA on electric vehicle uptake, projecting between 39 and 48 percent Class 4–8 ZEV sales in 2030 across three scenarios and between 47 and 56 percent in 2035.[245]

One of the most important factors influencing the extent to which BEVs are available for purchase and market entry is the cost of lithium-ion batteries, the single most expensive component of a BEV. According to Bloomberg New Energy Finance, average lithium-ion battery costs have decreased by more than 85 percent since 2010, primarily due to global investments in battery production and ongoing improvements in battery technology.[246] A number of studies, including the Sharpe and Basma meta-study of direct manufacturing costs from a variety of papers, show that battery pack costs are projected to continue to fall during this decade.[247,248,249] Cost reductions in battery packs for electric trucks are anticipated due to continued improvement of cell and battery pack performance and advancements in technology associated with energy density, materials for cells, and battery packaging and integration.[250]

As the cost of components has come down, manufacturers have increasingly announced their projections for zero-emission HD vehicles, and these projections signify a rapid increase in BEVs and FCEVs over the next decade. For example, Volvo Trucks and Scania announced a

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[243] Environmental Defense Fund. “Electric Vehicle Market Update: Manufacturer Commitments and Public Policy Initiatives Supporting Electric Mobility in the U.S. and Worldwide”. September 2022. Available online: *https://blogs.edf.org/climate411/files/2022/09/ERM-EDF-Electric-Vehicle-Market-Report_September2022.pdf.*

[244] Robo, Ellen and Dave Seamonds. Technical Memo to Environmental Defense Fund: Investment Reduction Act Supplemental Assessment: Analysis of Alternative Medium- and Heavy-Duty Zero-Emission Vehicle Business-As-Usual Scenarios. ERM. August 19, 2022. Available online: *https://www.erm.com/contentassets/154d08e0d0674752925cd82c66b3e2b1/edf-zev-baseline-technical-memo-addendum.pdf.*

[245] ICCT and Energy Innovation. “Analyzing the Impact of the Inflation Reduction Act on Electric Vehicle Uptake in the United States”. January 2023. Available online: *https://theicct.org/wp-content/uploads/2023/01/ira-impact-evs-us-jan23-2.pdf.*

[246] Bloomberg. “Battery Pack Prices Cited Below $100/kWh for the First Time in 2020, While Market Average Sits at $137/kWh”. Available online: *https://about.bnef.com/blog/battery-pack-prices-cited-below-100-kwh-for-the-first-time-in-2020-while-market-average-sits-at-137-kwh/.*

[247] Mulholland, Eamonn. “Cost of electric commercial vans and pickup trucks in the United States through 2040.” Page 7. January 2022. Available at *https://theicct.org/wp-content/uploads/2022/01/cost-ev-vans-pickups-us-2040-jan22.pdf.*

[248] Environmental Defense Fund. “Technical Review of Medium- and Heavy-Duty Electrification Costs for 2027-2030.” February 2, 2022. Available online: *https://blogs.edf.org/climate411/files/2022/02/EDF-MDHD-Electrification-v1.6_20220209.pdf.*

[249] Sharpe, Ben and Hussein Basma. “A meta-study of purchase costs for zero-emission trucks”. The International Council on Clean Transportation, Working Paper 2022-09 (February 2022). Available online: *https://theicct.org/wp-content/uploads/2022/02/purchase-cost-ze-trucks-feb22-1.pdf.*

[250] Sharpe, Ben and Hussein Basma. “A meta-study of purchase costs for zero-emission trucks”. The International Council on Clean Transportation. *https://theicct.org/wp-content/uploads/2022/02/purchase-cost-ze-trucks-feb22-1.pdf.*

global electrification target of 50 percent of trucks sold being electric by 2030.[251] Daimler Trucks North America has committed to offering only what they refer to as "carbon-neutral" trucks in the United States by 2039 and expects that by 2030 as much as 60 percent of its sales will be ZEVs.[252,253] Navistar has a goal of having 50 percent of its sales volume be ZEVs by 2030, and it has committed to achieve 100 percent zero emissions by 2040.[254] Cummins targets net-zero carbon emissions by 2050.[255,256]

On a parallel path, large private HD fleet owners are also increasingly committing to expanding their electric fleets.[257] A report by the International Energy Agency (IEA) provides a comprehensive accounting of recent announcements made by UPS, FedEx, DHL, Walmart, Anheuser-Busch, Amazon, and PepsiCo for fleet electrification.[258] Amazon and UPS, for example, placed orders in 2020 for 10,000 BEV delivery vans from EV start-ups Rivian and Arrival, respectively, and Amazon has plans to scale up to 100,000 BEV vans by 2030.[259,260] Likewise, in December 2022, PepsiCo added the first of 100 planned Tesla Semis to its fleet.[261] These announcements include not only orders for electric delivery vans and semi-trucks, but more specific targets and dates to full electrification or net-zero emissions. Amazon, FedEx,

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[251] Scania, 'Scania's Electrification Roadmap,' Scania Group, November 24, 2021, *https://www.scania.com/group/en/home/newsroom/news/2021/Scanias-electrification-roadmap.html*; AB Volvo, 'Volvo Trucks Launches Electric Truck with Longer Range,' Volvo Group, January 14, 2022, *https://www.volvogroup.com/en/news-and-media/news/2022/jan/news-4158927.html*.

[252] David Cullen, 'Daimler to Offer Carbon Neutral Trucks by 2039,' (October 25, 2019). *https://www.truckinginfo.com/343243/daimler-aims-to-offer-only-co2-neutral-trucks-by-2039-in-key-markets*.

[253] Deborah Lockridge, 'What Does Daimler Truck Spin-off Mean for North America?,' Trucking Info (November 11, 2021). *https://www.truckinginfo.com/10155922/what-does-daimler-truck-spin-off-mean-for-north-america*.

[254] Navistar presentation at the Advanced Clean Transportation (ACT) Expo, Long Beach, CA (May 9-11, 2022).

[255] Cummins, Inc. "Cummins Unveils New Environmental Sustainability Strategy to Address Climate Change, Conserve Natural Resources." November 14, 2019. Last accessed on September 10, 2021 at *https://www.cummins.com/news/releases/2019/11/14/cummins-unveils-new-environmental-sustainability-strategy-address-climate*.

[256] Environmental Defense Fund (2022) September 2022 Electric Vehicle Market Update: Manufacturer Commitments and Public Policy Initiatives Supporting Electric Mobility in the U.S. and Worldwide, available online at: *https://blogs.edf.org/climate411/files/2022/09/ERM-EDF-Electric-Vehicle-Market-Report_September2022.pdf.*

[257] Environmental Defense Fund (2021) EDF analysis finds American fleets are embracing electric trucks. July 28, 2021. Available online at: *https://blogs.edf.org/energyexchange/2021/07/28/edf-analysis-finds-american-fleets-are-embracing-electric-trucks/.*

[258] International Energy Association. Global EV Outlook 2021. April 2021. Available online at: *https://iea.blob.core.windows.net/assets/ed5f4484-f556-4110-8c5c-4ede8bcba637/GlobalEVOutlook2021.pdf*.

[259] Amazon, Inc. "Introducing Amazon's first custom electric delivery vehicle." October 8, 2020. Last accessed on October 18, 2022 at *https://www.aboutamazon.com/news/transportation/introducing-amazons-first-custom-electric-delivery-vehicle.*

[260] Arrival Ltd. "UPS invests in Arrival and orders 10,000 Generation 2 Electric Vehicles." April 24, 2020. Last accessed on October 18, 2022 at *https://arrival.com/us/en/news/ups-invests-in-arrival-and-orders-10000-generation-2-electric-vehicles.*

[261] Akash Sriram. "Musk delivers first Tesla truck, but no update on output, pricing." *Reuters*. December 2, 2022. Last accessed on January 4, 2023 at *https://www.reuters.com/business/autos-transportation/musk-delivers-first-tesla-semi-trucks-2022-12-02/.*

DHL, and Walmart have set a commitment to fleet electrification and/or achieving net-zero emissions by 2040.[262][263,264,265,266][267]

The lifetime total cost of ownership (TCO), of which payback calculations play a critical part, also includes maintenance and fuel costs, is likely a primary factor for HD vehicle and fleet owners considering BEV and FCEV purchases. In fact, a 2018 survey of fleet owners showed "lower cost of ownership" as the second most important motivator for electrifying their fleet.[268] An ICCT analysis from 2019 suggests that TCO for light and medium heavy-duty BEVs could reach cost parity with comparable diesel ICE vehicles in the early 2020s, while heavy HD BEVs and FCEVs are likely to reach cost parity with comparable diesel ICE vehicles closer to the 2030 timeframe.[269] Recent findings from Phadke et al. suggest that BEV TCO could be 13 percent less than that of a comparable diesel ICE vehicle if electricity pricing is optimized.[270] These studies do not consider the IRA. The Rocky Mountain Institute found that because of the IRA, the TCO of electric trucks will be lower than the TCO of comparable diesel trucks about five years faster than without the IRA. They expect cost parity as soon as 2023 for urban and regional duty cycles that travel up to 250 miles and 2027 for long-hauls that travel over 250 miles.[271]

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[262] We recognize that certain delivery vans will likely fall into the Class 2b and 3 regulatory category, the vast majority of which are not covered in this rule's proposed updates; we are addressing this category in a separate light and medium-duty vehicle rulemaking.

[263] Robo, Ellen and Dave Seamonds. Technical Memo to Environmental Defense Fund: Investment Reduction Act Supplemental Assessment: Analysis of Alternative Medium- and Heavy-Duty Zero-Emission Vehicle Business-As-Usual Scenarios. ERM. August 19, 2022. Available online: *https://www.erm.com/contentassets/154d08e0d0674752925cd82c66b3e2b1/edf-zev-baseline-technical-memo-addendum.pdf*.

[264] FedEx Corp. "FedEx Commits to Carbon-Neutral Operations by 2040." March 3, 2021. Last accessed on October 18, 2022 at *https://newsroom.fedex.com/newsroom/asia-english/sustainability2021*.

[265] Deutsche Post DHL Group. "Zero emissions by 2050: DHL announces ambitious new environmental protection target." March 2017. Last accessed on October 18, 2022 at *https://www.dhl.com/global-en/delivered/sustainability/zero-emissions-by-2050.html*.

[266] Walmart Inc. "Walmart Sets Goal to Become a Regenerative Company." September 21, 2020. Last accessed on October 18, 2022 at *https://corporate.walmart.com/newsroom/2020/09/21/walmart-sets-goal-to-become-a-regenerative-company*.

[267] Complete heavy-duty vehicles at or below 14,000 pounds. GVWR are chassis-certified under 40 CFR part 86, while incomplete vehicles at or below 14,000 pounds. GVWR may be certified to either 40 CFR part 86 (meeting standards under subpart S) or 40 CFR part 1037 (installed engines would then need to be certified under 40 CFR part 1036). Class 2b and 3 vehicles are primarily chassis-certified complete commercial pickup trucks and vans. We intend to pursue a combined light-duty and medium-duty rulemaking to set more stringent standards for complete and incomplete vehicles at or below 14,000 pounds. GVWR that are certified under 40 CFR part 86, subpart S. The standards proposed in this rule would apply for all heavy-duty vehicles above 14,000 pounds. GVWR, except as noted in 40 CFR 1037.150(l). The proposed standards in this rule would also apply for incomplete heavy-duty vehicles at or below 14,000 pounds. GVWR if vehicle manufacturers opt to certify those vehicles under 40 CFR part 1037 instead of certifying under 40 CFR part 86, subpart S.

[268] The primary motivator for fleet managers was "Sustainability and environmental goals"; the survey was conducted by UPS and GreenBiz.

[269] ICCT (2019) "Estimating the infrastructure needs and costs for the launch of zero-emissions trucks"; available online at: *https://theicct.org/publications/zero-emission-truck-infrastructure*.

[270] Phadke, A., et. al. (2021) "Why Regional and Long-Haul Trucks are Primed for Electrification Now"; available online at: *https://eta-publications.lbl.gov/sites/default/files/updated_5_final_ehdv_report_033121.pdf*.

[271] Kahn, Ari, et. al. "The Inflation Reduction Act Will Help Electrify Heavy-Duty Trucking". Rocky Mountain Institute. August 25, 2022. Available online: *https://rmi.org/inflation-reduction-act-will-help-electrify-heavy-duty-trucking/*.

As the ICCT and Phadke et al. studies suggest, fuel costs are an important part of TCO. While assumptions about vehicle weight and size can make direct comparisons between HD ZEVs and ICE vehicles challenging, data show greater energy efficiency of battery-electric and fuel cell technology relative to ICE technologies.[272,273] Better energy efficiency leads to lower electricity or hydrogen fuel costs for ZEVs relative to ICE fuel costs.[274,275] Maintenance and service costs are also an important component within TCO; although there is limited data available on actual maintenance costs for HD ZEVs, early experience with BEV medium HD vehicles and transit buses suggests the potential for lower maintenance costs after an initial learning period component durability should be greatly improved.[276] We expect similar trends for FCEVs, as discussed in Chapter 2 of the RIA.

To facilitate HD fleets transitioning to ZEVs, some manufacturers are currently including maintenance in leasing agreements with fleets. It is unclear the extent to which a full-service leasing model will persist or will be transitioned to a more traditional purchase model after an initial period of learning.[277,278]

The growth in federal and state incentive programs will continue to play an important role in the HD ZEV market. In a 2017 survey of fleet managers, upfront purchase price was listed as the primary barrier to HD fleet electrification. This suggests that federal incentive programs like those in the BIL and IRA (discussed in Section 1.3) to offset ZEV purchase costs, as well as state and local incentives and investments, can be influential in the near term, with improvements in BEV and FCEV component costs playing an increasing role in reducing costs in the longer term.[279,280] For example, BEV incentive programs for transit and school buses have experienced growth and are projected to continue to influence BEV markets. The Los Angeles Department of Transportation (LADOT) is one of the first transit organizations in the country to develop a program committed to transitioning its transit fleets to ZEVs by 2030—a target that is 10 years sooner than CARB's Innovative Clean Transportation (ICT) regulation requiring all public

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[272] NACFE (2019) "Guidance Report: Viable Class 7/8 Electric, Hybrid and Alternative Fuel Tractors", available online at: *https://nacfe.org/downloads/viable-class-7-8-alternative-vehicles/*.

[273] Nadel, S. and Junga, E. (2020) "Electrifying Trucks: From Delivery Vans to Buses to 18-Wheelers". American Council for an Energy-Efficient Economy White Paper, available online at: *https://aceee.org/white-paper/electrifying-trucks-delivery-vans-buses-18*.

[274] NACFE (2019) "Guidance Report: Viable Class 7/8 Electric, Hybrid and Alternative Fuel Tractors", available online at: *https://nacfe.org/downloads/viable-class-7-8-alternative-vehicles/*.

[275] Nadel, S. and Junga, E. (2020) "Electrifying Trucks: From Delivery Vans to Buses to 18-Wheelers". American Council for an Energy-Efficient Economy White Paper, available online at: *https://aceee.org/white-paper/electrifying-trucks-delivery-vans-buses-18*.

[276] U.S. Department of Energy Alternative Fuels Data Center (AFDC), "Developing Infrastructure to Charge Plug-In Electric Vehicles", *https://afdc.energy.gov/fuels/electricity_infrastructure.html* (accessed 2-27-20).

[277] Fisher, J. (2019) "Volvo's First Electric VNR Ready for the Road." Fleet Owner, September 17. *www.fleetowner.com/blue-fleets/volvo-s-first-electric-vnr-ready-road*.

[278] Gnaticov, C. (2018). "Nikola One Hydrogen Electric Semi Hits the Road in Official Film." Carscoops, Jan. 26. *www.carscoops.com/2018/01/nikola-one-hydrogen-electric-semi-hits-road-official-film/*.

[279] Other barriers that fleet managers prioritized for fleet electrification included: Inadequate charging infrastructure-- our facilities, inadequate product availability, inadequate charging infrastructure-- public; for the full list of top barriers see Nadel and Junga (2020), citing UPS and GreenBiz 2018.

[280] Nadel, S. and Junga, E. (2020) "Electrifying Trucks: From Delivery Vans to Buses to 18-Wheelers". American Council for an Energy-Efficient Economy White Paper, available online at: *https://aceee.org/white-paper/electrifying-trucks-delivery-vans-buses-18*.

transit to be electric by 2040.[281] Since these announcements, LADOT has purchased 27 BEV transit and school buses from BYD and Proterra; by 2030, the number of BEV buses in the LADOT fleet is expected to grow to 492 buses. Outside of California, major metropolitan areas including Chicago, Seattle, New York City, and Washington, DC, have zero-emissions transit programs with 100 percent ZEV target dates ranging from 2040 to 2045.[282,283,284,285] EV school bus programs, frequently in partnership with local utilities, are also being piloted across the country and are expanding under EPA's Clean School Bus Program (CSB).[286] These programs initially included school districts in, but not limited to, California, Virginia, Massachusetts, Michigan, Maryland, Illinois, New York, and Pennsylvania.[287,288,289,290,291] Going forward, they will continue to expand with BIL funding of over $5 billion over the next five years (FY 2022–2026) to replace existing school buses with zero-emission and low-emission models, as discussed more in Section 1.3.

There are also extensive federal and state incentive programs to support transportation electrification infrastructure. For example, as discussed in more detail in this section, Federal Highway Administration (FHWA) -approved plans providing $1.5 billion in funding for expanding charging on over 75,000 miles of highway encourage states to consider station designs and power levels that could support heavy-duty vehicles. See further discussion in RTC section 6.1.

In summary, the HD ZEV market is growing rapidly, and ZEV technologies are expected to expand to many applications across the HD sector. As the industry is dynamic and changing rapidly, the examples presented here represent only a sampling of the ZEV HD investment

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[281] LADOT, (2020). "LADOT Transit Zero-Emission Bus Rollout Plan" *https://ww2.arb.ca.gov/sites/default/files/2020-12/LADOT_ROP_Reso_ADA12172020.pdf.*

[282] Sustainable Bus. "CTA Chicago tests electric buses and pursues 100% e-fleet by 2040". April 29, 2021. Available online: *https://www.sustainable-bus.com/electric-bus/cta-chicago-electric-buses/.*

[283] Pascale, Jordan. "Metro Approves Plans For Fully Electric Bus Fleet By 2045". DCist. June 10, 2021. Available online: https://dcist.com/story/21/06/10/metro-goal-entirely-electric-bus-fleet-2045/.

[284] King County Metro. "Transitioning to a zero-emissions fleet". Available online: *https://kingcounty.gov/depts/transportation/metro/programs-projects/innovation-technology/zero-emission-fleet.aspx*.

[285] Hallum, Mark. "MTA's recent purchase of zero emissions buses will be 33% bigger than expected". AMNY. May 25, 2021. Available online: *https://www.amny.com/transit/mta-says-45-to-60-more-buses-in-recent-procurement-will-be-zero-emissions/.*

[286] U.S. Environmental Protection Agency. "Clean School Bus Program". Available online: *https://www.epa.gov/cleanschoolbus*.

[287] Commonwealth of Massachusetts. "EV Programs & Incentives". Available online: *https://www.mass.gov/info-details/ev-programs-incentives*.

[288] Morris, Charles. "NYC's new school bus contract includes electric bus pilot". *Charged—Electric Vehicles Magazine*. July 7, 2021. Available online: *https://chargedevs.com/newswire/nycs-new-school-bus-contract-includes-electric-bus-pilot/.*

[289] Soneji, Hitesh, et. al. "Pittsburg USD Electric School Bus Final Project Report". Olivine, Inc. September 23, 2020. Available online: *https://olivineinc.com/wp-content/uploads/2020/10/Pittsburg-USD-Electric-School-Bus-Final-Project-Report-Final.pdf.*

[290] Shahan, Cynthia. "Largest Electric School Bus Program in United States Launching in Virginia". *CleanTechnica*. January 12, 2020. Available online: *https://cleantechnica.com/2020/01/12/largest-electric-school-bus-program-in-united-states-launching-in-virginia/.*

[291] St. John, Jeff. "Highland Electric Raises $235M, Lands Biggest Electric School Bus Contract in the US". *gtm*. February 25, 2021. Available online: *https://www.greentechmedia.com/articles/read/on-heels-of-253m-raise-highland-electric-lands-biggest-electric-school-bus-contract-in-the-u.s.*

policies and markets. The following sections provide a more detailed characterization of the HD ZEV technologies in the current and projected ZEV market.

The current heavy-duty market offers battery electric vehicles available for sale as both new design BEVs and through conversions of ICE vehicles to BEVs. This market has been growing since MY 2018 and is projected to reach about 180 models of heavy-duty battery electric trucks by MY 2024,[292] see Figure 1-13 for a summary of the number of battery electric heavy-duty trucks available by model year as identified by literature review.

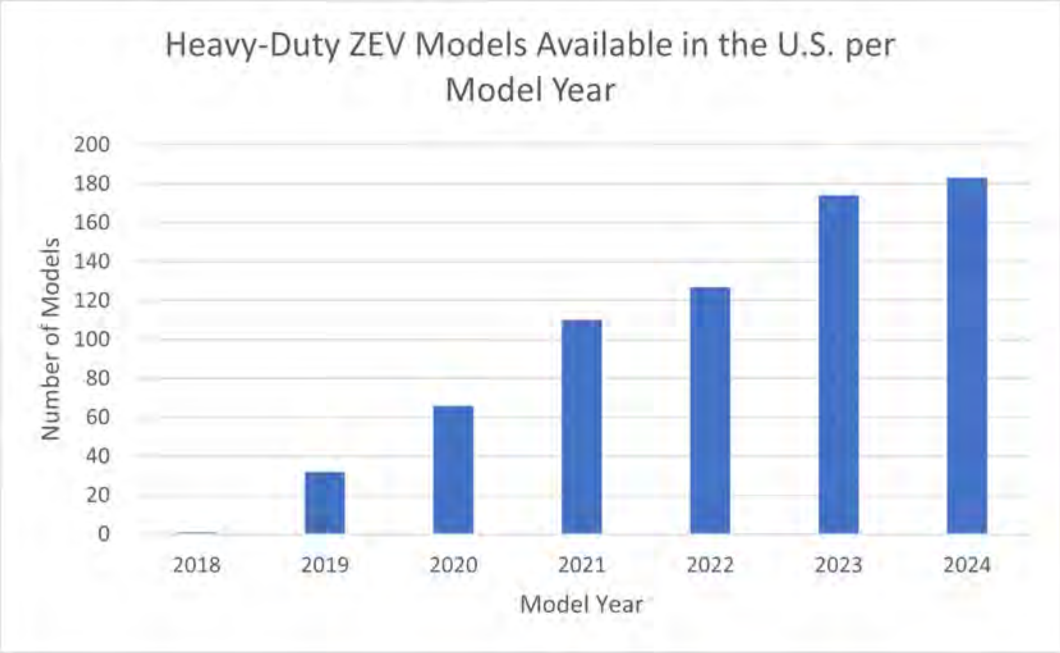

Figure 1-13 Heavy-Duty Electric Trucks Available in the U.S. by Model Year

A list of battery electric heavy-duty trucks available to the public through MY 2024 is in Table 1-23.

Table 1-23 Models of Battery Electric Heavy-Duty Vehicles through 2024

Make	Model	Vehicle Type	Weight Class	New Design or Existing Design Conversion	First Model Year
ARBOC Specialty Vehicles	Equess Charge[293]	Transit Bus	Class 7; Class 8	New	2021
Arrival	Van[294]	Panel Van	Class 4	New	2021
Arrival	Bus[295]	Transit Bus	Class 7	New	2024
Autocar	E-ACTT[296]	Yard Truck	Class 8	New	2021

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[292] Miller, Neil. Memorandum to docket EPA-HQ-OAR-2022-0985. “Heavy-Duty ZEV Models Available in the US through MY2024.” October 2023.

[293] ARBOC Specialty Vehicles. Equess Charge. Available online: https://arbocsv.com/models/equess-charge/.

[294] Arrival. Van. Available online: https://arrival.com/us/en/topic/van

[295] Arrival. Bus. Available online: https://arrival.com/topic/bus

[296] Autocar. E-ACTT. Available online: https://www.autocartruck.com/actt/eactt/

Make	Model	Vehicle Type	Weight Class	New Design or Existing Design Conversion	First Model Year
Avevai	E12 303[297]	Transit Bus	Class 8	New	2023
Avevai	E12 373[298]	Transit Bus	Class 8	New	2023
Avevai	XL[299]	Panel Van	Class 4	New	2024
Battle Motors	LET[300]	Refuse	Class 6; Class 7; Class 8	New	2022
Battle Motors	LET 2[301]	Refuse	Class 7	New	2022
Blue Arc	EV[302]	Panel Van	Class 3; Class 4; Class 5; Class 6	New	2022
Blue Arc	EV5[303]	Straight Truck	Class 5	New	2023
Blue Bird	Electric All American Bus[304]	Shuttle Bus; Transit Bus	40 - 59 ft; Class 8	New	2019
Blue Bird	Electric All American Bus[304]	Shuttle Bus; Transit Bus	40 - 59 ft; Class 7	New	2019
Blue Bird	Electric All American School Bus[304]	Public School Bus	Class 8	New	2019
Blue Bird	Electric All American School Bus[304]	Public School Bus	Class 7	New	2019
Blue Bird	Electric Vision Bus[305]	Shuttle Bus; Transit Bus	30 - 39 ft; Class 6; Class 7	New	2019
Blue Bird	Electric Vision School bus[305]	Public School Bus	Class 6; Class 7	New	2020
Blue Bird	Micro Bird G5[306]	Public School Bus	Class 4	Conversion	2020
Bollinger Motors	B4[307]	Chassis Cab	Class 4	New	2022
Bollinger Motors	B5[308]	Chassis Cab	Class 5	New	2023

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[297] Avevai. E12 303. Available online: https://avevai.com/wp-content/uploads/2023/08/AVEVAI-A12-Tech-Specs.pdf

[298] Avevai. E12 373. Available online: https://avevai.com/wp-content/uploads/2023/08/AVEVAI-A12-Tech-Specs.pdf

[299] Avevai. XL. Available online: https://avevai.com/iona-xl/

[300] Battle Motors. LET. Available online: https://battlemotors.com/pages/lnt-ev

[301] Battle Motors. LET 2. Available online: https://battlemotors.com/pages/let-ii-ev-specs

[302] Blue ARC. EV. Available online: https://bluearcev.com/#specifications

[303] Blue ARC. EV5. Available online: https://bluearcev.com/wp-content/uploads/2023/03/bluearc-ev5-sell-sheet.pdf

[304] Blue Bird. All American Electric. Available online: https://www.blue-bird.com/images/RE_Electric_Spec_Sheet_09_30_22.pdf

[305] Blue Bird. Vision Electric. Available online: https://www.blue-bird.com/buses/vision/vision-electric-bus

[306] Blue Bird Micro Bird. G5 Electric. Available online: https://www.microbird.com/g5-electric

[307] Bollinger Motors. B4. Available online: https://bollingermotors.com/trucks/

[308] Bollinger Motors. B5. Available online: https://bollingermotors.com/trucks/

Make	Model	Vehicle Type	Weight Class	New Design or Existing Design Conversion	First Model Year
BrightDrop	ZEVO 600[309]	Panel Van	Class 3	New	2023
BrightDrop	ZEVO 400[310]	Panel Van	Class 3	New	2023
BYD Motors	6F[311]	Straight Truck	Class 6	New	2020
BYD Motors	6F/6F+[311]	Straight Truck	Class 6	New	2021
BYD Motors	6R[312]	Refuse	Class 6	New	2020
BYD Motors	8R[313]	Refuse	Class 8	New	2019
BYD Motors	8TT[314]	Tractor	Class 8	New	2019
BYD Motors	8Y[315]	Yard Truck	Class 8	New	2019
BYD Motors	C10M[316]	Coach Bus	> 40 ft; Class 8	New	2020
BYD Motors	C10MS[317]	Coach Bus	> 40 ft; Class 8	New	2019
BYD Motors	C6M[318]	Coach Bus	20 - 24 ft; Class 4; Class 5	New	2019
BYD Motors	C8M[319]	Coach Bus	30 - 39 ft; Class 8	New	2019
BYD Motors	C8MS[320]	Coach Bus	30 - 39 ft; Class 8	New	2021
BYD Motors	C9M[321]	Coach Bus	30 - 39 ft; Class 8	New	2019
BYD Motors	K11M[322]	Transit Bus	> 40 ft; Class 8	New	2019
BYD Motors	K7M[323]	Transit Bus	30 - 39 ft; Class 7	New	2020

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[309] Brightdrop. ZEVO 600. Available online: https://www.gobrightdrop.com/products/brightdrop-zevo

[310] Brightdrop. ZEVO 400. Available online: https://www.gobrightdrop.com/products/brightdrop-zevo

[311] BYD. 6F. Available online: https://en.byd.com/truck/class-6-truck/#:~:text=Cab%20%26%20Chassis-,The%20BYD%206F%20is%20the%20world's%20first%20commercially%20available%20all,of%20performance%2C%20endurance%20and%20reliability.

[312] BYD. 6R. Available online: https://en.byd.com/truck/class-6-refuse-truck/

[313] BYD. 8R. Available online: https://en.byd.com/truck/class-8-refuse-truck/

[314] BYD. 8TT. Available online: https://en.byd.com/truck/class-8-day-cab/

[315] BYD. 8Y. Available online: https://en.byd.com/truck/terminal-tractor/

[316] BYD. C10M. Available online: https://en.byd.com/bus/bus-c10m/

[317] BYD. C10MS. Available online: https://en.byd.com/bus/bus-c10ms/

[318] BYD. C6M. Available online: https://en.byd.com/bus/bus-c6m/

[319] BYD. C8M. Available online: https://en.byd.com/bus/bus-c8m/

[320] BYD. C8MS. Available online: https://en.byd.com/bus/bus-c8ms/

[321] BYD. C9M. Available online: https://en.byd.com/bus/bus-c9m/

[322] BYD. K11M. Available online: https://en.byd.com/bus/k11m/

[323] BYD. K7M. Available online: https://en.byd.com/bus/k7m/

Make	Model	Vehicle Type	Weight Class	New Design or Existing Design Conversion	First Model Year
BYD Motors	K7M-ER[324]	Shuttle Bus; Transit Bus	30 - 39 ft; Class 8	New	2020
BYD Motors	K8M[325]	Transit Bus	30 - 39 ft; Class 8	New	2019
BYD Motors	K9M[326]	Transit Bus	30 - 39 ft; Class 8	New	2019
BYD Motors	K9MD[327]	Transit Bus	30 - 39 ft; Class 8	New	2019
BYD Motors	Type D School Bus[328]	Public School Bus	Class 8	New	2021
BYD Motors	Type A School Bus[329]	Public School Bus	Class 6	New	2023
Canoo	MPDV 1[330]	Panel Van	Class 3	New	2024
CityFreighter	CF1[331]	Step Van	Class 4; Class 5	New	2024
Complete Coach Works	ZEPS[332]	Transit Bus	Class 8	Conversion	2020
Dulevo	D.zero2[333]	Street Sweeper		New	2020
ElDorado National	AXESS EVO 32[334]	Transit Bus	Class 8	New	2023
ElDorado National	AXESS EVO 35[334]	Transit Bus	Class 8	New	2023
ElDorado National	AXESS EVO 40[334]	Transit Bus	Class 8	New	2023
Envirotech Drive Systems Incorporated	C Series[335]	Panel Van	Class 4	New	2019
Envirotech Drive Systems Incorporated	C Series Cutaway, Urban Cab Over[336]	Straight Truck	Class 4	New	2019

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[324] BYD. K7MER. Available online: https://en.byd.com/bus/k7mer/
[325] BYD. K8M. Available online: https://en.byd.com/bus/k8m/
[326] BYD. K9M. Available online: https://en.byd.com/bus/k9m/
[327] BYD. K9MD. Available online: https://en.byd.com/bus/k9md/
[328] BYD. Type D Electric School Bus. Available online: https://en.byd.com/bus/school-bus/school-bus-d/
[329] BYD. Type A School Bus. Available online: https://en.byd.com/bus/school-bus/school-bus-a/
[330] Canoo. MPDV 1. Available online: https://www.canoo.com/mpdv/
[331] CityFreighter. CF1. Available online: https://www.cityfreighter.com/
[332] Complete Coach Works. ZEPS. Available online: http://www.completecoach.com/wp-content/uploads/2013/07/ZEPS-Brochure.pdf
[333] Dulevo. D.Zero2. Available online: https://www.dulevo.com/us/products/street-sweepers/dulevo-d-zero2/
[334] ElDorado National. Axess EVO Specifications. Available online: https://www.eldorado-ca.com/axess-evo-be
[335] Envirotech Drive Systems. Logistics Van. Available online: https://evtvusa.com/vehicles/logistics-van/
[336] Envirotech Drive systems. Cutaway Van. Available online: https://evtvusa.com/vehicles/cutaway-van/

Make	Model	Vehicle Type	Weight Class	New Design or Existing Design Conversion	First Model Year
Envirotech Drive Systems Incorporated	Urban Cab Over[337]	Straight Truck	Class 3	New	2020
Ford	eTransit[338]	Panel Van	Class 4	New	2022
Freightliner	eCascadia[339]	Tractor	Class 8	New	2022
Freightliner	eM2[340]	Straight Truck	Class 6; Class 7	New	2023
Freightliner	MT50e[341]	Step Van; Straight Truck	Class 5	New	2020
Gillig	29[342]	Transit Bus	25 - 29 ft; 30 - 39 ft; Class 8	New	2020
Global Environmental Products	M3EV[343]	Street Sweeper	Class 6; Class 7	New	2020
Global Environmental Products	M4EV[344]	Street Sweeper	Class 6; Class 7	New	2020
GreenPower Motor Company	BEAST[345]	Public School Bus	Class 8	New	2020
GreenPower Motor Company	Nano Beast[346]	Public School Bus	Class 5	New	2023
GreenPower Motor Company	AV Star[347]	Shuttle Bus	Class 4	New	2020
GreenPower Motor Company	EV Star CarGo[348]	Panel Van	Class 4	New	2019
GreenPower Motor Company	EV Star CarGo Plus[349]	Straight Truck	Class 4	New	2021

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[337] Envirotech Drive Systems. Urban Truck. Available online: https://evtvusa.com/vehicles/urban-truck/

[338] Ford. E-Transit Cargo Van. Available online: https://www.ford.com/commercial-trucks/e-transit/models/cargo-van/

[339] Freightliner. eCascadia. Available online: https://freightliner.com/trucks/ecascadia/specifications/#tab-1

[340] Freightliner. eM2. Available online: https://freightliner.com/trucks/em2/specifications/

[341] Freightliner Custom Chassis. eM2 Walk-in Van. Available online: https://www.electricwalkinvan.com/

[342] Gillig. Battery Electric Bus. Available online: https://www.gillig.com/battery-electric

[343] Global Environmental Products. M3EV. Available online: https://globalsweeper.com/products/mechanical/m3-electric-100-plug-in

[344] Global Environmental Products. M4EV. Available online: https://globalsweeper.com/products/mechanical/m4-electric-100-plug-in

[345] Greenpower Motor Company. Beast. Available online: https://greenpowermotor.com/wp-content/uploads/Brochures/BEAST_Brochure.pdf

[346] GreenPower Motor Company. Nano Beast. Available online: https://greenpowermotor.com/gp-products/nano-beast-school-bus/

[347] Greenpower Motor Company. AV Star. Available online: https://greenpowermotor.com/gp-products/av-star/

[348] Greenpower Motor Company. EV Star Cargo. Available online: https://greenpowermotor.com/wp-content/uploads/Brochures/EVSTARC_Brochure.pdf

[349] Greenpower Motor Company. EV Star Cargo +. Available online: https://greenpowermotor.com/wp-content/uploads/Brochures/EVSTARC+_Brochure.pdf

Make	Model	Vehicle Type	Weight Class	New Design or Existing Design Conversion	First Model Year
GreenPower Motor Company	EV Star CC[350]	Straight Truck	Class 4	New	2021
GreenPower Motor Company	EV Star[351]	Shuttle Bus	Class 4	New	2020
GreenPower Motor Company	EV Star Plus[352]	Paratransit; Shuttle Bus	Class 4	New	2020
GreenPower Motor Company	EV250[353]	Transit Bus	30 - 39 ft; Class 8	New	2019
GreenPower Motor Company	EV350[354]	Transit Bus	40 - 59 ft; Class 8	New	2019
GreenPower Motor Company	EV550[355]	Transit Bus	> 40 ft; Class 8	New	2019
GreenPower Motor Company	SYNAPSE 72[356]	Public School Bus	Class 8	New	2019
GreenPower Motor Company	SYNAPSE[357]	Shuttle Bus; Transit Bus	30 - 39 ft; Class 8	New	2019
Hino	L6e[358]	Straight Truck	Class 6	New	2023
Hino	M5e[359]	Straight Truck	Class 5	New	2023
Hometown Manufacturing	Villager[360]	Transit Bus	Class 6; Class 7	New	2021
Hometown Manufacturing	Mainstreet[361]	Transit Bus	Class 6; Class 7	New	2021
Hometown Manufacturing	Streetcar[362]	Transit Bus	Class 7; Class 8	New	2021

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[350] Greenpower Motor Company. EV Star CC. Available online: https://greenpowermotor.com/wp-content/uploads/Brochures/EVSTARCC_Brochure.pdf

[351] Greenpower Motor Company. EV Star. Available online: https://greenpowermotor.com/wp-content/uploads/Brochures/EVSTAR_Brochure.pdf

[352] Greenpower Motor Company. EV Star +. Available online: https://greenpowermotor.com/wp-content/uploads/Brochures/EVSTAR+_Brochure.pdf

[353] Greenpower Motor Company. EV250. Available online: https://greenpowermotor.com/wp-content/uploads/Brochures/EV250_brochure.pdf

[354] Greenpower Motor Company. EV350. Available online: https://greenpowermotor.com/wp-content/uploads/Brochures/EV350_brochure.pdf

[355] Greenpower Motor Company. EV550. Available online: https://greenpowermotor.com/gp-products/ev550-bus/

[356] Greenpower Motor Company. Synapse 72. Available online: https://greenpowermotor.com/greenpowers-synapse-72-school-bus-commences-demonstration-tour/

[357] Greenpower Motor Company. Synapse Shuttle Bus. Available online: https://greenpowermotor.com/greenpower-delivers-synapse-shuttle/

[358] Hino. L6e. Available online: https://www.hino.com/electricvehicle.html

[359] Hino. M5e. Available online: https://www.hino.com/electricvehicle.html

[360] Hometown Manufacturing. Villager. Available online: https://hometown-mfg.com/trolleys/villager

[361] Hometown Manufacturing. Mainstreet. Available online: https://hometown-mfg.com/trolleys/mainstreet

[362] Hometown Manufacturing. Streetcar. Available online: https://hometown-mfg.com/trolleys/streetcar

Make	Model	Vehicle Type	Weight Class	New Design or Existing Design Conversion	First Model Year
Hometown Manufacturing	View[363]	Transit Bus	Class 6; Class 7	New	2021
Hometown Manufacturing	Commuter[364]	Transit Bus	Class 7; Class 8	New	2021
Hometown Manufacturing	Urban[365]	Transit Bus	Class 7; Class 8	New	2021
Hyundai	Electric City[366]	Transit Bus	Class 7	New	2020
IC Bus	CE Electric[367]	Public School Bus	Class 7	New	2021
Kalmar	T2E+[368]	Yard Truck	Class 8	New	2020
Kenworth	K270E[369]	Straight Truck	Class 6	New	2020
Kenworth	K370E[369]	Straight Truck	Class 7	New	2020
Kenworth	T680E[370]	Tractor	Class 8	New	2020
Lightning Systems	Transit Bus[371]	Transit Bus	Class 6	Conversion	2020
Lightning Systems	Transit Cargo Van[372]	Panel Van	Class 4	Conversion	2020
Lightning Systems	ZEV4[373]	Shuttle Bus	Class 4	Conversion	2023
Lightning Systems	ZEV4[374]	Public School Bus	Class 4	Conversion	2023
Lightning Systems	ZEV4[375]	Straight Truck	Class 4	Conversion	2023
Lightning Systems	ZEV3[376]	Panel Van	Class 3	Conversion	2023
Lightning Systems	ZEV3[377]	Ambulance	Class 3	Conversion	2023

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[363] Hometown Manufacturing. View. Available online: https://hometown-mfg.com/buses/view

[364] Hometown Manufacturing. Commuter. Available online: https://hometown-mfg.com/buses/commuter

[365] Hometown Manufacturing. Urban. Available online: https://hometown-mfg.com/buses/low-floor-urban

[366] Hyundai. Elec City. Available online: https://trucknbus.hyundai.com/global/en/products/bus/elec-city

[367] IC Bus. CE Electric. Available online: https://www.icbus.com/-/media/Project/Navistar/ICBus/ICBus/Electric/NAV22_IC_BUS_eCE_SpecSheet_2022_rd02.pdf

[368] Kalmar Ottawa. T2E+. Available online: https://www.kalmarglobal.com/4946e2/globalassets/media/268794/268794_Kalmar-Ottawa-Electric-Terminal-Tractor-T2E-_Brochure-web.pdf.pdf

[369] Kenworth. K270e K370e. Available online: https://www.kenworth.com/trucks/k270e-k370e/

[370] Kenworth. T680e. Available online: https://www.kenworth.com/trucks/t680e/

[371] Lightning eMotors. City Transit Bus Repower. Available online: https://lightningemotors.com/buses/

[372] Lightning eMotors. ZEV3 Transit Cargo Van. Available online: https://lightningemotors.com/zev3-transit-cargo-van/

[373] Lightning eMotors. ZEV4 Shuttle Bus. Available online: https://lightningemotors.com//lightningelectric-class4-shuttle/

[374] Lightning eMotors. ZEV4 Public School Bus. Available online: https://lightningemotors.com/type-a-school-bus/

[375] Lightning eMotors. ZEV4 Straight Truck. Available online: https://lightningemotors.com//lightningelectric-class4-cutaway/

[376] Lightning eMotors. ZEV3 Ambulance. Available online: https://lightningemotors.com/ambulances/

[377] Lightning eMotors. ZEV3 Panel Van. Available online: https://lightningemotors.com/zev3-transit-cargo-van/

Make	Model	Vehicle Type	Weight Class	New Design or Existing Design Conversion	First Model Year
Lion Electric	Lion5[378]	Straight Truck	Class 5	New	2023
Lion Electric	Lion6[379]	Straight Truck	Class 6	New	2021
Lion Electric	Lion8P ASL[379]	Refuse	Class 8	New	2021
Lion Electric	Lion8P[379]	Straight Truck	Class 8	New	2019
Lion Electric	Lion8P Rel[379]	Refuse	Class 8	New	2021
Lion Electric	Lion8T[379]	Tractor	Class 8	New	2021
Lion Electric	Bucket Truck[379]	Bucket Truck	Class 8	New	2021
Lion Electric	LionA[380]	Public School Bus	Class 6	New	2019
Lion Electric	LionC[381]	Public School Bus	Class 6; Class 7	New	2019
Lion Electric	LionD[382]	Public School Bus	Class 8	New	2019
Lion Electric	LionM[383]	Paratransit	Class 6	New	2020
Mack Trucks	LR[384]	Refuse; Straight Truck	Class 8	New	2021
Mack Trucks	MD[385]	Straight Truck	Class 5	New	2023
Mercedes Benz	eCitaro[386]	Transit Bus	Class 8	New	2021
Mercedes Benz	eACTROS 600[387]	Straight Truck	Class 8	New	2023
Mercedes Benz	eACTROS 600[387]	Tractor	Class 8	New	2023
Motiv Power Systems	E-450[388]	Straight Truck	Class 4	Conversion	2021
Motiv Power Systems	E-450[389]	Shuttle Bus	Class 6	Conversion	2020
Motiv Power Systems	F-53[390]	Step Van	Class 6	Conversion	2021

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[378] Lion Electric. Lion5. Available online: https://thelionelectric.com/documents/en/LionTruck-SpecSheet-202305-SCREEN-ENUS.pdf

[379] Lion Electric. Lion6, Lion8, Lion8 Bucket, Lion8 Refuse ASL, Lion8 Refuse REL, Lion8T. Available online: https://thelionelectric.com/documents/en/Lion8_all_applications.pdf

[380] Lion Electric. LionA. Available online: https://thelionelectric.com/documents/en/onepager_LionA_EN.pdf

[381] Lion Electric. LionC. Available online: https://thelionelectric.com/documents/en/BrochureLionCang.pdf

[382] Lion Electric. LionD. Available online: https://thelionelectric.com/documents/en/liond_specs_en.pdf

[383] Lion Electric. LionM. Available online: https://thelionelectric.com/documents/en/spec_LionM_EN_US.pdf

[384] Mack Trucks. LR Electric. Available online: https://www.macktrucks.com/trucks/lr-electric/specs/

[385] Mack Trucks. MD Electric. Available online: https://www.macktrucks.com/trucks/md-electric/

[386] Mercedes Benz Bus. eCitaro. Available online: https://www.mercedes-benz-bus.com/en_DE/models/ecitaro/technology.html

[387] Mercedes Benz Truck. eACTROS 600. Available online: https://eactros600.mercedes-benz-trucks.com/int/en/eactros-600/showroom.html#eactros600_technical-data

[388] Motiv Power Systems. E-450. Available online: https://www.motivps.com/application/electric-box-truck/

[389] Motiv Power Systems. Shuttle Bus. Available online: https://www.motivps.com/application/electric-step-van/

[390] Motiv Power Systems. Step Vans. Available online: https://www.motivps.com/vehicles/step-vans/

Make	Model	Vehicle Type	Weight Class	New Design or Existing Design Conversion	First Model Year
Motiv Power Systems	Argo[391]	Straight Truck	Class 6	New	2024
Motor Coach Industries	D45 CRT Charge[392]	Coach Bus	40 – 59 ft; Class 8	New	2020
Motor Coach Industries	D45 CRTe LE[392]	Coach Bus	40 - 59 ft; Class 8	New	2020
Motor Coach Industries	J4500e[392]	Coach Bus	40 - 59 ft; Class 8	New	2020
Navistar	eMV[393]	Straight Truck	Class 6; Class 7	New	2021
New Flyer	XCELSIOR Charge NG[394]	Transit Bus	35, 40, 60 ft; Class 7; Class 8	New	2021
Nikola	Tre[395]	Tractor	Class 8	New	2023
Nova Bus	LFSe[396]	Transit Bus	Class 8	New	2018
Nova Bus	LFSe+[397]	Transit Bus	Class 8	New	2021
Optimal Inc	S1[398]	Shuttle Bus	Class 5	Conversion	2021
Optimal Inc	E1[399]	Chassis Cab	Class 5	Conversion	2021
Orange EV	HUSK-e[400]	Yard Truck	Class 8	New	2023
Orange EV	eTriever[401]	Yard Truck	Class 8	New	2021
Peterbilt	220EV[402]	Straight Truck	Class 6; Class 7	New	2021
Peterbilt	520EV[403]	Refuse; Straight Truck	Class 8	New	2021
Peterbilt	579EV[404]	Tractor	Class 8	New	2021

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[391] Motiv Power Systems. Argo. Available online: https://www.motivps.com/vehicles/building-the-future/

[392] Motor Coach Industries. Electric Series Specs. Available online: https://www.mcicoach.com/coach/electric-series/specs/

[393] International Trucks. eMV. Available online: https://www.internationaltrucks.com/trucks/emv-series/detailed-specs

[394] New Flyer. Xcelsior Charg NG. Available online: https://www.newflyer.com/bus/xcelsior-charge-ng/

[395] Nikola. Tre BEV. Available online: https://nikolamotor.com/tre-bev

[396] Nova Bus. LFSe. Available online: https://us.novabus.com/blog/bus/lfse/

[397] Nova Bus. LFSe+. Available online: https://us.novabus.com/blog/bus/lfse-plus/

[398] Optimal EV. S1. Available online: https://www.optimal-ev.com/s1

[399] Optimal EV. E1. Available online: https://www.optimal-ev.com/e1

[400] Orange EV. HUSK-e. Available online: https://orangeev.com/wp-content/uploads/2023/09/OEV-HUSK-e-Product-Sheet.pdf

[401] Orange EV. eTriever. Available online: https://orangeev.com/etriever/

[402] Peterbilt. 220EV. Available online: https://www.peterbilt.com/trucks/electric/220EV

[403] Peterbilt. 520EV. Available online: https://www.peterbilt.com/trucks/electric/520EV

[404] Peterbilt. 579EV. Available online: https://www.peterbilt.com/trucks/electric/579EV

Make	Model	Vehicle Type	Weight Class	New Design or Existing Design Conversion	First Model Year
Phoenix	E450[405]	Shuttle Bus	25 - 29 ft; Class 4	New	2019
Phoenix	E450[405]	Straight Truck	Class 4	New	2020
Phoenix	E450[406]	Public School Bus	Class 4	New	2019
Proterra	ZX5+ 35'[407]	Transit Bus	35 ft; Class 8	New	2021
Proterra	ZX5+ 35'[407]	Transit Bus	35 ft; Class 8	New	2021
Proterra	ZX5+ 40'[408]	Transit Bus	40 ft; Class 8	New	2021
Proterra	ZX5+ 40'[408]	Transit Bus	40 ft; Class 8	New	2021
Proterra	ZX5 MAX[408]	Transit Bus	40 ft; Class 8	New	2021
Proterra	ZX5 MAX[408]	Transit Bus	40 ft; Class 8	New	2021
Rizon	e16M[409]	Straight Truck	Class 4	New	2023
Rizon	e16L[409]	Straight Truck	Class 4	New	2023
Rizon	e18M[409]	Straight Truck	Class 5	New	2023
Rizon	e18L[409]	Straight Truck	Class 5	New	2023
SEA Electric	5e[410]	Straight Truck	Class 5	New	2023
SEA Electric	Ford F-59e[411]	Panel Van	Class 5, Class 6	Conversion	2021
SEA Electric	SV6e[412]	Straight Truck	Class 6	New	2023

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[405] Phoenix. E450 Shuttle Bus and Straight Truck. Available online: https://www.phoenixmotorcars.com/wp-content/uploads/2021/08/ZEUS-400-500-FLYER-TRUCKS-AND-SHUTTLE-FOR-SITE-AUGUST-2021.pdf

[406] Phoenix. E450 Public School Bus. Available online: https://www.phoenixmotorcars.com/products/#bus

[407] Proterra. ZX5+ 35’ Bus. Available online: https://www.proterra.com/wp-content/uploads/2022/09/SPEC_35_001_Q4_2022_V1_09_01_22.pdf

[408] Proterra. ZX5+ and ZX5 Max 40’ Bus. Available online: https://www.proterra.com/wp-content/uploads/2022/09/SPEC_40_001_Q4_2022_V1_09_01_22-1.pdf

[409] Rizon. e16M, e16L, e18M, e18L. Available online: https://assest.rizontruck.com/rizonassets/2023/10/RIZON-Product-Brochure-Oct-23-min.pdf?_fsi=8UPB9mCy

[410] SEA Electric. 5e. Available online: https://www.sea-electric.com/wp-content/uploads/2023/06/SEA-5e-eBrochure-0623.pdf

[411] SEA Electric. F-59e. Available online: https://www.sea-electric.com/wp-content/uploads/2023/08/SEA-F59e-eBrochure-0723-%E2%80%93-USA.pdf

[412] SEA Electric. SV6e. Available online: https://www.sea-electric.com/wp-content/uploads/2023/08/SEA-SV6e-eBrochure-0223.pdf

Make	Model	Vehicle Type	Weight Class	New Design or Existing Design Conversion	First Model Year
SEA Electric	Type C School Bus[413]	Public School Bus	Class 6	Conversion	2022
Terraline	Tangra LH1[414]	Tractor	Class 8	New	2023
Terberg	YT203-EV[415]	Yard Truck	Class 8	New	2020
Tesla	Semi[416]	Tractor	Class 8	New	2024
Thomas Built	eC2 Jouley[417]	Public School Bus	Class 7	New	2019
US Hybrid	eVan[418]	Panel Van	Class 3	Conversion	2022
Van Hool NV	CX45E[419]	Coach Bus; Shuttle Bus; Transit Bus	Class 8	New	2020
Van Hool NV	TDX25e[420]	Coach Bus	Class 8	New	2023
Vicinity Motors	VMC 1200[421]	Straight Truck	Class 3	New	2023
Vicinity Motors	Lightning EV[422]	Transit Bus	Class 6	New	2020
Volvo	VNR[423]	Tractor	Class 8	New	2021
Volvo	VNR[423]	Straight Truck	Class 8	New	2021
Workhorse Group Inc.	W4 CC[424]	Straight Truck	Class 4	New	2023
Workhorse Group Inc.	W750[425]	Panel Van	Class 4	New	2023
Workhorse Group Inc.	W56[426]	Step Van	Class 5, Class 6	New	2023
Xos	SV	Step Van	Class 6	New	2023
Xos	HDXT[427]	Tractor	Class 8	new	2022

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[413] SEA Electric. Type C Public School Bus. Available online: https://www.sea-electric.com/wp-content/uploads/2023/08/SEA-Type-C-School-Bus-eBrochure-0223.pdf

[414] Terraline. Tangra LH1. Available online: https://terralinetrucks.com/tangra-lh1/

[415] Terberg Special Vehicles. YT203-EV. Available online: https://www.terbergspecialvehicles.com/en/vehicles/terminal-tractors/#YT203-EV

[416] Tesla. Semi. Available online: https://www.tesla.com/semi

[417] Thomas Built Buses. Saf-T-Liner C2 Jouley. Available online: https://thomasbuiltbuses.com/school-buses/saf-t-liner-c2-jouley/

[418] US Hybrid. eVan. Available online: https://ushybrid.com/wp-content/uploads/2022/05/USH_eVan_Productsheet_2022_V8.pdf

[419] Van Hool. CX45e. Available online: https://www.vanhool.com/en/vehicles/coaches/coaches-usa/cx45e

[420] Van Hool. TDX25e Astromega. Available online: https://www.vanhool.com/en/vehicles/coaches/coaches-usa/tdx25e-astromega-usa

[421] Vicinity Motor Co. VMC 1200. Available online: https://vicinitymotorcorp.com/images/pdf/VMC1200SpecificationsFlyer.pdf

[422] Vicinity Motor Co. Lightning EV. Available online: https://vicinitymotorcorp.com/modelsm/vicinity-lightning-ev.html

[423] Volvo. VNR Electric. Available online: https://www.volvotrucks.us/trucks/vnr-electric/

[424] Workhorse Group. W4 CC. Available online: https://workhorse.com/wp-content/uploads/2023/05/CV-W4CC-Specs-2305v6.pdf

[425] Workhorse Group. W750. Available online: https://workhorse.com/wp-content/uploads/2023/05/CV-W750-Specs-2305v4.pdf

[426] Workhorse Group. W56. Available online: https://workhorse.com/wp-content/uploads/2023/05/CV-W56-Specs-2305v2.pdf

[427] XOS Trucks. HDXT. Available online: https://www.xostrucks.com/hdxt

Make	Model	Vehicle Type	Weight Class	New Design or Existing Design Conversion	First Model Year
Xos	MDXT[428]	Straight Truck	Class 6; Class 7	New	2022
Hexagon	Purus eM2[429]	Straight Truck	Class 6; Class 7	Conversion	2021
Zeus	Electric Chassis[430]	Straight Truck	Class 5; Class 7	New	2023

1.5.5.1 Purchase Commitments of Battery Electric Vehicles

A report by The Environmental Defense Fund (EDF) summarized several publicly announced heavy-duty electric vehicle purchase commitments during 2022.[431] These announcements can be found at the references in Table 1-24 below. These announcements were made prior to the passage of the Inflation Reduction Act and therefore do not include purchase commitments that may result from consideration of the various tax incentives and other incentives that currently are available in the market, as summarized in Chapter 1.3.2 of this document.

Table 1-24 List of HD BEV Purchase Commitments Compiled by EDF (2022)[431]

Fleet	EVs Deployed / Ordered	Vehicles Delivered	Vehicle Type	Vehicle Model
4 Gen Logistics	20	No	Class 8 Tractor	-Kenworth T680E
A. Duie Pyle Inc.	2	Yes	Class 4 Box Truck	-FUSO eCanter
A.P. Moller-Maersk	300	No	Class 8 Tractor	-Einride AB
A&R Logistics	2	Yes	Class 8 Tractor	-Peterbilt Model 579EV
AE Cargo Group Inc,	1	No	Yard tractor	N/A
AJR Trucking	15	No	Class 8 Tractor	-Kenworth T680E
Albertsons Cos.	12	Partially	Class 8 Tractor	-10 Tesla semitrucks -2 Volvo VNR Electric truck
Alco	1	Yes	Terminal Tractor	-Orange EV T-Series
Alsco	4	Yes	Class 4 Step Van	-EPIC F-59 F
Amazon	102,500	Partially	Class 2b Cargo Van Class 8 Tractor Class 6 Tractor Class 2b Delivery Van	-100,000 Rivian Cargo Van -1250 Lion Electric -1250 Lion Electric -TBA BEV ProMaster
Amherst County	2	No	Class 8 Tractor	-N/A
Anderson DuBose	1	Yes	Terminal Tractor	-Orange EV
Anheuser-Busch Cos.	841	Partially	Class 8 Tractor	-21 BYD 8TT -800 Nikola Fuel Cell -40 Tesla semi trucks

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[428] XOS Trucks. MDXT. Available online: https://www.xostrucks.com/mdxt

[429] Hexagon Purus. eM2. Available online: https://hexagonpurus.com/our-solutions/battery-and-fuel-cell

[430] Zeus. Electric Vocational Trucks. Available online: https://zeuselectricchassis.com/electric-vocational-trucks/

[431] Environmental Defense Fund. Electric Fleet Deployment & Commitment List. Available here: https://docs.google.com/spreadsheets/d/1l0m2Do1mjSemrb_DT40YNGou4o2m2Ee-KLSvHC-5vAc/edit#gid=2049738669

Fleet	EVs Deployed / Ordered	Vehicles Delivered	Vehicle Type	Vehicle Model
ARAMARK and Operating Companies	31	Yes	Class 5 Step Van	-Motiv Power Systems F-59
Benore Logistic Systems	1	Yes	Class 8 Tractor	-Peterbilt Model 579EV
Best Transportation	4	No	Terminal tractors	N/A
Bettaway Beverage Distributors Inc.	2	No	Distribution tractors	N/A
Biagi Bros. Inc.	1	Yes	Class 8 Tractor	-Peterbilt 579EV
Bimbo Bakeries USA and Operating Companies	105	Yes	Class 5 Step Van Class 5 Step Van	-100 Motiv F-59 -5 Motiv F-59
Black Horse Carriers	1	Yes	Class 8 Tractor	-Freightliner eCascadia
Blue Earth Compost, Inc	1	No	Class 5 Step Van	-N/A
Borough of Bergenfield	2	No	Class 8 Refuse	N/A
C&V Contractors	1	Yes	Class 4 Truck	-Phoenix Motorcars Zeus 500
Camrett Logistics	1	Yes	Class 8 Tractor	-Volvo VNR
City Furniture	6	Partial	Terminal Tractor Class 8 Tractor	-1 Kalmar Ottawa Electric -5 Tesla Semis
City of Englewood	2	No	Class 8 Refuse	N/A
City of Hyattsville	1	No	Class 6 Refuse	-BYD 6R
City of Jersey City	5	Yes	Class 6 Refuse	-BYD 6R
City of Los Angeles Center for Green Innovation	1	Yes	Class 6 Box Truck	-ROUSH CleanTech's Ford F-650
City of Madison Fire Department	1	Yes	Class 8 Fire Truck	-Pierce Volterra zero-emissions pumper
City of Newark	2	No	Class 8 Refuse	N/A
City of Ocala	5	No	Class 6 Refuse	-BYD 6R
City of Paterson	2	No	Class 8 Refuse	N/A
City of Perth Amboy	2	No	Class 8 Refuse	N/A
City of Pittsburgh	7	No	Class 8 Bucket Truck Class 3 Vans Class 8 fire trucks	N/A
City of Trenton	2	No	Class 8 Refuse	N/A
City of Wilmington, NC	1	No	Class 8 Refuse	-Lion Electric
City of Woodland, CA	2	Yes	Class 4 Truck	-Phoenix Motorcars Zeus 500
Consolidated Edison of New York	1	No	Class 8 Bucket Truck	-Custom built by Lion Electric and Posi-Plus
Core-Mark International Inc.	1	Yes	Class 8 Tractor	-Freightliner eCascadia
Costco	1	Yes	Class 8 Tractor	-Freightliner eCascadia
County of Chautauqua	1	Yes	Yard Tractor	-Orange EV T-Series
Covenant Logistics	50	No	Class 8 Tractor	-10 Nikola Tre (BEVs) - 40 Nikola Tre (FCEV)
DHE	12	Partially	Class 8 Tractor	-12 Volvo VNR Electric

Fleet	EVs Deployed / Ordered	Vehicles Delivered	Vehicle Type	Vehicle Model
DHL Worldwide Express	256	Partially	Class 8 Tractor Class 3 Step Van Class 3 Delivery Van	-100N/A Tesla Semi -4 BYD 8TT -63 Workhorse NGEN-1000 -100 Lightning Electric
Dickinson Fleet Services LLC	5	No	Class 6 Work Truck	-Xos Medium Duty
Dimension Fabricators	1	Yes	Terminal Tractor	-Orange EV T-Series
DocGo	1	Yes	Class 3 ambulance	-Ford Transit T350 Type II
Dole	5	Yes	Yard Tractor	-Orange EV
Donlen	100	No	Class 4	-Udelv Transporters
Dot Foods Inc./ Dot Transportation	1	Yes	Terminal Tractor	-Orange EV T-Series
Eco-Cycle	1	Yes	Class 8 Refuse	-Mack LR Electric
EcoMaine	2	No	Class 8 Refuse	-Lion Refuse
Einride	200	No	Class 8 Tractor	-BYD 8TT
Elate Moving, LLC	1	No	Class 6 Box Truck	-N/A
Elizabeth Board of Education	4	No	Class 8 Refuse Class 4 Delivery Trucks	-N/A
eTrucks	20	No	Class 3 Step Van	-Workhorse C1000
EV Semi-Fleet	50	No	Class 8 Tractor	-50 Tesla Semi -1 Nikola Tre BEV
F&G, LLC	1	No	Yard Tractor	-NA
Fairfax County Department of Public Works and Environmental Services	5	No	Class 8 Refuse Class 4 Van	-Workhorse C1000
Fastenal Co.	1	Yes	Class 6 Box Truck	-Freightliner eM2
FedEx Corp.	2,641	Partially	Class 3 Cargo Van Class 8 Tractor Class 4 Step Van Class 4 Medium-duty truck	-2500 GM Zevo 600 Cargo Van -20 Tesla semi-trucks -1 Workhorse Progen concept Step Van -120 XOS
Firefly Transportation Services	1	Yes	Terminal Tractor	-T-Series Tandem
Fleetmaster Express Inc.	18	Partially	Class 8 Tractor	-12 Volvo VNR Electric -2 Peterbilt Model 579EV -2 Tesla Semis -2 Dana Inc.
Fluid Truck	50	Yes	Class 4 Box Truck	- Lightning Electric
Forest River, Inc.	150	No	Class 4 Cutaway	-EV Star Cab and Chassis
Frito-Lay North America	50	Partially	Class 6 Box Truck Terminal Tractor Class 2b Van	-6 Peterbilt 220ev -3 BYD 8Y -41 Ford E-Transit
GATR Truck Centers	1,150	No	Class 5 Box Truck	-SEA Hino M5
Glovis America	30	No	Class 8 Tractor	-Hyundai XCIENT

Fleet	**EVs Deployed / Ordered**	**Vehicles Delivered**	**Vehicle Type**	**Vehicle Model**
Goodwill Industries International	11	Yes	Class 6 Box Truck	- BYD T7
Green Mountain Power Corp.	2	No	Class 8 Bucket Truck	-Lion8 Bucket Truck
GSC Logistics	3	Yes	Class 8 Tractor	-BYD 8TT
Harbor Freight Transportation Corp	2	No	Yard tractor	N/A
Heniff Transportation Systems Inc.	100	No	Class 8 Tractor	-Nikola Tre
Heritage Environmental Services, LLC	100	No	Class 8 Tractor Class 6 Box Truck	-80 Lion8 -20 Lion6
Hub Group	1	Yes	Class 8 Tractor	-Freightliner eCascadia
Hudson County Motors Inc	4	No	Class 8 Tractor	N/A
IKEA Distribution Services North America	5	Yes	Terminal Tractor	- Kalmar's Ottawa T2 terminal tractor
Intelligent Labor and Moving	1	Yes	Class 6 Box Truck	-SEA Electric
International Motor Freight	4	No	Yard tractors Class 8 Tractor	N/A
Iron Mountain Information Management Inc.	1	Yes	Class 6 Box Truck	-Freightliner eM2
J.B. Hunt	8	Partially	Class 8 Tractor Class 6 Box Truck Class 4 Box Truck	- 1 Navistar Fuel Cell Truck -1 Freightliner eCascadia -1 Freightliner eM2 - 5 Mitsubishi Fuso eCanter
J&M Sanitation	2	Yes	Class 8 Refuse	-BYD 8R
Jackson Township School District	2	No	Class 8 Refuse	N/A
Jersey City	5	No	Class 8 Refuse	-BYD 8R
Karat Packaging	10	No	Class 8 Tractor	-Tesla Semi
KeHE Distributors	2	Yes	Class 8 Tractor	-Freightliner eCascadia
King County	1	Yes	Class 8 Tractor	-Kenworth T680E
Kingbee Rentals	25	No	Class 4 Cargo Van	-Envirotech Vehicles
Knight-Swift Transportation Holdings	1	Yes	Class 8 Tractor	-Freightliner eCascadia
Kraft Heinz Company	3	Yes	Terminal Tractor	-Orange EV T-Series
L&R Group	50	No	Class 4 Shuttle Bus	-Phoenix Motorcars Zeus 400
Lazer Spot Inc.	25	No	Yard Tractor	-Orange EV
Lemcor Solid Waste Transfer Station	2	No	Yard Tractor	N/A
Liberty Ashes, Inc	2	No	Class 6 Refuse	-1 Battle One Severe Duty Refuse -1 Battle One Crew Cab
Manhattan Beer Distributors LLC	5	No	Class 8 Tractor	-Volvo VNR Electric truck

Fleet	EVs Deployed / Ordered	Vehicles Delivered	Vehicle Type	Vehicle Model
McLane Co Inc.	12	Yes	Terminal Tractor Class 8 Tractor	-Orange EV Terminal Truck -XOS HDXT
MDB Transportation	10	No	Class 6 Box Truck	-Kenworth K270E
Meijer	4	No	Class 8 Tractor	- Tesla Semi
Merchants Fleet	18,010	Partially	Class 3 Cargo Van Class 2b Cargo Van Class 5 Step Van	-12600 GM Zevo 600 -5,400 GM Zevo 400 -10 XOS Step van
Mesa Fire and Medical Department	1	No	Class 8 Fire engine	-E-ONE Vector fire truck
Mondelez International Inc.	1	Yes	Class 8 Tractor	-Freightliner eCascadia
Municipality of Anchorage Department of Solid Waste Services	2	Yes	Class 8 Tractor	-Peterbilt Model 220EV and Model 520EV
Murphy Road Recycling, LLC	1	No	Yard Tractor	-N/A
National Grid Service Co and Operating Companies	TBA	No	Class 2b Van	-TBA Ford E-Transit
New Legend Inc	50	No	Class 8 Tractor	-Freightliner eCascadia
Airgas	2	No	Class 8 Tractors	-Hyzon Fuel Cell
New York City Department of Sanitation	17	Yes	Class 8 Refuse	-Mack LR Electric
NFI Transportation	117	Yes	Class 8 Tractor Yard Tractor	-30 Freightliner eCascadia -27 Kalmar Ottawa Electric T2E Terminal Tractors -60 Volvo VNR
Pacific Gas & Electric (PG&E)	10	No	Class 4 Step Van	-MT50e
Pan-O-Gold Baking Co.	4	No	-N/A	-N/A
Patton Logistics Group	5	No	Class 8 Tractor	-Volvo VNR
Penske Logistics	814	Partially	Class 8 Tractor Class 6 Box Truck Class 4 Box Truck Class 2b van Yard Tractor	-10 Freightliner eCascadia -10 Freightliner eM2 -21 Freightliner eCascadia/eM2 -4 Fuso eCanter -2 ROUSH Ford F650 -5 Navistar International eMV trucks -751 Ford E-Transit -TBA
PepsiCo Inc.	149	Partially	Class 8 Tractor Class 6 Box Truck Terminal Tractor Class 2b vans	-100 Tesla semi-trucks - 40 Ford E-Transit
Performance Team	126	No	Class 8 Tractor	-Volvo VNR Electric
PGT Trucking Inc.	100	No	Class 8 Tractor	-Nikola Tre

Fleet	EVs Deployed / Ordered	Vehicles Delivered	Vehicle Type	Vehicle Model
Phil Haupt Electric	1	Yes	Class 4 Utility Truck	-ZEUS 500 Electric Utility Truck
Pitt Ohio Transportation Group	6	Yes	Class 4 Box Trucks Class 8 Tractors Class 7 Box Trucks	-N/A -N/A -Vovo VNR Electric
Port of Oakland	42	Yes	Class 4 Utility Truck Class 8 Tractor	-2 Phoenix Motorcars Zeus 500 -10 Peterbilt Model 579EV - 30 XCIENT Fuel Cell heavy-duty tractors
Port of San Diego	14	No	Class 3 trucks Class 3 vans	-N/A -N/A
Pride Group Enterprises	6,570	Partially	Class 8 Tractor Class 3 Step Van Class 6 Box Trucks Class 8 Box trucks	-150 Tesla Semi -6320 Workhorse C-1000 -100 Lion6 and Lion8 trucks
Pritchard Auto Company	500	No	Class 3 Step Van	-Workhorse C-1000
Producers Dairy Foods Inc.	2	Yes	Class 8 Tractor	-Volvo VNR
Purolator	1	Yes	Class 6 Delivery Van	-Cummins Step Van
Quality Custom Distribution	44	Yes	Class 8 Tractor	-Volvo VNR Electric
Rail Management Services	10	Yes	Yard Tractor	-Orange EV T-Series
Ramsey/Washington Recycling & Energy	1	Yes	Yard Tractor	-Orange EV T-Series
Recology	2	Yes	Class 8 Refuse	-BYD 8R
Red Hook Terminals LLC	10	Yes	Yard tractors	-BYD 8Y
Regional Industries LLC	5	No	Class 8 Refuse	N/A
Republic National Distributing Company	5	No	Class 7 Tractor	-XOS MDXT
Republic Services Inc.	1	Yes	Class 8 Refuse	-Mack LR Electric
Reyes Holdings and Operating Companies	30	No	Class 8 Tractor	-Tesla Semi
Ruan	8	Partially	Terminal Tractor Class 8 Tractor	-3 Orange EVs -5 Tesla semi-trucks
Ryder System, Inc.	6	Partially	Class 5 Cargo Van Class 6 Box Truck Class 8 Tractor	-1 Freightliner eM2 -1 Freightliner eCascadia -4 N/A
Sacramento County	2	Yes	Class 8 Refuse	-ElecTruck
Sacramento Municipal Utility District	5	Yes	Class 3 Work Truck	-Zeus Electric Work Truck
Saia Inc.	103	Yes	Class 8 Tractor Class 6 Box Truck	-2 VNR Electric trucks -1 Freightliner eM2 -100 Nikola Tre
Santa Barbara Public Library	1	Yes	Class 4 Step Van	-Ford F-450 Retrofit
Schneider National Inc.	50	Yes	Class 8 Tractor	-Freightliner eCascadia

Fleet	EVs Deployed / Ordered	Vehicles Delivered	Vehicle Type	Vehicle Model
Shippers Transport Express Inc.	15	No	Class 8 Tractor	-Peterbilt Model 579EV
Sonwil Distribution Center, In	1	Yes	Yard Tractor	-Orange EV T-Series
Southern California Edison Co.	1	Yes	Class 8 Tractor	-Freightliner eCascadia
Southern Counties Express	1	Yes	Class 8 Tractor	-Toyota (Kenworth) T680E
Staples Inc.	1	Yes	Class 5 Box Truck	-SEA Hino 195 EV
Stolt Trucking, Inc.	3	No	-N/A	-N/A
Sunbelt Rentals Inc.	5	Yes	Class 8 Tractor	-Peterbilt Model 579EV
Super Store Industries	1	Yes	Yard Tractor	-Orange EV T-Series
Sysco and Operating Companies	851	Partially	Class 8 Tractor	-50 Tesla semi-trucks -801 Freightliner eCascadia
Tacoma Harbor	6	No	Yard Tractor	-N/A
Temco Logistics	1	Yes	Class 6 Box Truck	-Freightliner eM2
Terminal Consolidation Co	1	Yes	Terminal Tractor	-Orange EV T-Series
The Kroger Co.	10	No	Class 8 Tractor	-Tesla semi-trucks
The Los Angeles City Fire Department	1	Yes	Class 8 Fire engine	-Rosenbauer RTX Fire Truck
Titan Freight	4	No	Class 8 Tractor	-Freightliner eCascadia
Toms River Township	1	No	Class 8 Refuse	N/A
Total Transportation Services	104	Partially	Class 8 Tractor Class 8 Drayage	-2 Toyota (Kenworth) T680E -100 Nikola Tre -1 Transpower Fuel Cell -1 U.S. Hybrids Fuel Cell
Town of Cary	1	No	Class 8 Refuse	-N/A
Town of North Stonington	1	No	Class 8 Refuse	- N/A
Town of West New York	4	No	Class 8 Garbage trucks Class 4 Shuttle buses	N/A
Township of Woodbridge	5	No	Class 8 Refuse Class 4 Shuttle buses	N/A
Two Men and a Truck Columbus	1	No	Class 6 Box Truck	-SEA Electric Conversion
UniFirst Corp.	3	Yes	Class 5 step van	-Xos Medium Duty
UPS Inc.	12,635	Partially	Class 8 Tractor Class 6 Delivery Van Class 6 Box Truck Class 4 Step Van Retrofit Class 4 Step Van Class 4 Cargo Van Class 3 Step Van	-4 Fuel Cell Electric Vehicle Delivery Van -3 Toyota (Kenworth) T680E -N/A Xos Medium Duty -1000 Workhorse C1000 -125 Tesla Semi -10000 Arrival Van -2 Fuso eCanter -1 Freightliner eCascadia - 1500 Unique Electric Solutions

Fleet	EVs Deployed / Ordered	Vehicles Delivered	Vehicle Type	Vehicle Model
US Foods	30	Yes	Class 8 Tractor Class 6 Box Truck	-Freightliner eCascadia -Freightliner eM2
USA Truck Inc.	10	No	Class 8 Tractor	-10 Nikola Tre
USPS	10,034	Yes	Class 3 Step Van Class 4 Step Van	-8 Cummins -7 Motiv E-450 -10,019 Oshkosh Defense Next Generation Delivery Vehicle
Valley Malt	1	Yes	Class 2b	-Ford E-Transit
Velocity Truck Rental & Leasing	1	Yes	Class 8 Tractor	-Freightliner eCascadia
Wakefern Food Corp.	4	No	Terminal Tractor	N/A
Walmart Inc.	6,110	No	Class 3 Cargo Van Class 2b Van	-5000 GM Zevo 400 and Zevo 600 Cargo Van -1110 Ford E-Transit
Waste Connections and Operating Companies	2	yes	Class 8 Refuse	-Lion 8R
Waste Resource Technology, Inc.	1	Yes	Class 8 Refuse	-BYD 8R
Watsontown Trucking Company	1	No	Class 8 Tractor	-Volvo VNR
WattEV	50	No	Class 8 Tractor	-Volvo VNR
Werner Enterprises	1	Yes	Class 8 Tractor	-Peterbilt 579EV
XPO Logistics	102	Partially	Class 8 Tractor Class 6 Box Truck Class 4 Box Truck	-1 Freightliner eCascadia -1 Freightliner eM2 -100 CityFreighter CF1
Yellow Corp. (YRC Freight)	4	Yes	Terminal Tractor	-Orange EV
Estes	12	No	Class 8 Tractor	-Freightliner eCascadia
XL Fleet	1	Yes	Class 6 Refuse Truck	-Curbtender
Giant	2	Yes	Class 5 Step Van	-Motiv F-59
Xcel Energy	2	No	Class 8 Bucket Truck	-Terex Optima 55
Oatly	5	No	Class 8 Tractor	-Einride AB
Paterson Fire Department	2	No	Class 6 Ambulance	-Demers eFX Prototype Ambulances
RoadOne	1	Yes	Class 8 Tractor	-Nikola Tre
United Rental	30	No	Class 2b Cargo Van	-Ford E-Transit
GE Appliance	N/A	No	N/A	N/A
Sunburst Truck Lines	1	Yes	Class 8 Drayage	-Nikola
Zeem Solutions	10	No	Class 5 Stepvan	-XOS Stepvan
City of Mobile	1	No	Class 8 Refuse	-Mack LR Electric
City of Gilbert	1	No	Class 8 Fire Truck	-Pierce Manufacturing Volterra
Altec	1	Yes	Class 8 Bucket Truck	-Navistar eMV
Michigan State University	18	No	Class 2b	-Ford e-Transit
Wegmans	9	No	Yard Tractor	-N/A
Beyond Meat	5	No	Class 8 Tractor	-Einride AB

1.5.5.2 BEV Components Manufacturers

A small number of HD ICE vehicle component suppliers and startups have developed components specifically for HD BEVs. See Table 1-25 for a partial list of manufacturers of HD BEV components.

Table 1-25 Manufacturers of HD BEV Components

Component	Manufacturers
Low Voltage Battery	Same manufacturers as for ICE vehicles[432]
Charge Port	ITT Cannon, Phoenix Contact, TE Connectivity
DC/DC Converter	Borg Warner, Eaton, EG Tronics, InMotion
Traction Motor	BAE, Borg Warner, Cummins, Dana, Lightning Systems, Meritor, Proterra, SEA Drive, Siemens, ZF
Onboard Charger	Borg Warner, Dana, Eaton
Power Electronics Controller	Borg Warner, EG Tronics
Thermal System	Same manufacturers as for ICE vehicles[433]
Traction Battery Pack	Borg Warner, CATL, Cummins, Dana, LG Chem, Panasonic, Proterra, Samsung SDI, Tesla, Volvo, XALT
Transmission	Eaton
Aux System - Air Conditioner Compressor	Guchen, Rheinmetal
Aux System - Heater	Guchen, Rheinmetal, Webasto
Aux System - Blower	Same manufacturers as for ICE vehicles[434]
Aux System - Power Steering Pump	Allied Motion, Bosch, HydraPulse, ZF
Aux System - Air Compressor	Hydrovane, Ingersoll Rand, Wabco
Auxiliary Power Unit (APU)	Carrier, Go Green APU, Phillips & Temro, Thermo King

1.5.6 BEV Research and Development

DOE has a Vehicle Technologies Office focused on research, development, and demonstration of electrification technologies across sectors, including transportation. Through the 21st Century Truck Partnership, DOE is collaborating with truck manufacturers, major suppliers, and interagency partners to focus on removing barriers to wide-scale truck electrification. They are working directly with industry through SuperTruck 3 to reduce emissions of freight transportation, with the projects listed in Table 1-26awarded for 2022 through 2026 focused on HD BEVs.[435]

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[432] Manufacturers of Low Voltage Batteries includes Alliance and East Penn

[433] Manufacturers of Thermal Systems includes American Radiator, AP Air Inc, and CoolStar

[434] Manufacturers of Aux System – Blower includes Four Seasons, Mahle, TYC, UAC, and Valeo

[435] U.S. Department of Energy. "DOE Projects Zero Emissions Medium- and Heavy-Duty Electric Trucks Will Be Cheaper than Diesel-Powered Trucks by 2035". March 2022. Available online: https://www.energy.gov/articles/doe-projects-zero-emissions-medium-and-heavy-duty-electric-trucks-will-be-cheaper-diesel.

Table 1-26 DOE Funded BEV Projects Awarded in 2022[436]

Company	Project Description	Award Amount*
PACCAR Inc	Develop eighteen Class-8 battery electric and fuel cell vehicles with advanced batteries and a megawatt charging station will also be developed and demonstrated.	$32,971,041
Volvo Group North America, LLC	Develop 400-mile range Class 8 battery electric tractor-trailer as well as megawatt charging station.	$18,070,333
General Motors, LLC	Develop and demonstrate four hydrogen fuel cell and four battery electric Class 4-6 trucks. The project will also focus on development of clean hydrogen via electrolysis and clean power for fast charging	$26,061,726

* Subject to appropriations.

1.6 BEV Charging Infrastructure

1.6.1 Overview of BEV Charging Infrastructure

The work performed by heavy-duty vehicles has been described in Chapter 1.5 of this document. HD BEVs require electricity for charging their batteries before work can be performed. It is necessary for this electric power be delivered at the appropriate time, rate, and location such that business or other operational needs are met. This section provides an overview of BEV charging infrastructure today; upcoming infrastructure investments; and considerations, challenges and costs associated with future infrastructure needs for HD BEVs.

1.6.1.1 Definitions

BEV charging infrastructure consists of the equipment (hardware and software) used to charge an electric vehicle. Terminology for charging infrastructure varies in the literature, with terms like “charger”, “plug”, “outlet”, and “port” sometimes being used interchangeably.[437] In this RIA, we generally use the following terminology, which is consistent with DOE’s Alternative Fuels Data Center.[438] A station is the physical location where charging occurs. A station may have multiple electric vehicle supply equipment (EVSE) ports that provide electricity to a vehicle.[439] The number of vehicles that can simultaneously charge at the station is equal to the number of EVSE ports. Each port may also have multiple connectors or plugs to accommodate vehicles that use different connector types, but each port can charge just one vehicle at a time. The relationship between a station, EVSE ports, and connectors is shown in Figure 1-14.[440]

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[436] U.S. Department of Energy. “DOE Announces Nearly $200 Million to Reduce Emissions From Cars and Trucks. November 1, 2021. Available online: https://www.energy.gov/articles/doe-announces-nearly-200-million-reduce-emissions-cars-and-trucks.

[437] Except where noted, when citing external studies, we attempt to map the terms used in the study to those we define above for consistency.

[438] U.S. Department of Energy. Alternative Fuels Data Center. “Electric Vehicle Charging Stations”. Available online: https://afdc.energy.gov/fuels/electricity_stations.html.

[439] EVSE ports may be part of a wall-mounted unit or on a pedestal in the ground.

[440] Ibid.

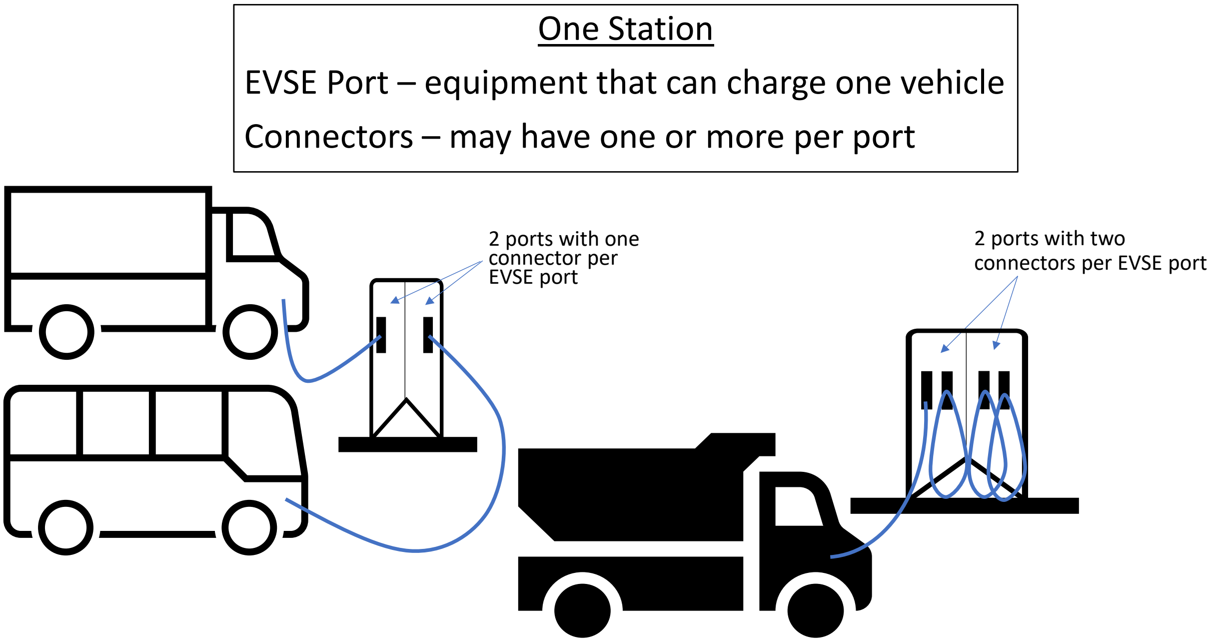

Figure 1-14 Example charging station with four EVSE ports and six connectors

We do not include electric power infrastructure—power generation, transmission, and distribution systems—in our definition of BEV charging infrastructure. We discuss the relationship between BEV charging infrastructure and electric power infrastructure in Chapters 1.6.4 and 1.6.5.

1.6.1.2 Types of EVSE Ports and Connectors

EVSE ports vary by power type and power level. There are two power types: alternating current (AC) charging, where AC-to-direct current (DC) conversion takes place on-board the vehicle, and DC fast charging (DCFC), where AC-to-DC conversion takes place prior to entering the vehicle. Both AC charging and DCFC are further delineated by different power outputs, though generally DCFC offers higher power and therefore faster charging times. Common AC charging types are Level 1 (up to about 2 kilowatt (kW))[441] and Level 2 (up to 19.2 kW),[442] though there is also a standard for higher-powered AC charging.[443] DCFC is available today in a wide range of power levels (e.g., 50–350 kW). Most vehicle models currently use the SAE J1772 standard connector for Level 1 and 2 charging.[444] There are multiple connectors for DCFC, including Combined Charging System (CCS), CHAdeMO, and the North American Charging

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[441] Schey, Stephen, Kang-Ching Chu, and John Smart. 2022. "Breakdown of Electric Vehicle Supply Equipment Installation Costs. Idaho National Laboratory." Available online: https://inldigitallibrary.inl.gov/sites/sti/sti/Sort_63124.pdf.

[442] U.S. Department of Energy. Alternative Fuels Data Center. "Electric Vehicle Charging Stations". Available online: https://afdc.energy.gov/fuels/electricity_stations.html.

[443] SAE. "SAE International Releases New Specification (SAE J3068) for Charging of Medium and Heavy Duty Electric Vehicles". April 26, 2018. Available online: https://www.sae.org/news/press-room/2018/04/sae-international-releases-new-specification-sae-j3068-for-charging-of-medium-and-heavy-duty-electric-vehicles.

[444] Tesla vehicles use the NACS connector for AC charging, though a J1772 adapter is available.

Standard (NACS) connector[445] developed by Tesla.[446,447] OEMs producing HD BEVs may also use proprietary connectors.[448]

How much time it takes a vehicle to charge will vary significantly based on the power level of the EVSE port and the amount of electricity (kWh) needed, among other factors. For example, using a 19.2 kW-rated Level 2 port, it will take longer than three hours to add 60 kWh[449], which we assessed as the amount of electricity that would be sufficient for many Class 4–5 Step Vans on most days. By contrast, it may take under one-and-a-half hours using DCFC-50 kW and just under 30 minutes with DCFC-150 kW. In this example, Level 2 charging would be sufficient provided the vehicle has the necessary three or more hours to charge. Otherwise, DCFC may be needed. (See also further discussion regarding dwell times for charging in Chapter 2.6). Level 1 charging in this same example could take over 30 hours, illustrating that Level 1 may not be practical for HD BEV applications and therefore are not part of EPA's analysis of the costs of the Phase 3 rule. For this reason, we focus the remainder of our infrastructure discussion and analysis on AC Level 2 and DCFC ports.

A standard for even higher-powered DCFC, the Megawatt Charging System (MCS), is currently under development and being advanced by the National Renewable Energy Laboratory (NREL), the Charging Interface Initiative (CharIN), and others.[450] The MCS standard (expected to be finalized in 2024) has a potential charge rate of 3.75 MW.[451] An MCS system from ABB E-Mobility was tested with a Scania electric truck as part of a pilot this year; ABB is planning commercial release as early as 2024.[452] Daimler Truck North America and Portland General Electric opened a megawatt-level charging for HD BEVs at the "Electric Island" station near Daimler's North American headquarters, with most of the eight chargers available for public use.[453]

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[445] The NACS connector began as a proprietary standard. It is currently undergoing the standardization process by SAE.

[446] U.S. Department of Energy. Alternative Fuels Data Center. "Electric Vehicle Charging Stations". Available online: https://afdc.energy.gov/fuels/electricity_stations.html.

[447] SAE. "SAE International Announces Standard for NACS Connector, Charging PKI and Infrastructure Reliability". June 27, 2023. Available online: https://www.sae.org/news/press-room/2023/06/sae-international-announces-standard-for-nacs-connector.

[448] Alexander, Matt et al. California Energy Commission. "Assembly Bill 2127 Electric Vehicle Charging Infrastructure Assessment Analyzing Charging Needs to Support Zero-Emission Vehicles in 2030". Available online: https://www.energy.ca.gov/programs-and-topics/programs/electric-vehicle-charging-infrastructure-assessment-ab-2127. See Commission Report (July 2021).

[449] Charging rate may also vary based on the state of charge of the battery, e.g., by slowing down when the battery is nearly full. In these examples (intended to be illustrative), we assume charging occurs at or near the stated power of the EVSE.

[450] National Renewable Energy Laboratory (NREL). "Industry Experts, Researchers Put Charging Systems for Electric Trucks to the Test". August 30, 2021. Available online: https://www.nrel.gov/news/program/2021/industry-experts-researchers-put-charging-systems-for-electric-trucks-to-test.html.

[451] Kane, Mark. "CharIN Officially Launches The Megawatt Charging System (MCS)". Inside EVs. June 15, 2022. Available online: https://insideevs.com/news/592360/megawatt-charging-system-mcs-launch/.

[452] Manthey, Nora. "Scania tests ABB's megawatt charging system for next-gen electric trucks". Electrive. October 5, 2023. Available online: https://www.electrive.com/2023/05/10/scania-tests-abbs-megawatt-charging-system-for-next-gen-electric-trucks/.

[453] Daimler Truck North America. "Daimler Trucks North America, Portland General Electric open first-of-its-kind heavy-duty electric truck charging site." April 2021. Available online: https://northamerica.daimlertruck.com/PressDetail/daimler-trucks-north-america-portland-general-2021-04-21/

Other charging methods that could become more common in the future include wireless and pantograph charging. With wireless charging (covered by the SAE J2954/2 standard[454]) a vehicle is parked above a charging pad and power is transferred via induction to charge the battery.[455] For pantograph charging systems (covered by the SAE J3105/2 standard[456]), structures on top of the HD vehicle roof connect to overhead charging. HD BEVs may be able to charge via pantograph while parked overnight or at critical locations on their routes.[457] Since these pantograph systems can supply power en-route, the truck battery can potentially be downsized, keeping cost and weight down while allowing space for additional cargo. Prototype systems exist in Europe and development is underway by Siemens Mobility, Continental Engineering Services, Webasto, and RWTH Aachen University.[458, 459]

1.6.1.3 Types of Charging Stations

While charging stations may be deployed in a wide variety of locations and configurations based on future needs, for our purposes, we broadly categorize charging as either depot or en-route charging. Depot stations may be at warehouses, yards, distribution centers, secure lots, or other locations where the vehicles are parked off shift. HD vehicles with return-to-base operations, in which vehicles return to a centralized location to park overnight, may be particularly well suited for depot charging. As described in Chapter 2.6, we anticipate that many heavy-duty BEV owners will opt to purchase and install sufficient EVSE ports for depot charging at or near the time of vehicle purchase to ensure operational needs are met. We expect many depot stations to be privately owned or operated for fleets.

En-route charging allows vehicles to charge during their shift or on the way to their next location. We expect many en-route charging stations to be publicly accessible and for simplicity we refer to en-route charging as public charging throughout this document. However, we note that some en-route charging may also occur at privately owned and operated stations. We project that BEV sleeper cab tractors, coach buses, and certain day cab tractors, will utilize public charging in our modeled potential compliance pathway supporting the standards' feasibility. See RIA Chapter 2.6.

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[454] SAE International. "Wireless Power Transfer for Heavy-Duty Electric Vehicles". December 16, 2022. Available online: https://www.sae.org/standards/content/j2954/2_202212/.

[455] Oak Ridge National Laboratory. "Successful delivery: ORNL demonstrates bi-directional wireless charging on hybrid UPS truck". April 21, 2020. Available online: https://www.ornl.gov/news/successful-delivery-ornl-demonstrates-bi-directional-wireless-charging-hybrid-ups-truck.

[456] SAE International. "Electric Vehicle Power Transfer System Using Conductive Automated Connection Devices Vehicle-Mounted Pantograph (Bus-Up)". January 20, 2020. Available online: https://www.sae.org/standards/content/j3105/2_202001/.

[457] Transport for London. "New rapid, wireless bus charging technology introduced as part of the capital's journey to zero emission". October 26, 2022. Available online: https://tfl.gov.uk/info-for/media/press-releases/2022/october/new-rapid-wireless-bus-charging-technology-introduced-as-part-of-the-capital-s-journey-to-zero-emission.

[458] Randall, Chris. "Continental & Siemens to cooperate on truck pantographs". ElectricDrive.com. July 29, 2021. Available online: https://www.electrive.com/2021/07/29/continental-siemens-to-cooperate-on-truck-pantographs/.

[459] Webasto. "E-Truck with pantograph: Webasto supports pioneering pilot project". August 29, 2022. Available online: https://www.automotiveworld.com/news-releases/e-truck-with-pantograph-webasto-supports-pioneering-pilot-project/.

1.6.2 Status and Outlook of BEV Charging Infrastructure

1.6.2.1 Stations and EVSE Ports Available Today

DOE's Alternative Fuels Data Center (AFDC) Station Locator provides counts of charging stations and EVSE ports. These counts show the rapid growth in overall charging infrastructure in recent years. There are over 60,000 public charging stations in the U.S. today with more than 160,000 EVSE ports.[460,461] This is more than double the 74,000 EVSE ports as of the end of 2019.[462] Table 1-27 shows the breakdown in U.S. public stations and EVSE ports as of February 18, 2024, for Level 2 and DCFC charging.[463]

Table 1-27 Public Charging Stations and EVSE Port Counts

Type	Stations[464]	EVSE Ports
Level 2	53,482	124,396
DCFC	9,278	39,347

However, it is important to note that many of these stations may not be designed to accommodate large vehicles. For example, stations designed for HD vehicles may require more space for ingress and egress, higher canopies or roofs that can fit tall cargo boxes, and longer charging cords. Stations may also not be designed to commingle passenger cars with trucks and buses.[465] Notwithstanding those limitations, some stations designed for light-duty vehicles may be able to accommodate (or be modified in the future to accommodate) medium-duty or small heavy-duty vehicles and so we include discussion of them here. As previously noted, AC Level 1 ports are less likely to meet HD BEV needs so they are not included in these counts. As discussed in Chapter 1.6.1.2 of this document, there is no universal connector type for DCFC at this time, so the number of stations and ports that can serve a given vehicle may be lower than what is shown in Table 1-27.[466,467]

In addition to public charging infrastructure, the AFDC Station Locator includes counts of private EVSE ports used by fleets. Collecting information on private ports is challenging and the data set is not complete. For the private port data that has been collected as of the third calendar

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[460] U.S. Department of Energy. Alternative Fueling Station Locator. Alternative Fuels Data Center. Available online: https://afdc.energy.gov/stations/#/analyze?country=US&fuel=ELEC.

[461] If we include EVSE ports that are temporarily unavailable for maintenance or other short-term causes, the number of ports is over 170,000.

[462] U.S. Department of Energy, Alternative Fuels Data Center. U.S. Public Electric Vehicle Charging Infrastructure. 2023. Available online: https://afdc.energy.gov/data/10972.

[463] U.S. Department of Energy. Alternative Fueling Station Locator. Alternative Fuels Data Center. Available online: https://afdc.energy.gov/stations/#/analyze?country=US&fuel=ELEC.

[464] Stations with both L2 and DCDC ports are listed in both rows.

[465] While the downloadable data for AFDC Station Locator includes a field designating the largest class of vehicle that can access a station, many public stations in the data set have no such identifier.

[466] Adapters are available that allow Tesla vehicles (which use NACS connectors) to plug into J1772/CCS (and CHAdeMO) ports. Most stations in the U.S. have either a J1772/CCS or a NACS connector.

[467] DOE, Alternative Fuels Data Center. "Electric Vehicle Charging Stations." Available at: https://afdc.energy.gov/fuels/electricity_stations.html.

quarter of 2023,[468] NREL reports that about 44% of the private EVSE ports were used primarily for fleets.[469] Figure 1-15 shows a breakdown of AC Level 2 and DCFC private fleet EVSE ports in the Station Locator by vehicle type.[470,471] NREL notes that efforts are underway to increase data collection for private fleets including school buses, transit buses, and other fleets serving MD and HD vehicles.

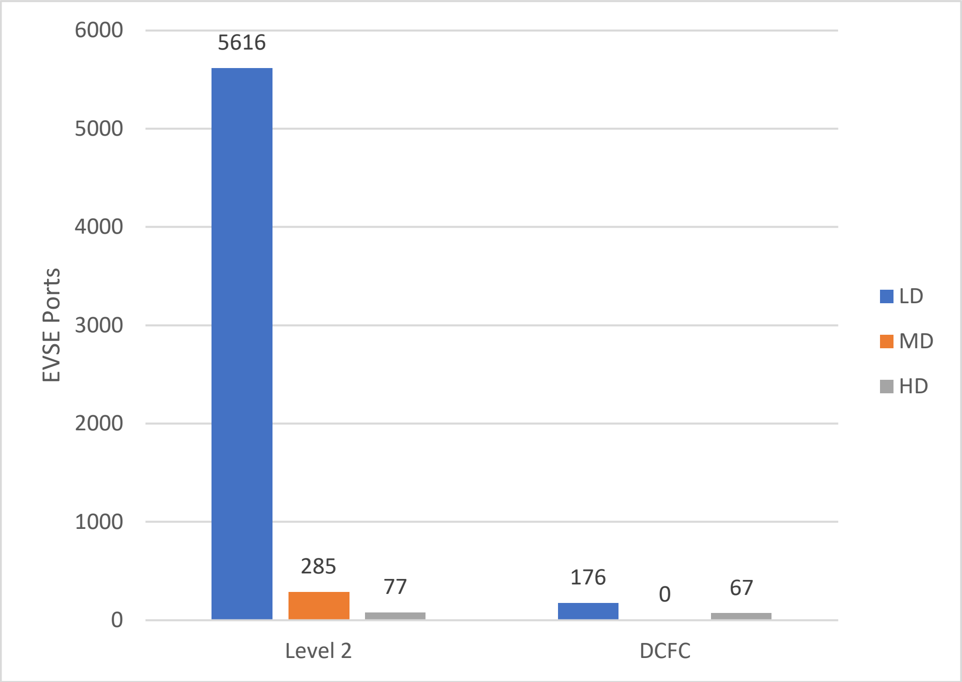

Figure 1-15 Private Fleet Level 2 and DCFC Ports (Data Source: AFDC Station Locator as shown in Brown et al. 2024[472])

We also note that there are a variety of charging stations for heavy-duty vehicles that are planned or in development, as discussed in the following section, and these would not yet be reflected in the Station Locator.

1.6.2.2 Charging infrastructure Investments and Outlook

While dedicated HD charging infrastructure may be limited today, we expect it to expand significantly over the next decade. A recent assessment by Atlas Public Policy estimated that $30 billion in public and private investments had been committed as of the end of 2023 specifically

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[468] Among the private ports in the AFDC Station Locator, information on fleet use and vehicle classes was collected for about 88% of ports.

[469] Brown, Abby, Jeff Cappellucci, Alexia Heinrich, and Emma Cost. “Electric Vehicle Charging Infrastructure Trends from the Alternative Fueling Station Locator: Third Quarter 2023.” Golden, CO: National Renewable Energy Laboratory. NREL/TP-5400-88223. 2024. Available online: https://www.nrel.gov/docs/fy24osti/88223.pdf.

[470] Multiple vehicle types (e.g., LD, MD, or HD) may use the same EVSE stations or ports. Categorizations in the chart reflect the largest class of vehicle that can use a given station.

[471] The NREL report also includes private fleet Level 1 EVSE ports. We did not include these in the figure.

[472] Ibid.

for charging infrastructure for medium- and heavy-duty BEVs.[473] The U.S. government is making large investments in charging infrastructure through the BIL[474] and the IRA,[475] as discussed in Chapter 1.3.2 of this document. This includes extending and modifying a tax credit that could cover up to 30% of the costs for procuring and installing certain charging infrastructure (subject to a $100,000 per item cap) and billions of dollars in funding programs that could support charging infrastructure either on its own or alongside the purchase of a HD BEV.

Private investments will also play a critical role in meeting future infrastructure needs. Much of this will likely be charging infrastructure purchased by individual BEV or fleet owners for depot charging. (See Chapter 2.6 of this document for information on our analysis of depot charging needs and costs.) However, vehicle manufacturers, charging network providers, energy companies and others are also investing in public or other stations that could support public charging.

Several projects aim to offer public charging for electric trucks or other commercial vehicles. For example, Daimler Truck North America is involved in Greenlane, an initiative in the U.S. with electric power generation company NextEra Energy Resources and BlackRock Renewable Power to collectively invest $650 million to create a nationwide charging network for commercial electric vehicles.[476] They plan to start with construction in Southern California in early 2024 and expand to cover key routes on the East and West Coast and in Texas with a later stage of the project also supporting hydrogen fueling stations.[477] Volvo Group and Pilot announced their intent to offer public charging for medium- and heavy-duty BEVs at priority locations throughout the network of 750 Pilot and Flying J North American truck stops and travel plazas[478,479] In 2022, TeraWatt secured over $1 billion in capital to build public charging stations and turnkey infrastructure solutions[480] in 19 states and acquired land for 7 charging stations along a freight corridor that connects California's Port of Long Beach with El Paso,

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[473] Lepre, Nicole. "Estimated $30 Billion Committed to Medium- and Heavy-Duty Charging Infrastructure in the United States." Atlas Public Policy. EV Hub. January 26, 2024. Available online: https://www.atlasevhub.com/data_story/estimated-30-billion-committed-to-medium-and-heavy-duty-charging-infrastructure-in-the-united-states/.

[474] Infrastructure Investment and Jobs Act, Pub. L. No. 117-58, 135 Stat. 429 (2021). Available online: https://www.congress.gov/117/plaws/publ58/PLAW-117publ58.pdf.

[475] Inflation Reduction Act, Pub. L. No. 117-169, 136 Stat. 1818 (2022). Available online: https://www.congress.gov/117/plaws/publ169/PLAW-117publ169.pdf

[476] NextEra Energy. News Release: "Introducing Greenlane: Daimler Truck North America, NextEra Energy Resources and BlackRock Forge Ahead with Public Charging Infrastructure Joint Venture." April 28, 2023. Accessible online: https://newsroom.nexteraenergy.com/2023-04-28-Introducing-Greenlane-Daimler-Truck-North-America,-NextEra-Energy-Resources-and-BlackRock-Forge-Ahead-with-Public-Charging-Infrastructure-Joint-Venture?l=12.

[477] Greenhalgh, Keiron. "Greenlane to Break Ground on Charging Network in Early 2024". October 4, 2023. Available online: https://www.ttnews.com/articles/greenlane-charging-2024.

[478] Adler, Alan. "Pilot and Volvo Group add to public electric charging projects". *FreightWaves.* November 16, 2022. Available online: https://www.freightwaves.com/news/pilot-and-volvo-group-add-to-public-electric-charging-projects.

[479] Kane, Mark. "Pilot and Flying J Stations To Get Fast Chargers for EV Trucks". InsideEVs. December 30, 2022. Available online: https://insideevs.com/news/628605/pilot-stations-fast-chargers-ev-trucks/.

[480] TW. "TeraWatt Raises Over $1 Billion to Scale Commercial EV Charging Centers Across America". September 13, 2022. Available online: https://terawattinfrastructure.com/ideas/terawatt-raises-over-1-billion-to-scale-commercial-ev-charging-centers-across-america/.

Texas.[481] In late 2023, they broke ground on a site in the ports area of South Los Angeles with 20 pull-through stalls for up to 125 trucks per day, scheduled to be operational in 2024.[482] Two sites in California's Inland Empire region to support up to 500 trucks per day are scheduled to open in 2025.[483] Tesla is developing charging equipment for their semi-trucks that will recharge up to 70 percent of the Tesla semi-truck's 500-mile range in 30 minutes.[484]

Fleets are installing chargers. IKEA is collaborating with Electrify America and its business unit, Electrify Commercial, to install over 200 150-kW and 350-kW fast chargers for public use and delivery fleets at 25 retail locations in 18 states by the end of 2023.[485] Amazon says it has already deployed thousands of chargers for its fleet of electric delivery vans at over 100 sites nationwide.[486] Amazon has also installed close to 300 chargers for HD BEVs.[487] Walmart announced plans to grow their network of 1,300 fast chargers at more than 280 locations to thousands at Walmart and Sam's Club locations from coast-to-coast by 2030.[488] FedEx is also installing charging infrastructure, and has already deployed 500 chargers at its California facilities.[489]

Other investments will support regional or local travel needs. For example, in California, Forum Mobility announced a $400 million investment led by CBRE Investment Management for DCFCs for BEV trucks that are planned for operation at the San Pedro and Oakland ports.[490,491] The company received an additional $100 million from Homecoming Capital. They are building seven stations by the end of 2024 plus two stations in 2025 with a total of more than 700 chargers. By the end of 2027, they plan to install charging at another 15 sites to service 1,900

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[481] Marshall, Aarian. "The Trans-American Race to Build Chargers for Electric Trucks". March 28, 2023. Wired. Available online: https://www.wired.com/story/the-trans-american-race-to-build-chargers-for-electric-trucks/

[482] Morris, Charles. "TeraWatt Infrastructure breaks ground on heavy-duty EV charging site near Port of Long Beach". Charged. November 29, 2023. Available online: https://chargedevs.com/newswire/terawatt-infrastructure-breaks-ground-on-heavy-duty-ev-charging-site-near-port-of-long-beach/.

[483] Greenhalgh, Keiron. "TerraWatt Buys Two California Sites for Heavy-Duty EV Charging: Facilities to be Operational in 2025". Transport Topics. October 23, 2023. Available online: https://www.ttnews.com/articles/terawatt-california-ev-charge.

[484] Tesla. "Semi: The Future of Trucking is Electric." Available online: https://www.tesla.com/semi.

[485] Electrify America. "IKEA U.S. and Electrify America announce collaboration for ultra-fast public and fleet charging at over 25 IKEA retail locations". Available online: https://media.electrifyamerica.com/en-us/releases/191.

[486] Amazon staff. "Everything you need to know about Amazon's electric delivery vans from Rivian." October 17, 2023. Available online: https://www.aboutamazon.com/news/transportation/everything-you-need-to-know-about-amazons-electric-delivery-vans-from-rivian.

[487] Keith, Scott. "Amazon adds 5,000th Rivian electric delivery van to U.S. fleet". FleetOwner. July 18, 2023. Available online: https://www.fleetowner.com/emissions-efficiency/media-gallery/21269714/amazon-now-has-5000-rivian-electric-delivery-vans-in-us-fleet.

[488] Kapadia, Vishal. "Leading the Charge: Walmart Announces Plans to Expand Electric Vehicle Charging Network." April 6, 2023. Available online: https://corporate.walmart.com/news/2023/04/06/leading-the-charge-walmart-announces-plan-to-expand-electric-vehicle-charging-network.

[489] Sickels, David. "Brightdrop produces 150 electric delivery vans for FedEx Fleet". August 10, 2022. Available online: https://www.thebuzzevnews.com/brightdrop-electric-vans-fedex/.

[490] Joint Office of Energy and Transportation. "Private Sector Continues to Play Key Part in Accelerating Buildout of EV Charging Networks." February 15, 2023. Available online: https://driveelectric.gov/news/private-innvestment.

[491] Margaronis, Stas. "Backed by Amazon & CBRE, Forum Mobility is building harbor truck charging stations in California". American Journal of Transportation. April 4, 2023. Available online: https://www.ajot.com/insights/full/ai-backed-by-amazon-cbre-forum-mobility-is-building-harbor-truck-charging-stations-in-california.

trucks.[492] Forum Mobility also received $4.5 million to build a BEV charging depot in Livermore, CA, as part of a network of chargers for drayage trucking carriers moving freight.[493] Logistics and supply chain corporation NFI Industries is partnering with Electrify America to install 34 DCFC ports (150 kW and 350kW) to support their BEV drayage[494] fleet that will service the ports of LA and Long Beach.[495] In El Monte California, Schneider National has installed a 4.8 megawatt station with 16 EV chargers that can each charge two HD BEVs.[496,497] With funding from California, Volvo is partnering with Shell Recharge Solutions and three truck dealerships to deploy five publicly accessible charging stations by 2023 that will serve medium- and heavy-duty BEVs in southern California between ports and industrial centers.[498]

Outside of California, DTNA is working with the State of Michigan and DTE to develop a truck stop charging station in Michigan that could serve as a prototype for broader truck stop deployment.[499] Voltera aims to build a BEV charging station in Garden City, GA,[500] and has committed billions to developing sites in the U.S.[501] One Energy recently announced the energization of a 30 megawatt charging hub intended to service multiple HD BEV fleet operators in Findlay, Ohio; the site has the capacity to charge 90 trucks at the same time.[502,503]

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[492] Margaronis, Stas. “Backed by Amazon & CBRE, Forum Mobility is building harbor truck charging stations in California”. American Journal of Transportation. April 4, 2023. Available online: https://www.ajot.com/insights/full/ai-backed-by-amazon-cbre-forum-mobility-is-building-harbor-truck-charging-stations-in-california.

[493] East Bay Community Energy. “East Bay Community Energy and Forum Mobility Announce Innovative Financing for First of Its Kind Electric Truck Charging Depot in Livermore”. PR Newswire. Available online: https://www.prnewswire.com/news-releases/east-bay-community-energy-and-forum-mobility-announce-innovative-financing-for-first-of-its-kind-electric-truck-charging-depot-in-livermore-301849030.html.

[494] Drayage trucks typically transport containers or goods a short distance from ports to distribution centers, rail facilities, or other nearby locations.

[495] NFI. “Electrify America and NFI Industries Collaborate on Nation’s Largest Heavy-Duty Electric Charging Infrastructure Project.” September 1, 2021. Available online: https://www.nfiindustries.com/about-nfi/news/nations-largest-electric-truck-charging-infrastructure-project/.

[496] Carpenter, Susan. “New charging depot can power 32 heavy-duty electric trucks at the same time”. Spectrum News. June 7, 2023. Available online: https://spectrumnews1.com/ca/la-west/environment/2023/06/07/new-charging-depot-can-power-32-heavy-duty-electric-trucks-at-the-same-time

[497] Adler, Alan. “Megawatt charging for electric trucks arriving in small loads”. June 9, 2023. Available online: https://www.freightwaves.com/news/megawatt-charging-for-electric-trucks-arriving-in-small-loads.

[498] Borras, Jo. “Volvo Trucks Building an Electric Semi Charging Corridor”. *CleanTechnica*. July 16, 2022. Available online: https://cleantechnica.com/2022/07/16/volvo-trucks-building-an-electric-semi-charging-corridor/.

[499] Daimler Trucks North America Press Release. “State of Michigan partners with Daimler Truck North America and DTE Energy to build Michigan’s ‘truck stop of the future.” June 29, 2023. Available online: https://northamerica.daimlertruck.com/pressdetail/state-of-michigan-partners-with-daimler-2023-06-29/

[500] Guan, Nancy. “EVs trucks are coming to Georgia Ports. A charging station is planned for Garden City”. Savannah Morning News. Available online: https://www.savannahnow.com/story/news/2023/05/29/ev-truck-charging-station-garden-city/70254024007/.

[501] Voltera. “Voltera Launches as Turnkey Charging Infrastructure Solution for Companies Operating EVs, with Plans for Multibillion-Dollar Investment”. Globe Newswire. August 9, 2022. Available online: https://www.globenewswire.com/news-release/2022/08/09/2495043/0/en/Voltera-Launches-as-Turnkey-Charging-Infrastructure-Solution-for-Companies-Operating-EVs-With-Plans-for-Multibillion-Dollar-Investment.html.

[502] BusinessWire. “One Energy Energizes the Largest Electric Semi-Truck Charging Site in US at 30 MW Megawatt Hub Site in Ohio”. October 9, 2023. Available online: https://www.businesswire.com/news/home/20231009589668/en/.

[503] HDT Truckinginfo. “Megawatt Truck Charging Hub in Ohio”. October 12, 2023. Available online: https://www.truckinginfo.com/10207881/megawatt-truck-charging-hub-opens-in-ohio.

A variety of solutions are being offered for, or explored by, fleets. For example, WattEV is planning a network of public charging depots connecting ports to warehouses and distribution centers as part of its “Truck-as-a-Service” model, in which customers pay a per mile rate for use of, and charging for, a HD electric truck. [504] They opened a five megawatt public truck charging station that can charge 26 trucks simultaneously at the Port of Long Beach in 2023.[505] WattEV's first station under construction in Bakersfield, CA, is planned to have integrated solar and eventually be capable of charging 200 trucks each day;[506] additional stations are under development in San Bernardino and Gardena.[507] Zeem Solutions also offers charging to fleets along with a lease for one of its medium- or heavy-duty BEVs (via its “Transportation-as-a-Service” model). Zeem’s first depot station opened last year in the Los Angeles area and will support the charging of vans, trucks, airport shuttles, and tour buses (among other vehicles) with its 77 DCFC ports and 53 L2 ports.[508]

Some other companies are starting with mobile charging units while they test or pilot vehicles.[509] For example, PACCAR has partnered with Heliox to offer 40 kW and 50 kW mobile charging units to its dealers and customers of the Kenworth and Peterbilt brands[510] and Sysco, which plans to deploy 800 Class 8 tractors in the next few years, plans to use mobile charging units to begin their truck deployments while 14 charging stations are being installed.[511] Dannar offers mobile power platforms with up to 500 kWh of energy (or “exportable power”) for offroad work vehicles and emergency applications.[512] BP pulse offers portable charging on wheels as well as upcycled shipping containers with built in electrical infrastructure that can be used with different charging equipment and placed onsite without significant construction.[513] Mullen Automotive offers a mobile charging truck that can deliver up to 150 kW of power through either L2 or DCFC ports.[514] Xos Hub mobile charging units offer up to 390 kWh of energy and can

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[504] WattEV. “WattEV Orders 50 Volvo VNR Electric Trucks”. May 23, 2022. Available online: https://www.wattev.com/post/wattev-orders-50-volvo-vnr-electric-trucks.

[505] Adler, Alan. “WattEV opens public truck charging depot in Long Beach port”. July 24, 2023. Available online: https://www.freightwaves.com/news/wattev-opens-public-truck-charging-depot-in-long-beach-port.

[506] WattEV. “WattEV Breaks Ground on 21st Century Truck Stop”. December 16, 2021. Available online: https://www.wattev.com/post/wattev-breaks-ground-on-21st-century-truck-stop.

[507] WattEV. “Our Charging Sites”. Available online: https://www.wattev.com/charging-stations.

[508] Zeem. “Zeem Solutions Launches First Electric Vehicle Transportation-As-A-Service Depot.” March 30, 2022. Available online:https://www.businesswire.com/news/home/20220330005269/en/Zeem-Solutions-Launches-First-Electric-Vehicle-Transportation-As-A-Service-Depot.

[509] Mobile charging units are EVSE that can move to different locations to charge vehicles. Depending on the unit’s specifications and site, mobile charging units may be able to utilize a facility’s existing infrastructure (e.g., 240 V wall outlets) to recharge. Mobile charging units may have wheels for easy transport.

[510] Hampel, Carrie. “Heliox to be global charging partner for Paccar”. *Electrive.com.* September 24, 2022. Available online: https://www.electrive.com/2022/09/24/heliox-to-be-global-charging-partner-for-paccar/.

[511] Morgan, Jason. “How Sysco Corp. plans to deploy 800 battery electric Class 8 trucks (and that’s just the beginning)”. *Fleet Equipment*. November 14, 2022. Available online: https://www.fleetequipmentmag.com/sysco-battery-electric-trucks/.

[512] DANNAR. “DANNAR platforms provide off-grid export power along with power for planned daily and seasonal needs, as well as unexpected emergency response”. Available online: https://www.dannar.us.com/platforms/.

[513] BP pulse. “Rapidly deploy EV charging infrastructure with Inrush mobile and non-permanent charging solutions.” Available online: https://bppulsefleet.com/fleet/products/non-permanent-and-mobile-charging/.

[514] Mullen. “Mullen Announces New Mobile EV Charging Truck Delivering Level 2 and Level 3 DC Fast Charging”. Available online: https://news.mullenusa.com/mullen-announces-new-mobile-ev-charging-truck-delivering-level-2-and-level-3-dc-fast-charging.

charge up to five vehicles at a time.[515] Cummins and Heliox are partnering on a mobile 50 kW DC charger.[516]

Truck manufacturers are working closely with their customers to support depot charging infrastructure. For example, PACCAR sells a range of EVSEs to customers directly.[517] Mack Trucks partnered with two charging solution companies so that they can offer customers the ability to acquire EVSE solutions directly from their dealers.[518] DTNA also announced a partnership to provide their customers with EVSE solutions.[519] Similarly, Navistar partnered with Quanta Services, Inc. to provide BEV infrastructure solutions, that include support in the design, construction, and maintenance of EVSE at depots.[520] Nikola has partnered with ChargePoint to provide fleet customers with a suite of options for charging infrastructure and software (e.g., for charge management).[521] AMPLY Power, which was acquired by BP in 2021, provides charging equipment and services for a variety of fleets, including van, truck, and bus fleets.[522]

Domestic manufacturing capacity is also increasing. DOE estimates that over $500 million in investments to support the domestic manufacturing of BEV charging equipment, with companies planning to produce more than one million chargers (including 60,000 DCFCs) in the U.S. each year.[523,524] The White House estimates over $25 billion in commitments to expand the U.S. charging network has been announced as of January 2024.[525] Workforce development is on the

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[515] XOS. “XOS Energy Solutions”. Available online: https://www.xostrucks.com/xes/#mobilecharging.

[516] Cummins. “Cummins and Heliox to Partner on Electric Vehicle Charging Solutions for Fleet Customers”. May 23, 2023. Available online: https://www.cummins.com/news/releases/2023/05/16/cummins-and-heliox-partner-electric-vehicle-charging-solutions-fleet.

[517] PACCAR. “Electric Vehicle Chargers.” Accessed on November 1, 2023. Available online: https://www.paccarparts.com/technology/ev-chargers/

[518] Volvo Group Press Release. “Mack Trucks Enters Partnerships with Heliox, Gilbarco to Increase Charging Accessibility.” February 14, 2023. Available online: https://www.volvogroup.com/en/news-and-media/news/2023/feb/mack-trucks-enters-partnerships-with-heliox-gilbarco-to-increase-charging-accessibility.html

[519] Daimler Trucks North America Press Release. “Electrada, Daimler partner for electric charging.” October 3, 2023. Available online: https://www.truckpartsandservice.com/alternative-power/battery-electric/article/15635568/electrada-daimler-partner-for-chargers

[520] Navistar Press Release. “Navistar Partners With Infrastructure Solutions Provider Quanta Services.” May 3, 2023. Available online: https://news.navistar.com/2023-05-03-Navistar-Partners-With-Infrastructure-Solutions-Provider-Quanta-Services

[521] Nikola. “Nikola and ChargePoint Partner to Accelerate Charging Infrastructure Solutions”. November 8, 2022. Available online: https://nikolamotor.com/press_releases/nikola-and-chargepoint-partner-to-accelerate-charging-infrastructure-solutions-212/.

[522] BP. Press Release: “bp takes first major step into electrification in the US by acquiring EV fleet charging provider AMPLY Power”. December 7, 2021. Available online: https://www.bp.com/en/global/corporate/news-and-insights/press-releases/bp-takes-first-major-step-into-electrification-in-us-by-acquiring-ev-fleet-charging-provider-amply-power.html.

[523] U.S. Department of Energy, Vehicle Technologies Office. “FOTW #1314, October 30, 2023: Manufacturers Have Announced Investments of Over $500 million in More Than 40 American-Made Electric Vehicle Charger Plants”. October 30, 2023. Available online: https://www.energy.gov/eere/vehicles/articles/fotw-1314-october-30-2023-manufacturers-have-announced-investments-over-500.

[524] DOE, “Building America’s Clean Energy Future”. 2024. Available online: https://www.energy.gov/invest.

[525] The White House, “FACT SHEET: Biden-Harris Administration Announces New Actions to Cut Electric Vehicle Costs for Americans and Continue Building Out a Convenient, Reliable, Made-in-America EV Charging Network”, January 19, 2024. Accessed at: https://www.whitehouse.gov/briefing-room/statements-releases/2024/01/19/fact-sheet-biden-harris-administration-announces-new-actions-to-cut-electric-vehicle-costs-for-americans-and-continue-building-out-a-convenient-reliable-made-in-america-ev-charging-network/.

rise. For example, the Siemens Foundation announced they will invest $30 million over ten years focused on the EV charging sector.[526] As of early 2023, about 20,000 people had been certified to install EV charging stations through a national Electric Vehicle Infrastructure Training Program.[527] These important early actions and market indicators suggest strong growth in charging and refueling ZEV infrastructure in the coming years.

States and utilities are also engaged. Seventeen states plus the District of Columbia (and the Canadian province Quebec) developed a "Multi-State Medium- and Heavy-Duty Zero-Emission Vehicle Action Plan," which includes recommendations for planning for, and deploying, charging infrastructure.[528] California is planning to invest $1.9 billion in state funding through 2027 in BEV charging and hydrogen fueling infrastructure (and related projects), including about one billion specific to infrastructure for trucks and buses.[529] The Edison Electric Institute estimates that electric companies are investing about $4 billion to advance charging infrastructure and fleets.[530] The National Electric Highway Coalition, a group that includes more than 60 electric companies and cooperatives that serve customers in 48 states and D.C.[531] aims to provide fast charging along major highways in their service areas. Other utilities, like the Jacksonville Electric Authority (JEA) are supporting infrastructure through commercial electrification rebates. JEA is offering rebates of up to $30,000 for DCFC stations and up to $5,200 for Level 2 stations.[532] In the west, Nevada Energy was supporting fleets by offering rebates for up to 75% of the project costs for Level 2 ports and up to 50% of the project costs for DCFC stations (subject to caps and restrictions).[533,534]

And there are additional initiatives that are gearing up to further support HD ZEV infrastructure deployment. For example, in March 2024, the U.S. released a National Zero-Emission Freight Corridor Strategy[535] that, "sets an actionable vision and comprehensive approach to accelerating the deployment of a world-class, zero-emission freight network across

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[526] Lienert, Paul. "Siemens to invest $30 million to train U.S. EV charger technicians". Reuters. September 6, 2023. Available online: https://www.reuters.com/business/autos-transportation/siemens-invest-30-million-train-us-ev-charger-technicians-2023-09-06/.

[527] IBEW. "IBEW Members Answer Call for National Electric Vehicle Program". April 2023. Available online: https://www.ibew.org/articles/23ElectricalWorker/EW2304/Politics.0423.html.

[528] ZEV Task Force. "Multi-State Medium- and Heavy-Duty Zero-Emission Vehicle Action Plan: A Policy Framework to Eliminate Harmful Truck and Bus Emissions". July 2022. Available online: https://www.nescaum.org/documents/multi-state-medium-and-heavy-duty-zev-action-plan-dual-page.pdf.

[529] California Energy Commission. "CEC Approves $1.9 Billion Plan to Expand Zero-Emission Transportation Infrastructure". February 14, 2024. Available online: https://www.energy.ca.gov/news/2024-02/cec-approves-19-billion-plan-expand-zero-emission-transportation-infrastructure.

[530] Joint Office of Energy and Transportation. "Private Sector Continues to Play Key Part in Accelerating Buildout of EV Charging Networks." February 15, 2023. https://driveelectric.gov/news/#private-investment.

[531] Edison Electric Institute. Issues & Policy: National Electric Highway Coalition. Available online: https://www.eei.org/en/issues-and-policy/national-electric-highway-coalition.

[532] U.S. Department of Energy. Alternative Fuels Data Center. Florida Laws and Incentives." See Docket ID EPA-HQ-OAR-2022-0985-0290.

[533] Level 2 rebates are applicable to fleets with between 2 and 10 ports, and subject to a $5,000/port cap. DCFC rebates are limited to 5 stations and are capped to the lesser of $400/kW or $40,000 per station.

[534] U.S. Department of Energy. Alternative Fuels Data Center. Commercial Electric Vehicle Charging Station Rebates—Nevada Energy. Available online: https://afdc.energy.gov/laws/12118. (Note: the program ended in June 2023).

[535] Joint Office of Energy and Transportation. "National Zero-Emission Freight Corridor Strategy" DOE/EE-2816 2024. March 2024. Available at https://driveelectric.gov/files/zef-corridor-strategy.pdf.

the United States by 2040. The strategy focuses on advancing the deployment of zero-emission medium- and heavy-duty vehicle (ZE-MHDV) fueling infrastructure by targeting public investment to amplify private sector momentum, focus utility and regulatory energy planning, align industry activity, and mobilize communities for clean transportation."[536] The strategy has four phases. The first phase, from 2024-2027, focuses on establishing freight hubs defined "as a 100-mile to a 150-mile radius zone or geographic area centered around a point with a significant concentration of freight volume (e.g., ports, intermodal facilities, and truck parking), that supports a broader ecosystem of freight activity throughout that zone."[537] The second phase, from 2027-2030, will connect key ZEV hubs, building out infrastructure along several major highways. The third phase, from 2030-2045, will expand the corridors, "including access to charging and fueling to all coastal ports and their surrounding freight ecosystems for short-haul and regional operations."[538] The fourth phase, from 2035-2040, will complete the freight corridor network. This corridor strategy provides support for the development of HD ZEV infrastructure that corresponds to the modeled potential compliance pathway for meeting the final standards.

Also in 2024, Daimler, Volvo, and Navistar, who collectively represent approximately 70 percent of HD sales in the U.S., formed an industry group called the Powering America's Commercial Transportation (PACT) coalition to advance best practices and advocate for climate policies that can accelerate the construction of infrastructure for HD ZEV fleets.[539]

1.6.2.3 Future BEV Charging Infrastructure Needs

We expect the many public and private investments and initiatives described in Chapters 1.3.2 and 1.6.2.2 above to significantly expand BEV charging infrastructure for HD vehicles over the next decade. However, more infrastructure will be needed as BEV adoption grows. In Chapter 2.6 of this document, we describe how we accounted for charging infrastructure needs and costs associated with the utilization of HD BEV technologies in the potential compliance pathway that supports the feasibility of the final standards. In this section, we discuss a few recent assessments of charging infrastructure needs from the literature and how they compare to our final rule analysis.

Estimates of how much charging infrastructure will be needed to support BEVs vary widely among studies based on differing assumptions about the population and mix of BEVs, the assumed mix of depot versus public charging, charging power levels, and EVSE utilization

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[536] Joint Office of Energy and Transportation. "Biden-Harris Administration, Joint Office of Energy and Transportation Release Strategy to Accelerate Zero-Emission Freight Infrastructure Deployment." March 12, 2024. Available online: https://driveelectric.gov/news/decarbonize-freight.

[537] Joint Office of Energy and Transportation. "National Zero-Emission Freight Corridor Strategy" DOE/EE-2816 2024. March 2024. Available at https://driveelectric.gov/files/zef-corridor-strategy.pdf. See page 3.

[538] Joint Office of Energy and Transportation. "National Zero-Emission Freight Corridor Strategy" DOE/EE-2816 2024. March 2024. Available at https://driveelectric.gov/files/zef-corridor-strategy.pdf. See page 8.

[539] PACT. Updated Release. "Cross-Industry Coalition, Powering America's Commercial Transportation, Launches to Accelerate Zero-Emission Vehicle Infrastructure Deployments". BusinessWire. February 9, 2024. Available online: https://www.businesswire.com/news/home/20240130152674/en/Cross-Industry-Coalition-Powering-America%E2%80%99s-Commercial-Transportation-Launches-to-Accelerate-Zero-Emission-Vehicle-Infrastructure-Deployments.

among other factors. A recent ICCT study (Ragon et al. 2023)[540] estimated charging needs for 1.1 million Class 4 to 8 BEVs in 2030. The study projected that a mix of 522,000 (DC-50 kW and DC-150 kW) EVSE ports could meet overnight charging needs[541] along with 28,500 DC-350 kW ports and 9,540 DC-2 MW ports used for opportunity charging. An Atlas Public Policy analysis (McKenzie et al. 2021) estimated that about 500,000 EVSE ports (ranging from Level 2 to DC-150 kW) would be needed at depots to support over one million Class 3 to 8 trucks in 2030 along with a significant buildout of en-route charging infrastructure.[542] The study found that the number of en-route ports needed could vary significantly based on the power level, e.g., for long-haul trucking, up to 93,000 350-kW DCFC ports or up to 19,000 2-MW DCFC ports may be needed along with about 7,000–32,000 DCFCs used for en-route charging by other trucks.[543] A study by the Goldman School of Public Policy (Phadke et al. 2021)[544] projects that about 85,000 (DC-50 kW to DC-300 kW) ports, mainly at depots and warehouses, will be needed to support Class 2b–7 BEVs by 2035 and 300,000 (DC-125 kW to 1 MW) ports will be needed across 2,700 truck stops to support Class 7–8 tractors under a scenario in which 100 percent of new MD and HD vehicle sales are BEVs by 2035.

The Coordinating Research Council (CRC) released a study[545] in September 2023 that estimated charging and hydrogen refueling infrastructure needs to support ZEVs at levels consistent with several finalized CARB regulations and two of EPA's proposed vehicle standards, including those in the NPRM.[546] It found that 432,000 (L2 to DC-350 kW) EVSE ports would be needed at depots in 2030 along with about 45,500 (DC-150 kW to 1 MW) public ports to meet the charging needs of 920,000 MD and HD BEVs. The CRC projects that within two years infrastructure needs will grow to 709,000 depot ports and 91,800 public DCFC ports to support a fleet of 1.7 million MD and HD BEVs. Ricardo completed a feasibility study of the proposed rule (Kuhn et. al 2023) and estimated that about 1.5 million EVSE ports will be required at depots in 2032 along with about 7,500 highway ports to support about 1.5 million

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[540] Ragon, Pierre-Louis et al. "Near-term Infrastructure Deployment to Support Zero-Emission Medium- and Heavy-Duty Vehicles in the United States." May 2023. Available online: https://theicct.org/wp-content/uploads/2023/05/infrastructure-deployment-mhdv-may23.pdf.

[541541] Overnight charging in the study is expected at depots except for long-haul vehicles, which are expected to use public charging.

[542] McKenzie, Lucy, James Di Filippo, Josh Rosenberg, and Nick Nigro. "U.S. Vehicle Electrification Infrastructure Assessment: Medium- and Heavy-Duty Truck Charging". Atlas Public Policy. November 12, 2021. Available online: https://atlaspolicy.com/wp-content/uploads/2021/11/2021-11-12_Atlas_US_Electrification_Infrastructure_Assessment_MD-HD-trucks.pdf.

[543] Some numbers discussed for the Atlas study were taken from graphs and should be considered approximate. The Atlas study uses the term "on-road" charging.

[544] Phadke, Amol et al. Goldman School of Public Policy, University of California Berkeley. "2035, The Report—Transportation:
Plummeting Costs and Dramatic Improvements in Batteries Can Accelerate Our Clean Transportation Future". April 2021. Available online: http://www.2035report.com/transportation/wp-content/uploads/2020/05/2035Report2.0-1.pdf.

[545] Coordinating Research Council. "Assess the Battery-Recharging and Hydrogen-Refueling Infrastructure Needs, Costs and Timelines Required to Support Regulatory Requirements for Light-, Medium-, and Heavy-Duty Zero-Emission Vehicles." Prepared by ICF. September 2023. Available online: https://crcao.org/wp-content/uploads/2023/09/CRC_Infrastructure_Assessment_Report_ICF_09282023_Final-Report.pdf.

[546] The study accounted for CARB's Advanced Clean Cars II, Advanced Clean Trucks, and Advanced Clean Fleets regulations and EPA's proposed Multipollutant Emissions Standards for MY2027 and Later Light-Duty and Medium-Duty Vehicles and proposed Greenhouse Gas Emissions Standards – Phase 3.

medium- and heavy-duty BEVs.[547] A recent CEC assessment (Davis et al. 2023) estimated that 109,000 (L2 to DC-150 kW) EVSE ports will be needed at depots to support 155,000 BEVs expected in California in 2030 along with about 5,500 (DC-350 kW to 1.5 MW) public ports.[548]

As discussed in Chapter 2.10.3, in our final rule analysis, we estimate that about 520,000 EVSE ports at depots will be needed to support MY2027–MY2032 depot-charged BEVs (see RIA Chapter 2.8.7.2 for information on how this was estimated), at a ratio of 1.2 BEVs per EVSE port. It should be noted that the mix of depot charging equipment also differs among studies. Our analysis focused on the lowest cost EVSE option that could meet daily charging needs; as such, 88% of the projected EVSE ports in the final rule analysis are Level 2. The CRC and Ricardo studies also found the highest number of ports needed at depots would be Level 2 (consistent with our analysis), while the other studies focused more on DCFC.

The projected needs for public or en-route charging vary even more widely in the studies discussed above with power levels ranging from 125 kW to 2 MW. One of the key questions for future public charging needs, particularly for long-haul vehicles, is how many stations will be needed to provide geographic coverage across the country. Ragon et al. 2023 projects that as much as 85% of the charging needs for long-haul BEVs could be covered by building stations every 50 miles along the National Highway Freight Network (NHFN) for a total of just 844 stations.[549] McKenzie et al. 2021 also centered its long-haul analysis on the primary NHFN suggesting fewer than 500 stations would be needed if spaced every 100 miles.[550,551]

Another key question is the pace of charging infrastructure buildout. Ragon et al. 2023 found that early charging needs for MHD BEVs will be concentrated in select counties and states, e.g., estimating that Texas, California, and Florida will collectively account for almost 25% of charging needs (on an energy basis) in 2030.[552] In a supplemental analysis submitted to EPA that assumed 100 mile intervals between stations, ICCT estimated that only between 100 and 210 electrified truck stops on priority corridors may be needed by 2030, assuming a given level of BEV long-haul tractors.[553] Analyses of this type can help inform priority areas for infrastructure deployment and facilitate a phased buildout. See RTC 6.1 for additional discussion on recent

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[547] Kuhn et. al. “Feasibility study of EPA NPRM Phase 3 GHG standards for Medium Heavy-Duty Vehicles. Version: 3.0”. Ricardo, prepared for Truck and Engine Manufacturers Association. July 19, 2023.

[548] Davis, Adam et. al. California Energy Commission. “Assembly Bill 2127 Electric Vehicle Charging Infrastructure Assessment: Assessing Charging Needs to Support Zero-Emission Vehicles in 2030 and 2035.” August 2023. Available online: https://www.energy.ca.gov/publications/2023/second-assembly-bill-ab-2127-electric-vehicle-charging-infrastructure-assessment.

[549] Ragon, Pierre-Louis et al. “Near-term Infrastructure Deployment to Support Zero-Emission Medium- and Heavy-Duty Vehicles in the United States.” May 2023. Available online: https://theicct.org/wp-content/uploads/2023/05/infrastructure-deployment-mhdv-may23.pdf.

[550] The Atlas study (McKenzie et al. 2021) assumed stations would be spaced every 100 miles and have 10 ports each for a total of 4,151 ports across the primary NHFN or 5,785 ports across the full NHFN.

[551] McKenzie, Lucy, James Di Filippo, Josh Rosenberg, and Nick Nigro. “U.S. Vehicle Electrification Infrastructure Assessment: Medium- and Heavy-Duty Truck Charging”. Atlas Public Policy. Available online: https://atlaspolicy.com/wp-content/uploads/2021/11/2021-11-12_Atlas_US_Electrification_Infrastructure_Assessment_MD-HD-trucks.pdf.

[552] Ragon, Pierre-Louis et al. “Near-term Infrastructure Deployment to Support Zero-Emission Medium- and Heavy-Duty Vehicles in the United States.” May 2023. Available online: https://theicct.org/wp-content/uploads/2023/05/infrastructure-deployment-mhdv-may23.pdf.

[553] ICCT. “Supplemental comments of the International Council on Clean Transportation on the EPA Phase 3 GHG Proposal.” January 3, 2023. Docket ID: EPA-HQ-OAR-2022-0985-2703.

assessments of charging infrastructure needs from the literature and how they compare to our final rule analysis. See RTC 7 (Distribution) for EPA's further consideration of this issue in the context of needed distribution grid buildout and extent of an initial HD BEV public charging network. For a discussion of how we accounted for depot and public infrastructure costs, see Chapter 2.6. of this RIA.

1.6.2.4 Charging Costs

Beyond upfront costs, BEV owners will purchase the electricity that their vehicles consume. The cost of the electricity can vary based on the applicable retail electricity rate as determined by provider, location, time of use (TOU) and other factors. Fleets may also pay demand charges based on the maximum power used during a month. As noted in a report by the National Association of Regulatory Utility Commissioners, many utilities offer rates to incentivize charging at off-peak times such as time of use rates or real-time pricing.[554] Some utilities are also piloting approaches to reduce demand charges for BEV fleet customers or station providers, e.g., by suspending them or offering alternatives during initial years of operation.[555,556] Since demand charges are typically assessed based on the peak power (measured in kW) used in a billing cycle, they can be particularly challenging for stations with multiple high-powered DCFCs. Demand charge rates vary widely by utility[557] and location, ranging from $0/kW (no demand charge) to over $50/kW according to an NREL survey.[558] The use of onsite battery storage, renewable generation, or managed charging may help to lower peak demands at some stations and reduce these costs (as discussed in Chapter 1.6.5 of this document as well as in RTC section 7 (Distribution)).

The price to charge at public stations may be higher than for depot charging, as noted by a recent Atlas analysis, since the public charging price may incorporate the profit margin of the third-party charging provider along with operating expenses, and costs associated with charging equipment depreciation.[559] Prices at public stations may also vary in structure, e.g., costs may be assessed per kWh of electricity, per minute of charging, via a monthly subscription fee, or another method with rates varying based on power level or other factors.[560,561] See Chapter 2.6.4 for a description of how estimated public charging cost on a $/kWh, accounting for amortized

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[554] NARUC. "Electric Vehicles: Key Trends, Issues, and Considerations for State Regulators". October 2019. Available online: https://pubs.naruc.org/pub/32857459-0005-B8C5-95C6-1920829CABFE.

[555] Ibid.

[556] ZEV Task Force. "Multi-State Medium- and Heavy-Duty Zero-Emission Vehicle Action Plan: A Policy Framework to Eliminate Harmful Truck and Bus Emissions". July 2022. Available online: https://www.nescaum.org/documents/multi-state-medium-and-heavy-duty-zev-action-plan-dual-page.pdf

[557] In some cases, utilities may apply different demand charge rates ($/kW) based on whether a customer's maximum power usage in a given billing cycle occurs on or off peak.

[558] McLaren, Joyce, Nicholas Laws, and Kate Anderson. "Identifying Potential Markets for Behind-the-Meter Battery Energy Storage: A Survey of U.S. Demand Charges". National Renewable Energy Lab. August 2017. Available online: https://www.nrel.gov/docs/fy17osti/68963.pdf.

[559] Satterfield, Chris and Nick Nigro. "Assessing Financial Barriers to Adoption of Electric Trucks: A Total Cost of Ownership Analysis". Atlas Public Policy. February 2020. Available online: https://atlaspolicy.com/wp-content/uploads/2020/02/Assessing-Financial-Barriers-to-Adoption-of-Electric-Trucks.pdf.

[560] U.S. DOE Alternative Fuels Data Center. "Charging Infrastructure Operation and Maintenance." Available online: https://afdc.energy.gov/fuels/electricity_infrastructure_maintenance_and_operation.html.

[561] In some states, there are prohibitions for entities other than utilities to sell electricity. Charging may be priced by time or session instead of on a $/kWh basis.

cost of equipment, land costs, operation and maintenance, distribution upgrades, and profits, among other factors.

1.6.3 Other BEV Charging Infrastructure Considerations

There are challenges and important considerations beyond costs when developing and deploying charging infrastructure. These include interoperability, station design and siting considerations, and the potential need for distribution system upgrades or other grid considerations.

1.6.3.1 Interoperability

As discussed in Chapter 1.6.1, there is currently no universal standard for DCFC connectors, limiting the EVSE ports and stations a particular vehicle may use.[562] This may pose a challenge for public, en-route charging network providers trying to serve a wide range of vehicles and for BEV drivers who may need to travel longer distances to find a station with the right connector type. Depending on business requirements, fleets may also need to support varying makes and models of HD BEVs that use different connectors,[563] limiting the ability to share and optimize the use of depot charging equipment. Once fleet owners have installed a particular connector type at their depot, it could limit their ability to buy new vehicles without incurring additional EVSE costs. In some cases, adapters may be an option. For example, Tesla released a CCS Type 1 adapter in September of 2022 that allows some of their cars to charge at CCS ports installed by other providers.[564] We also note movement toward standardized connectors. For example, the National Electric Vehicle Standards and Requirements Final Rule issued by the Federal Highway Administration in February 2023[565] requires each DCFC port funded under the NEVI Formula Program, or as part of a publicly-accessible EV charging project under Title 23, U.S.C., to have a Combined Charging System (CCS) Type 1 connector.[566] Additionally, as discussed in Chapter 1.6.1.2, a non-proprietary standard for higher-power charging, MCS, is currently in development.[567]

Physical connectors are only one aspect of interoperability. Communication protocols between the network and chargers and between the charger and vehicle facilitate the flow of key charging and billing information such as authentication, vehicle state of charge, and power levels.[568] The National Electric Vehicle Standards and Requirements Final Rule requires the use

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[562] Some EVSE ports are available with multiple connector types.

[563] California Energy Commission. Electric Vehicle Charging Infrastructure Assessment—AB 2127. Available online: https://www.energy.ca.gov/programs-and-topics/programs/electric-vehicle-charging-infrastructure-assessment-ab-2127.

[564] Halvorson, Bengt. “$250 CCS adapter lets Tesla EVs roam other charging networks”. Green Car Reports. September 25, 2022. Available online: https://www.greencarreports.com/news/1137268_tesla-ccs-adapter-north-america-up-to-250-kw.

[565] 88 FR 12724. February 28, 2023. Available online: https://www.federalregister.gov/documents/2023/02/28/2023-03500/national-electric-vehicle-infrastructure-standards-and-requirements.

[566] Additional non-proprietary connectors are allowed, provided each DCFC port has a CCS Type 1 connector.

[567] SAE International. “Megawatt Charging System for Electric Vehicles J3271”. Available online: https://www.sae.org/standards/content/j3271/

[568] Alexander, Matt et al. California Energy Commission. “Assembly Bill 2127 Electric Vehicle Charging Infrastructure Assessment Analyzing Charging Needs to Support Zero-Emission Vehicles in 2030.” July 2021. Available online: https://www.energy.ca.gov/programs-and-topics/programs/electric-vehicle-charging-infrastructure-assessment-ab-2127.

of Open Charge Point Protocol for the former and ISO 15118 for the latter.[569] The rule also requires the use of Open Charge Point Interface for communication between charging networks.[570] Such requirements support standard communication for BEV charging—advancing interoperability. We also note that the MCS incorporates ISO 15118.[571]

1.6.3.2 Station Design and Siting Considerations

How to best design and site depot charging stations will depend on fleets' vehicle mix, operational needs, and site specifics. All sites need to have sufficient space for charging equipment, with some stations potentially needing to accommodate onsite storage and generation equipment as well.[572] The canopy or roof height of the station and charging cords need to be appropriately sized for the BEVs in the fleet and the station needs sufficient space for vehicle ingress and egress. As discussed in Chapter 2.6.2, installation costs may be higher for sites with longer distances between the charging equipment and electrical panel or where panel upgrades are needed. Site ownership is another consideration. As noted in a report by the California Energy Commission, installing charging equipment or making associated electrical upgrades could depend on landlord-tenant relationships.[573] In certain cases, responsibility for charging infrastructure may be shared among different parties—potentially complicating planning and upkeep. In addition to the above, siting and design for public or other en-route stations will need to account for the operational needs, characteristics, and travel patterns of the different BEVs they may support. See further discussion in RTC section 7 (Distribution).

The construction of any new charging station requires compliance with various building and safety regulations.[574] Permitting times vary based on state or local jurisdiction, site specifics, and other factors. For example, Electrify America reported that the permitting process took an average of 13 weeks for its U.S. "ultra-fast" DCFC stations in 2021, but took over twice as long for stations in New Jersey.[575] Utility interconnection also adds time to the process. After site construction was complete, Electrify America found an additional 12 weeks was required on average for inspection, commissioning and other steps before a site was energized.[576]

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[569] 88 FR 12724. February 28, 2023. Available online: https://www.federalregister.gov/documents/2023/02/28/2023-03500/national-electric-vehicle-infrastructure-standards-and-requirements.

[570] See rulemaking for required version numbers, implementation timeline and other details.

[571] Kane, Mark. "CharIN Officially Launches The Megawatt Charging System (MCS)". Inside EVs. June 15, 2022. Available online: https://insideevs.com/news/592360/megawatt-charging-system-mcs-launch/.

[572] National Renewable Energy Laboratory (NREL). "Medium- and Heavy-Duty Electric Vehicle Charging". Available online: https://www.nrel.gov/transportation/medium-heavy-duty-vehicle-charging.html.

[573] Alexander, Matt et al. California Energy Commission. "Assembly Bill 2127 Electric Vehicle Charging Infrastructure Assessment Analyzing Charging Needs to Support Zero-Emission Vehicles in 2030". July 2021. Available online: https://www.energy.ca.gov/programs-and-topics/programs/electric-vehicle-charging-infrastructure-assessment-ab-2127.

[574] Alexander, Matt et al. California Energy Commission. "Assembly Bill 2127 Electric Vehicle Charging Infrastructure Assessment Analyzing Charging Needs to Support Zero-Emission Vehicles in 2030". July 2021. Available online: https://www.energy.ca.gov/programs-and-topics/programs/electric-vehicle-charging-infrastructure-assessment-ab-2127.

[575] Electrify America. "2021 National Annual Report to U.S. EPA". April 30, 2022. Available online: https://media.electrifyamerica.com/assets/documents/original/872-2021AnnualReportNationalPublicFINAL.pdf.

[576] Electrify America. "2021 National Annual Report to U.S. EPA". April 30, 2022. Available online: https://media.electrifyamerica.com/assets/documents/original/872-2021AnnualReportNationalPublicFINAL.pdf.

Both permitting and utility interconnection times could be longer for larger, more complex, and/or higher-power charging stations. For example, California's "Electric Vehicle Charging Station Permitting Guidebook" notes that under a recent state law to help streamline the permitting process, jurisdictions have twice as long (50 business days) to review and either approve or deny a permit application for a site with 26 or more stations than one with 25 or fewer.[577] Special permits, such as a right of way permit or an encroachment permit may be required for stations that need a new utility electrical service or for which trenching under a current right of way is needed respectively—adding to the station deployment timeline. If upgrades to the electricity distribution system are required, this could further extend the timeline (as discussed in Chapter 1.6.5 of this document below.)

1.6.4 Power Generation and Transmission

HD BEV-related power generation and transmission actions and their costs are small when compared to historical levels of total power generation. Analysis by others concurs stating that, "the generation and transmission infrastructure that could be needed to meet the demand – is quite small relative to historic periods of growth in demand for electricity."[578] We project the additional generation needed to meet the demand of HD BEVs in the final rule to be relatively modest; the energy required for HD BEVs is estimated to be 22,000 GWh in 2032 and 120,000 GWh in 2050, as shown in Chapter 6.5. These loads represent only 0.5 percent and 3 percent, respectively, of the total 2022 electricity demand. Even when the electricity loads projected from the HD rule are combined with those from the in process Multi-Pollutant Emissions Standards for Model Years 2027 and Later Light-Duty and Medium-Duty Vehicles and other rules relating to the EGU sector, it is projected that the rules are unlikely to adversely affect resource adequacy.[579] Using MOVES analysis to determine demand and IPM to calculate the required electricity generation for these two rules combined shows the national increased generation from transportation electrification to be 0.4 percent at 2030 and 4.5 percent at 2050. Planning for and adding infrastructure for additional electricity generation and transmission is a standard practice for North American Electric Reliability Corporation (NERC), the six regional entities, and utilities, and is not a challenge specific to HD BEV needs. See Section II.D.2.c. of the Preamble and RTC section 7.1 for a discussion of grid reliability.

Electric transmission needs are defined in DOE's National Transmission Needs Study as "the existence of present or expected electric transmission capacity constraints or congestion in a geographic area". The study suggests that an "upgraded, uprated, or new transmission facility—including alternative transmission solutions" can help "improve the reliability and resilience of the power system; alleviate transmission congestion and unscheduled flows; alleviate power transfer capacity limits between neighboring regions; deliver cost-effective generation to meet demand; and/or meet projected future generation, electricity demand, or reliability

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[577] Hickerson, Heather and Hannah Goldsmith. CALIFORNIA GOVERNOR'S OFFICE OF BUSINESS AND ECONOMIC DEVELOPMENT. "Electric Vehicle Charging Station Permitting Guidebook". January 2023. Available online: https://static.business.ca.gov/wp-content/uploads/2019/12/GoBIZ-EVCharging-Guidebook.pdf.

[578] Hibbard, Paul. "Heavy Duty Vehicle Electrification Planning for and Development of Needed Power System Infrastructure". Analysis Group for EDF. June 2023. Available online: https://blogs.edf.org/climate411/wp-content/blogs.dir/7/files/Analysis-Group-HDV-Charging-Impacts-Report.pdf.

[579] U.S. EPA. "Technical Memorandum for Multi-Pollutant Emissions Standards for Model Years 2027 and Later Light-Duty and Medium-Duty Vehicles, and Greenhouse Gas Emissions Standards for Heavy-Duty Vehicles – Phase 3". February 2024

requirements."[580] This transmission needs study includes multiple scenarios with various levels of demand but is not specific to HD BEV power needs.

Technologies such as grid-enhancing technologies (GETs), which are supported by the Office of Electricity (OE), can help optimize transmission for HD BEVs and all users.[581] DOE support of transmission projects is shown by the $10.5 billion for the five-year period covering FY22 through FY26 to enhance the resilience of the electric grid, deploy technologies to enhance grid flexibility, and demonstrate innovative approaches to power sector infrastructure resilience and reliability.[582]

Electricity generation and transmission demand will depend on the time of day that charging occurs, the type or power level of charging, and the use of onsite storage and vehicle-to-grid (V2G) or other vehicle-grid integration technology, among other considerations. There are a variety of approaches that can reduce peak loads and/or align loads with plentiful or low carbon electricity. For example, depending on operational needs, BEVs may be scheduled to charge when the electricity demand is easier to meet. To illustrate the available energy based on time of day, the ERCOT (Electric Reliability Council of Texas) energy generation versus time of day is shown for July 19, 2023.[583] ERCOT and July 18 were chosen as the Texas grid was handling significant loads due to hot weather. The peak level of energy generated and transmitted of 82,182 MWh occurs at 6 pm as driven by customer use. The minimum power generated and transmitted is 54,419 MWh at 6 am. The theoretical energy available at 6 am (peak minus

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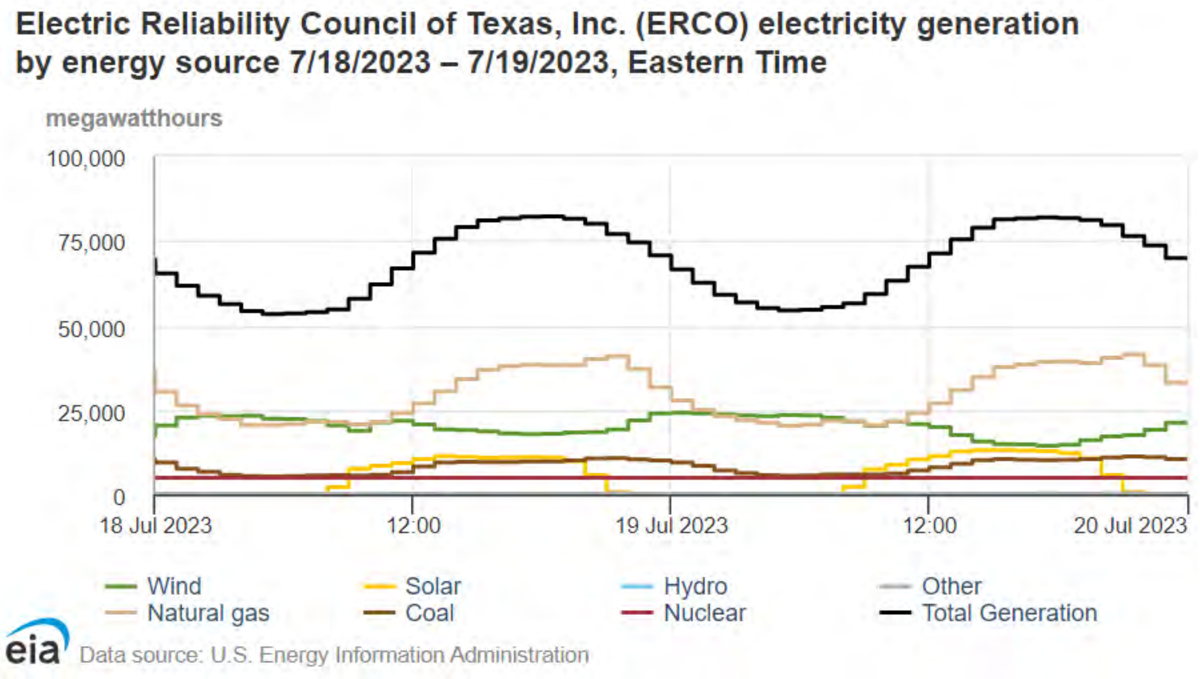
[580] U.S. Department of Energy. "National Transmission Needs Study". October 2023. Available Online: https://www.energy.gov/sites/default/files/2023-10/National_Transmission_Needs_Study_2023.pdf

[581] Jenkins, Sandra. "Grid-Enhancing Technologies: From R&D to Reality". Department of Electricity, Department of Energy. November 13, 2023. Available Online: https://www.energy.gov/oe/articles/grid-enhancing-technologies-rd-reality-0

[582] BIL–Grid Resilience and Innovation Partnerships (GRIP). NETL for DOE. Accessed February 26, 2024. . Available online: https://netl.doe.gov/bilhub/grid-resilience/grip.

[583] EIA. "U.S. Energy generation by energy source". Accessed November 24, 2023. Available online: https://www.eia.gov/electricity/gridmonitor/expanded-view/electric_overview/US48/US48/GenerationByEnergySource-4/edit

minimum) is 27,763 MWh, almost 34 percent of the peak. A check of minimum power vs maximum for the 48 lower states shows theoretical available power to again be 34%.


Electric Reliability Council of Texas, Inc. (ERCO) electricity generation by energy source 7/18/2023 – 7/19/2023, Eastern Time

Data source: U.S. Energy Information Administration

Figure 1-16 Example of Temporal Power Supply (Source: EIA)

Significant power is available overnight for use by depots (as well as public charging that occurs over night). Many HD BEV at depots will be able to start charging late at night when other loads have ceased, taking advantage of lower cost electricity that is readily available without grid improvements. HD BEV using public charging, and some unique depot applications, may not be able to draw power when it is plentiful and lower cost. These applications may decide to implement stationary batteries that draw power at times and loads that are convenient and lowest cost and then have the power available for HD BEV as needed. V2G technology, which allows electricity to be drawn from vehicles that are not in use, could even allow BEVs to enhance grid reliability.[584] V2G success was shown by San Diego Gas and Electric, Cajon Valley Union School District and Nuvve in the summer of 2022.[585] The DOE

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[584] Alexander, Matt et al. California Energy Commission. “Assembly Bill 2127 Electric Vehicle Charging Infrastructure Assessment Analyzing Charging Needs to Support Zero-Emission Vehicles in 2030”. July 2021. Available online: https://www.energy.ca.gov/programs-and-topics/programs/electric-vehicle-charging-infrastructure-assessment-ab-2127.

[585] Business Wire. “SDG&E and Cajon Valley Union School District Flip the Switch on Region’s First Vehicle-to-Grid Project Featuring Local Electric School Buses Capable of Sending Power to the Grid”. July 26, 2022. Available online: https://www.businesswire.com/news/home/20220726006137/en/SDGE-and-Cajon-Valley-Union-School-District-Flip-the-Switch-on-Region%E2%80%99s-First-Vehicle-to-Grid-Project-Featuring-Local-Electric-School-Buses-Capable-of-Sending-Power-to-the-Grid

Multi-State Transportation Electrification Impact Study (TEIS)[586] estimates the potential costs and benefits associated with electrical distribution system upgrades that may incur as a result of BEV demand resulting from this final rule in addition to demand from the LMDV rule. The TEIS reflects very significant reductions in peak demand (including an actual reduction in peak demand in some states between a no action case and a case reflecting GHG standards for both the LMHD and HDV sectors) even if only minimal managed charging techniques are utilized.[587]

1.6.5 Power Distribution

In addition to the infrastructure (EVSE and ports) needed for charging, some amount of supporting electrification infrastructure between a transmission line and the EVSE may be needed (see Figure 1-17). As discussed in Chapter 2.6.4, significant (and localized) increases in load from charging stations could, in some cases, require upgrades to the electricity distribution system. In general, such upgrades will be needed if the station power needs exceed the existing capacity on the system (or hosting capacity). This could include additional transformers, feeders, and new or upgraded substations. How much these upgrades cost and how long they take to implement will depend on the charging load.

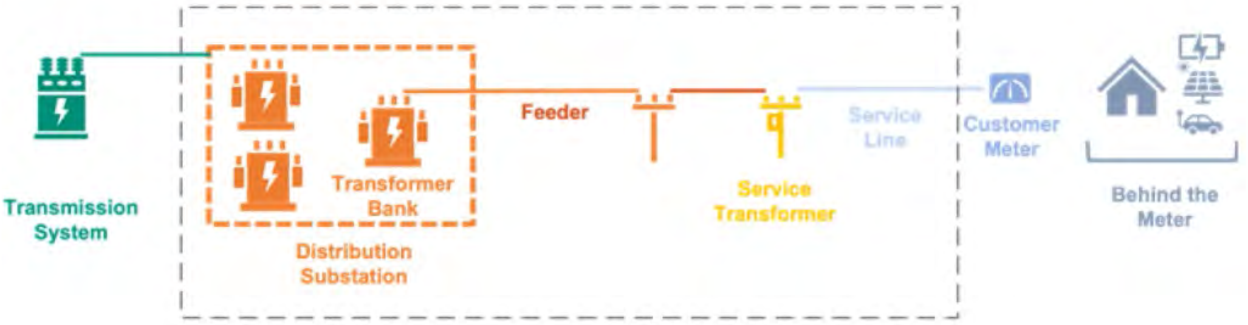

Figure 1-17 Electricity power distribution infrastructure is shown above and is that portion of the grid between the transmission system and the customer meter. Charging infrastructure for HD BEV is behind the meter. (Source: Kevala, as seen in TEIS)[588]

While needs will be site specific, one recent study (Borlaug et al. 2021) estimated that loads of just 200 kW or higher could trigger the need for an onsite distribution transformer, which could take three to eight months to deploy.[589] New charging loads of several megawatts or higher—likely only relevant for stations with many high-power DCFC unit ports, and especially

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[586] National Renewable Energy Laboratory, Lawrence Berkeley National Laboratory, Kevala Inc., and U.S. Department of Energy. "Multi-State Transportation Electrification Impact Study: Preparing the Grid for Light-, Medium-, and Heavy-Duty Electric Vehicles". DOE/EE-2818. U.S. Department of Energy. March 2024.

[587] See, e.g., TEIS at 62.

[588] National Renewable Energy Laboratory, Lawrence Berkeley National Laboratory, Kevala Inc., and U.S. Department of Energy. "Multi-State Transportation Electrification Impact Study: Preparing the Grid for Light-, Medium-, and Heavy-Duty Electric Vehicles". DOE/EE-2818. U.S. Department of Energy. March 2024 .

[588] National Renewable Energy Laboratory, Lawrence Berkeley National Laboratory, Kevala Inc., and U.S. Department of Energy. "Multi-State Transportation Electrification Impact Study: Preparing the Grid for Light-, Medium-, and Heavy-Duty Electric Vehicles". DOE/EE-2818. U.S. Department of Energy. March 2024.

[589] Borlaug, B., Muratori, M., Gilleran, M. et al. "Heavy-duty truck electrification and the impacts of depot charging on electricity distribution systems". Nat Energy 6, 673–682 (2021). Available online: https://www.nature.com/articles/s41560-021-00855-0.

for public stations where HD BEVs may require immediate charging—could require more significant distribution system upgrades such as those to feeder circuits, breakers, or, in certain situations, new substations. Borlaug et al. 2021 found that such upgrades could take months to several years to implement.[590]

An EPRI survey of distribution utilities with 18 respondents from different areas of the country found significant variation in the lead time needed for distribution upgrades, e.g., ranging from 18 months to 10 years for a new substation, though EPRI identified typical timeframes from the most common responses.[591] EPRI asked respondents to estimate the distribution component work usually required for various load sizes and, separately, to estimate typical interconnection times when these upgrades are needed. Taken together, EPRI found up to a year of lead time may be typical for 1 MW of new load and one to two years for 5 MW. Larger loads of 10 MW or 20 MW were associated with longer typical lead times of two to three and three to five years, respectively. However, as previously discussed, upgrades are not required if sufficient hosting capacity exists. In these cases, the EPRI survey found the typical interconnection time was under six months.[592] EPRI continues to work with utilities, fleet operators, manufacturers, and charging providers through their EVs2Scale initiative.[593]

Table 1-28 shows a summary of cost and timing estimates for distribution component upgrades or buildout in Borlaug et. al. 2021, the EPRI survey, and a recent ICCT study (Basma et al. 2023). These reports have different scopes, assumptions and methods. Borlaug et al. 2021 assessed distribution upgrades for depot stations, Basma et al. 2023 modeled charging costs associated with 20 MW public charging stations designed to serve class 8 long-haul trucks, and EPRI estimated typical lead times by surveying distribution utilities. Therefore, estimates shown may not be directly comparable. As discussed in Chapter 2.4, we accounted for distribution upgrade costs in final rule analysis, informed by Basma et al. 2023.

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[590] Ibid.

[591] EPRI. "EVs2Scale2030™ Grid Primer". August 29, 2023 Available online: https://www.epri.com/research/products/000000003002028010

[592] Ibid.

[593] EPRI. "EVs2Scale2030". Accessed February 26, 2024. Available Online: https://msites.epri.com/evs2scale2030

Table 1-28 Examples of distribution upgrade costs and lead times from the literature[594]

Component	ICCT (Basma et al. 2023)[595]	Borlaug et al. 2021[596]	EPRI[597,598]
New Substation	NA	$4–35M	
		24–48 months	36–60 months
Substation Upgrade	$3.1M[599]	$3–5M[600]	
		12–18 months	24–36 months
New/Upgraded Feeder	$0.9M	$2–12M	
		3–12 months	12–24 months (new) 6–12 months (upgraded)
Transformer	$0.6M	< $0.2M	NA
		3–8 months	

As described in RIA Chapter 2.10.3, we estimated the total number of EVSE ports that will be required to support the depot-charged BEVs in the potential compliance pathway's technology packages developed to support the MY 2027–2032 standards. We estimated approximately 520,000 EVSE ports will be needed across all six model years. The majority (88 percent) of these are Level 2 ports, followed by low-power DCFCs. It would take about fifty Level 2 (19.2 kW) EVSE ports or twenty DC-50 kW ports at a depot to generate 1 MW of additional (localized) load. As noted above, EPRI suggested the typical lead time for distribution upgrades at this level is up to a year. As seen in Table 1-28, the longest lead times are typically associated with the need for a new substation or upgrades to an existing substation. These upgrades are most likely to be needed at stations with many high-power DCFC ports (such as the 20 MW public stations modeled in Basma et al. 2023)—if the stations are sited in areas without sufficient capacity and without measures to mitigate the charging load. However, as described in detail in RTC 7 (Distribution), we project that only a handful of substation upgrades nationwide would be needed by 2032 to accommodate demand posed by the Phase 3 rule (assuming compliance via the potential compliance pathway modelled to support feasibility of the Phase 3 standards).

We discuss in preamble II.D.2.c.iii and RTC section 7 (Distribution) the potential demand posed by a HDV Phase 3 rule at the national, regional, and parcel level, including estimates of the amount of distribution grid buildout (i.e. transformers, feeders, and substations (both upgraded and new)) that could be needed within the Phase 3 rule's 2027-2032 timeframe.

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[594] See reports for more details on these estimates. Costs for metering are not shown above.

[595] Basma, Hussein. "Total Cost of Ownership of Alternative Powertrain Technologies for Class 8 Long-Haul Trucks in the United States". ICCT. 2023 Available online: https://theicct.org/publication/tco-alt-powertrain-long-haul-trucks-us-apr23/.

[596] Borlaug, B., Muratori, M., Gilleran, M. et al. "Heavy-duty truck electrification and the impacts of depot charging on electricity distribution systems". Nat Energy 6, 673–682 (2021). Available online: https://www.nature.com/articles/s41560-021-00855-0.

[597] As noted above, respondents of the EPRI survey provided a range of responses. In the table above, the most common interconnection time range selected by respondents is shown.

[598] EPRI. "EVs2Scale2030TM Grid Primer". August 29, 2023 Available online: https://www.epri.com/research/products/000000003002028010

[599] Includes $2M for a substation transformer and $1.1M for "feeders, tie, and transfer switches".

[600] A separate estimate of $0.4 M and 6–12 months was provided for adding a feeder breaker to a substation.

If distribution grid buildout is needed, then there are ways to minimize its extent, timing, and cost. A report by the Interstate Renewable Energy Council identified such utility coordination as an emerging best practice to help streamline station deployments. The report also highlighted the potential value of utilities providing hosting capacity maps (HCMs) that identify grid capacity constraints.[601] As of mid-2022, requirements for HCMs or related analyses were in place in ten states identified by Lawrence Berkeley National Laboratory.[602] While the specific requirements and contents of HCMs vary, where applicable, such maps could help station developers determine whether area feeders or substations have sufficient additional capacity for charging or other loads. As of January 2024, utilities offer 39 unique maps covering 24 states and the District of Columbia.[603] Should a new facility be involved, distribution system capacity and interconnection can be factored into the site selection process[604] and, when possible, utilities can work with station developers to evaluate multiple potential sites before a selection is made.[605]

One Energy is minimizing distribution upgrade costs at their recently energized 30 MW site in Findlay, Ohio (mentioned in Chapter 1.6.2.2). The Findlay Megawatt Hub is served by a 138,000 volt transmission line. The readily available power allows One Energy to target deployment of high-capacity charging equipment in months rather than years.[606] Station placement is optimized by locating where hosting capacity exists and thereby keeping power distribution infrastructure costs down.

Many of the actions that reduce peak loads and energy generation needs (discussed in 1.6.4 above) also minimize user costs, and at the same time, can reduce the extent of distribution buildout required. Some of the actions minimize upfront distribution system buildout cost and timing while other actions align power use with cheap and plentiful energy for ongoing operational savings. For example, managed charging covers a range of actions with varying degrees of complexity. Time of use (TOU) charges may motivate users to charge when power is plentiful and less expensive. Charging at lower power levels (e.g., 50 kW rather than 350 kW) is another way to reduce the instantaneous power demand on the grid while helping the user save on "demand charges", the maximum power level demanded over a given month (discussed in Chapter 1.6.2.4). As noted in a report by the California Energy Commission, managed or smart charging could also enable increasing renewable use if charging load is shifted to times with

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[601] Hernandez, Mari. IREC "Paving the Way Emerging Best Practices for Electric Vehicle Charger Interconnection". June 2022. Available online: https://irecusa.org/wp-content/uploads/2022/06/EV-Paper-3-Charger-Interconnection_compressed.pdf.

[602] Schwartz, Lisa. "State Regulatory Approaches for Distribution Planning". National Association of State Utility Consumer Advocates 2022 Mid-Year Meeting. June 14, 2022. Available online: https://www.nasuca.org/wp-content/uploads/2021/10/NASUCA-Schwartz-distribution-planning-20220610.pdf.

[603] U.S. Department of Energy. "U.S. Atlas of Electric Distribution System Hosting Capacity Maps". Accessed March 2024. Available online: https://www.energy.gov/eere/us-atlas-electric-distribution-system-hosting-capacity-maps.

[604] Pournazeri, Sam. "Criteria to consider when siting EV charging infrastructure for medium- and heavy-duty vehicles". ICF. April 28, 2022. Available online: https://www.icf.com/insights/transportation/medium-heavy-duty-ev-charging.

[605] Hernandez, Mari. IREC "Paving the Way Emerging Best Practices for Electric Vehicle Charger Interconnection". June 2022. Available online: https://irecusa.org/wp-content/uploads/2022/06/EV-Paper-3-Charger-Interconnection_compressed.pdf.

[606] Truckinginfo. "Megawatt Truck Charging Hub in Ohio". October 12, 2023. Available online: https://www.truckinginfo.com/10207881/megawatt-truck-charging-hub-opens-in-ohio

excess solar or wind power that might otherwise be curtailed.[607] Companies like Octopus Energy have developed systems and apps that help customers align their BEV charging with wind and solar energy when it is cheap and, and at the same time, plentiful.[608] The service was launched in Texas in 2023.[609] Onsite battery storage, if deployed at charging stations, could also reduce potential grid impacts by optimizing when power is drawn from the grid while still providing power to vehicles when needed. FreeWire is one example of a company offering charging solutions that combine stationary batteries with chargers. This FreeWire technology allows users to charge the unit's 160 kWh battery slowly when electric rates are low and then charge the BEV from the unit (not grid) at 200 kW when convenient.[610] Because the unit charges at low power, infrastructure costs and time to install may be reduced.

Other strategies could help station developers accommodate BEV charging demand for a selected site. For example, automated load management or power control systems are being explored as a way to dynamically limit total charging load and ensure it doesn't exceed available capacity[611]—potentially reducing the need for some distribution upgrades. As noted above, the use of onsite battery storage, managed charging, as well as onsite renewable generation may also be able to reduce demand on the grid; some station operators may also opt for these technologies to mitigate demand charges associated with peak power.[612] The virtual power plant (VPP) is an extension of this strategy. The VPP replaces historical electrical power generation, transmission, and distribution with aggregations of distributed energy resources (DER). The DER tend to use renewable sources like solar and wind that are spread through the network for their power source. Since continuity is not ensured with solar and wind, stationary batteries (and even available BEV) absorb excess electricity generation and store it for future use. When charging loads (from BEV or other electricity users) exceed the power generated at any point in time, the battery energy (stationary or even from available BEV) is deployed. The power generation systems communicate with the storage and user systems to ensure utility grade service.[613]

Finally, we note that innovative or alternative charging options could reduce costs and deployment time in some situations. Some of the options shared below allow the HD BEV user to immediately deploy charging resources without the need for distribution upgrades or interconnection to the grid. For example, as discussed in Chapter 1.6.2.2, some companies plan to use mobile charging units while stations are being deployed so BEVs can be incorporated into

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[607] Alexander, Matt et al. California Energy Commission. "Assembly Bill 2127 Electric Vehicle Charging Infrastructure Assessment Analyzing Charging Needs to Support Zero-Emission Vehicles in 2030". July 2021. Available online: https://www.energy.ca.gov/programs-and-topics/programs/electric-vehicle-charging-infrastructure-assessment-ab-2127.

[608] HD use is not yet reflected in this app.

[609] Octopus Energy. "Unlock the cheapest energy rates with smart features from Octopus Energy". Available online: https://octopusenergy.com/smart-features

[610] Freewire. "Boost Charger 200 - FreeWire's most powerful and flexible solution in ultrafast EV charging". Accessed November 11, 2023. Available online: https://freewiretech.com/dc-boost-charger-200/

[611] Nuvve and Enel X. "BRIEF – Automated Load Management for EVSE Interconnection". July 14, 2020. Available online: https://docs.cpuc.ca.gov/PublishedDocs/Efile/G000/M354/K191/354191323.PDF.

[612] Alexander, Matt et al. California Energy Commission. "Assembly Bill 2127 Electric Vehicle Charging Infrastructure Assessment Analyzing Charging Needs to Support Zero-Emission Vehicles in 2030". July 2021. Available online: https://www.energy.ca.gov/programs-and-topics/programs/electric-vehicle-charging-infrastructure-assessment-ab-2127.

[613] Downing, Jennifer, et al. "Pathways to Commercial Liftoff: Virtual Power Plants". September 2023. Available online: https://liftoff.energy.gov/wp-content/uploads/2023/10/LIFTOFF_DOE_VVP_10062023_v4.pdf

the fleet without waiting for EVSE installation and utility interconnection. Mobile charging units (and on-demand mobile charging services) are available at a variety of power levels and configurations (e.g., the dual port Mobi EV charger by FreeWire Technologies provides AC power up to 11 kW[614] while Lightning eMotors offers units with five 80 kW DCFC ports.[615]) Mobile charging units could also be a potential solution for locations in which it is challenging or costly to make upgrades needed to install EVSE ports,[616] as they can be recharged at locations (and times) with sufficient capacity. Standalone charging canopies with integrated solar cells and battery storage that don't need to be connected to the grid may be an option for remote or other locations where it is costly or difficult to install EVSE.[617] Integrated distributed generation and storage such as PV-integrated charging (i.e., off-grid solar),[618] linear generators,[619,620] and fuel cells[621] can potentially offer additional support.[622]

1.7 Fuel Cell Electric Vehicle Technology

Fuel cell technologies that run on hydrogen have been in existence for decades, though they are just starting to enter the heavy-duty transportation market. Hydrogen fuel cell electric vehicles (FCEVs) are similar to BEVs in that they have batteries and use an electric motor instead of an internal combustion engine to power the wheels. Unlike BEVs that need to be plugged in to recharge, FCEVs have fuel cell stacks that use a chemical reaction involving hydrogen to generate electricity. Fuel cells with electric motors are more efficient than ICEs that run on gasoline or diesel, requiring less energy to fuel.[623]

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[614] FreeWire Technologies. “Mobi EV Charger Data Sheet”. 2023 Available online: https://freewiretech.com/products/mobi-ev/.

[615] Lightning eMotors. “Lightning energy Lightning Mobile Go anywhere power for a go anywhere world.” January 2023. Available online: https://lightningemotors.com/wp-content/uploads/2023/01/LE_Lightning_Mobile_sheet_Jan2023_v1_online.pdf.

[616] Alexander, Matt et al. California Energy Commission. “Assembly Bill 2127 Electric Vehicle Charging Infrastructure Assessment Analyzing Charging Needs to Support Zero-Emission Vehicles in 2030”. July 2021. Available online: https://www.energy.ca.gov/programs-and-topics/programs/electric-vehicle-charging-infrastructure-assessment-ab-2127.

[617] Morris, Charles. “Solar-powered off-grid EV charging stations offer surprisingly attractive cost advantages”. Charged EV Fleet & Infrastructure News. December 13, 2022. Available online: https://chargedevs.com/features/solar-powered-off-grid-ev-charging-stations-offer-surprisingly-attractive-cost-advantages/.

[618] U.S. Department of Energy, Solar Energy Technologies Office. “Federal Solar Tax Credits for Businesses”. Available online: https://www.energy.gov/eere/solar/federal-solar-tax-credits-businesses.

[619] Mainspring. “Local power generation for the zero carbon future”. Available online: https://www.mainspringenergy.com/.

[620] Sandridge, Breanna. “DOE Funding GM Pilot Program to Demonstrate Real-Life Applications of Fuel Cells for Fleet and Commercial Customers”. EnergyTech. March 8, 2024. Available online: https://www.energytech.com/emobility/article/21284243/doe-funding-gm-pilot-program-to-demonstrate-real-life-applications-of-fuel-cells-for-fleet-and-commercial-customers.

[621] U.S. Department of Energy. “The #H2IQ Hour. Today’s Topic: Caterpillar Hydrogen Fuel Cell Generator Backup System”. March 2024. Available online: https://www.energy.gov/sites/default/files/2024-03/h2iqhour-02232024.pdf.

[622] ANL. Innovative Charging Solutions for Deploying the National Charging Network: Technoeconomic Analysis. March 2024.

[623] U.S. Department of Energy, Alternative Fuels Data Center. “Hydrogen Basics”. Available online: https://afdc.energy.gov/fuels/hydrogen_basics.html.

Hydrogen FCEVs are considered in the modeled potential compliance pathway due to several factors. They do not emit air pollution at the tailpipe—only heat and pure water.[624] With current and near-future technologies, energy can be stored more densely onboard a vehicle as gaseous or liquid hydrogen than it can as electrons in a battery, which enables longer ranges. HD FCEVs can package more energy onboard with less weight than batteries in today's BEVs, which allows for their potential use in HD sectors that are difficult for BEV technologies due to payload impacts. HD FCEVs also have rapid refueling times.[625]

The following sections discuss key technology components unique to heavy-duty FCEVs.

1.7.1 Fuel Cell System

A fuel cell stack is a module that may contain hundreds of fuel cell units that generate electricity, typically combined in series.[626] A heavy-duty FCEV may have several fuel cell stacks to meet the power needs of a comparable ICE vehicle. A fuel cell system includes the fuel cell stacks and "balance of plant" (BOP) components (e.g., pumps, sensors, compressors, humidifiers) that support the fuel cell operations.

Though there are many types of fuel cell technologies, polymer electrolyte membrane (PEM) fuel cells are typically used in transportation applications because they offer high power density, and therefore have low weight and volume. They can operate at relatively low temperatures, which allows them to start quickly.[627] PEM fuel cells are built using membrane electrode assemblies (MEA) and supportive hardware. The MEA includes the PEM electrolyte material, catalyst layers (anode and cathode), and gas diffusion layers.[628] Hydrogen fuel and oxygen enter the MEA and chemically react to generate electricity, which is either used to propel the vehicle or stored in a battery to meet future power needs. The process creates excess water vapor and heat.

Key BOP components include the air supply system that provides oxygen, the hydrogen supply system, and the thermal management system. With the help of compressors and sensors, these components monitor and regulate the pressure and flow of the gases supplied to the fuel cell along with relative humidity and temperature. Similar to ICEs and batteries, PEM fuel cells require thermal management systems to control the operating temperatures. It is necessary to control operating temperatures to maintain stack voltage and the efficiency and performance of the system. There are different strategies to mitigate excess heat that comes from operating a fuel cell. For example, a HD vehicle may include a cooling system that circulates cooling fluid through the stack.[629] As the fuel cell ages and becomes less efficient, more waste heat will be generated that requires removal. A cooling system may be designed to accommodate end-of-life

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[624] U.S. Department of Energy, Fuel Cell Technologies Office. "Fuel Cells". November 2015. Available online: https://www.energy.gov/sites/prod/files/2015/11/f27/fcto_fuel_cells_fact_sheet.pdf.

[625] U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office. "The #H2IQ Hour: Heavy-Duty Vehicle Decarbonization". September 21, 2023. Available online: https://www.energy.gov/sites/default/files/2023-10/h2iqhour-09212023.pdf.

[626] U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office. "Fuel Cell Systems". Available online: https://www.energy.gov/eere/fuelcells/fuel-cell-systems.

[627] U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office. "Types of Fuel Cells". Available online: https://www.energy.gov/eere/fuelcells/types-fuel-cells.

[628] U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office. "Parts of a Fuel Cell". Available online: https://www.energy.gov/eere/fuelcells/parts-fuel-cell.

[629] Hyfindr. "Fuel Cell Stack". Available online: https://hyfindr.com/fuel-cell-stack/.

needs, which can be up to two times greater than they are at the beginning of life.[630] Waste heat recovery solutions are also emerging.[631] The excess heat also can in turn be used to heat the cabin, similar to ICE vehicles. Power consumed to operate BOP components can also impact the fuel cell system's overall efficiency.[632,633]

Oxygen (O_2) from the air enters the positive electrode (cathode) of the cell and hydrogen gas (H_2) enters the negative electrode (anode). A catalyst separates the hydrogen molecules in the fuel into protons and electrons. The electrons create a direct flow of electricity. The protons flow through the electrolyte membrane and create excess water vapor, which is purged along with any contaminants. The electrochemical reaction also produced heat, which must be effectively managed.[634] To improve fuel cell performance, the air and hydrogen fuel that enter the system may be compressed, humidified, and/or filtered.[635] A fuel cell operates best when the air and the hydrogen are free of contaminants, since contaminants can poison and damage the catalyst. PEM fuel cells require hydrogen that is over 99 percent pure, which can add to the fuel production cost.[636,637] Hydrogen produced from natural gas tends to initially have more impurities (e.g., carbon monoxide and ammonia, associated with the reforming of hydrocarbons) than hydrogen produced from water through electrolysis.[638] There are standards such as ISO 14687 that include hydrogen fuel quality specifications for use in vehicles to minimize impurities.[639]

Fuel cell durability is important in heavy-duty applications, given that vehicle owners and operators often have high expectations for drivetrain lifetimes in terms of years, hours, and miles. Fuel cells can be designed to meet durability needs (i.e., the ability of the stack to maintain its performance over time). Considerations must be included in the design to accommodate operations in less-than-optimized conditions. For example, prolonged operation at

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[630] Pardhi, Shantanu, et. al. "A Review of Fuel Cell Powertrains for Long-Haul Heavy-Duty Vehicles: Technology, Hydrogen, Energy and Thermal Management Systems". Energies 15(24). December 2022. Available online: https://www.mdpi.com/1996-1073/15/24/9557.

[631] Baroutaji, Ahmad, et. al. "Advancements and prospects of thermal management and waste heat recovery of PEMFC". International Journal of Thermofluids: Volume 9. February 2021. Available online: https://www.sciencedirect.com/science/article/pii/S2666202721000021.

[632] Hoeflinger, Johannes and Peter Hofmann. "Air mass flow and pressure optimization of a PEM fuel cell range extender system". International Journal of Hydrogen Energy. Volume 45:53. October 30, 2020. Available online: https://www.sciencedirect.com/science/article/pii/S0360319920327841.

[633] Pardhi, Shantanu, et. al. "A Review of Fuel Cell Powertrains for Long-Haul Heavy-Duty Vehicles: Technology, Hydrogen, Energy and Thermal Management Systems". Energies 15(24). December 2022. Available online: https://www.mdpi.com/1996-1073/15/24/9557.

[634] U.S .Environmental Protection Agency. "Assessment of Fuel Cell Technologies at Ports". Prepared for EPA by Eastern Research Group, Inc. EPA-420-R-22-013. July 2022. Available online: https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P1015AQX.pdf.

[635] U.S .Environmental Protection Agency. "Assessment of Fuel Cell Technologies at Ports". Prepared for EPA by Eastern Research Group, Inc. EPA-420-R-22-013. July 2022. Available online: https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P1015AQX.pdf.

[636] Hyfindr. "Hydrogen PEM Fuel Cell". Available online: https://hyfindr.com/pem-fuel-cell/.

[637] U.S. DRIVE Partnership. "Hydrogen Production Tech Team Roadmap". U.S. Department of Energy. November 2017. Available online: https://www.energy.gov/eere/vehicles/articles/us-drive-hydrogen-production-technical-team-roadmap.

[638] Nguyen, Huu Linh, et. al. "Review of the Durability of Polymer Electrolyte Membrane Fuel Cell in Long-Term Operation: Main Influencing Parameters and Testing Protocols". Energies 14(13). July 2021. Available online: https://www.mdpi.com/1996-1073/14/13/4048.

[639] International Organization for Standardization. "ISO 14687: 2019, Hydrogen fuel quality—Product specification". November 2019. Available online: https://www.iso.org/standard/69539.html.

high voltage (low power) or when there are multiple transitions between high and low voltage can stress the system. As a fuel cell system ages, a fuel cell's MEA materials can degrade, and performance and maximum power output can decline. The fuel cell can become less efficient, which can cause it to generate more excess heat and consume more fuel.[640] DOE's ultimate long-term technology target for Class 8 HD trucks is a fuel cell lifetime of 30,000 hours, corresponding to an expected vehicle lifetime of 1.2 million miles.[641] A voltage degradation of 10 percent at rated power by end-of-life is considered by DOE when evaluating targets.

Currently, the fuel cell stack is the most expensive component of a heavy-duty FCEV,[642] which is the most expensive part of a heavy-duty FCEV, primarily due to the technological requirements of manufacturing rather than raw material costs.[643] Larger production volumes are anticipated as global demand increases for fuel cell systems for HD vehicles, which could improve economies of scale. Durability improvements are anticipated to also result in decreased operating costs, as they could extend the life of fuel cells and reduce the need for parts replacement.[644] Fuel cells contain PEM catalysts that typically are made using precious metals from the platinum group, which are expensive but efficient and can withstand conditions in a cell.

The U.S. Geological Survey's 2022 list of critical minerals includes platinum (as one of several platinum group metals, or PGMs), as used in catalytic converters. Critical minerals are defined in the Energy Act of 2020 as being essential to the economic or national security of the U.S. and vulnerable to supply chain disruption.[645] DOE's 2023 Critical Materials Assessment, performed independently from a global perspective and focused on the importance of materials to clean energy technologies in future years, identifies PGMs used in hydrogen electrolyzers such as platinum and iridium as critical. They screened out PGMs used in catalytic converters, such as rhodium and palladium. This distinction was made due to the increased focus on hydrogen technologies, including long-distance HD trucks, to achieve carbon emissions

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[640] Nhuyen, Huu Linh, et. al. "Review of the Durability of Polymer Electrolyte Membrane Fuel Cell in Long-Term Operation: Main Influencing Parameters and Testing Protocols". Energies 14(13). July 2021. Available online: https://www.mdpi.com/1996-1073/14/13/4048.

[641] Marcinkoski, Jason et. al. "Hydrogen Class 8 Long Haul Truck Targets". U.S. Department of Energy. October 31, 2019. Available online: https://www.hydrogen.energy.gov/pdfs/19006_hydrogen_class8_long_haul_truck_targets.pdf.

[642] Papageorgopoulos, Dimitrios. "Fuel Cell Technologies Overview". U.S. Department of Energy. June 6, 2023. Available online: https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/review23/fc000_papageorgopoulos_2023_o.pdf.

[643] Deloitte China and Ballard. "Fueling the Future of Mobility: Hydrogen and fuel cell solutions for transportation, Volume 1". 2020. Available online: https://www2.deloitte.com/content/dam/Deloitte/cn/Documents/finance/deloitte-cn-fueling-the-future-of-mobility-en-200101.pdf.

[644] Deloitte China and Ballard. "Fueling the Future of Mobility: Hydrogen and fuel cell solutions for transportation, Volume 1". 2020. Available online: https://www2.deloitte.com/content/dam/Deloitte/cn/Documents/finance/deloitte-cn-fueling-the-future-of-mobility-en-200101.pdf.

[645] 87 FR 10381. "2022 Final List of Critical Minerals". U.S. Geological Survey. February 24, 2022. Available online: https://www.federalregister.gov/documents/2022/02/24/2022-04027/2022-final-list-of-critical-minerals.

reductions, and an anticipated decrease in the importance of catalytic converters in the medium term (i.e., the 2025 to 2035 timeframe).[646]

Efforts are underway to minimize or eliminate the use of platinum in catalysts.[647] DOE issued a Funding Opportunity Announcement (FOA) in 2023 in anticipation of growth in hydrogen and fuel cell technologies and systems. A portion of the FOA is designed to enable improvements in recovery and recycling, and applicants are encouraged to find ways to reduce or eliminate PGMs from catalysts in both PEM fuel cells and electrolyzers to reduce reliance on virgin feedstocks.[648]

1.7.2 Fuel Cell and Battery Interaction

The instantaneous power required to move a FCEV can come from either the fuel cell, the battery, or a combination of both. Interactions between the fuel cells and batteries of a FCEV can be complex and may vary based on application. Each manufacturer likely will employ a unique strategy to optimize the durability of these components and manage costs. The strategy selected will impact the size of the fuel cell and the size of the battery.

The fuel cell can be used to charge the battery that in turn powers the wheels (series hybrid or range-extending), or it can work with the battery to provide power (parallel hybrid or primary power) to the wheels. In the emerging HD FCEV market, when used to extend range, the fuel cell tends to have a lower peak power potential and may be sized to match the average power needed during a typical use cycle, including steady highway driving. At idle, the fuel cell may run at minimal power or turn off based on state of charge of the battery. The battery is used during prolonged high-power operations such as grade climbing and is typically in charge-sustaining mode, which means the average state of charge is maintained above a certain level while driving. When providing primary power, the fuel cell tends to have a larger peak power potential, sized to match all power needs of a typical duty cycle and to meet instantaneous power needs. The battery is mainly used to capture energy from regenerative braking and to help with acceleration and other transient power demands.[649]

Based on how the fuel cell stacks and batteries are managed, manufacturers may use different types of batteries in HD FCEVs. Energy battery cells are typically used to store energy for applications with distance needs=. Power battery cells are typically used to provide additional high power for applications with high power needs.[650]

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[646] U.S. Department of Energy. “Critical Materials Assessment”. July 2023. Available online: https://www.energy.gov/sites/default/files/2023-07/doe-critical-material-assessment_07312023.pdf.

[647] Berkeley Lab. “Strategies for Reducing Platinum Waste in Fuel Cells. November 2021. Available online: https://als.lbl.gov/strategies-for-reducing-platinum-waste-in-fuel-cells/.

[648] U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office. “Bipartisan Infrastructure Law: Clean Hydrogen Electrolysis, Manufacturjng, and Recycling: Funding Opportunity Announcement Number DE-FOA-0002922”. March 15, 2023 (Last Updated: March 31, 2023). Available online: https://eere-exchange.energy.gov/Default.aspx#FoaIda9a89bda-618a-4f13-83f4-9b9b418c04dc.

[649] Islam, Ehsan Sabri, Ram Vijayagopal, Aymeric Rousseau. “A Comprehensive Simulation Study to Evaluate Future Vehicle Energy and Cost Reduction Potential”. Report to the U.S. Department of Energy, Contract ANL/ESD-22/6. October 2022. Available online: https://anl.app.box.com/s/an4nx0v2xpudxtpsnkhd5peimzu4j1hk/file/1406494585829.

[650] Sharpe, Ben and Hussein Basma. “A Meta-Study of Purchase Costs for Zero-Emission Trucks”. International Council on Clean Transportation. February 2022. Available online: https://theicct.org/publication/purchase-cost-ze-trucks-feb22/.

1.7.3 Onboard Hydrogen Storage Tanks

Fuel cell vehicles carry hydrogen fuel onboard using multiple large tanks. Hydrogen has high gravimetric density (amount of energy stored per unit of mass) but extremely low volumetric density (amount of energy stored per volume) so it must be compressed or liquified for use. There are various techniques for storing hydrogen onboard a vehicle, depending on how much fuel is needed to meet range requirements. Most transportation applications today use Type IV tanks,[651] which typically include a plastic liner wrapped with a composite material such as carbon fiber that can withstand high pressures with minimal weight.[652,653] High-strength carbon fiber accounts for over 50 percent of the cost of a Type IV onboard storage system at production volumes of over 100,000 systems per year.[654]

Some existing fuel cell buses use compressed hydrogen gas at 350 bars (~5,000 pounds per square inch, or psi) of pressure, but other applications are using tanks with increased compressed hydrogen gas pressure at 700 bar (~10,000 psi) for extended driving range.[655] A Heavy-Duty Vehicle Industry Group was formed in 2019 to standardize 700 bar high-flow fueling hardware components globally that meet fueling speed requirements (i.e. so that fill times are similar to comparable HD ICE vehicles, as identified in DOE technical targets for Class 8 long-haul tractor-trailers).[656] High-flow refueling rates for heavy-duty vehicles of 60 to 80 kg hydrogen in under 10 minutes were recently demonstrated in a DOE lab setting.[657,658,659]

As we stated in the NPRM, geometry and packing challenges may constrain the amount of gaseous hydrogen that can be stored onboard and, thus, the maximum range of trucks that travel

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[651] Type I-III tanks are not typically used in transportation for reasons related to low hydrogen density, metal embrittlement, weight, or cost.

[652] Langmi, Henrietta et. al. “Hydrogen storage”. Electrochemical Power Sources: Fundamentals, Systems, and Applications. 2022. Portion available online: https://www.sciencedirect.com/topics/engineering/compressed-hydrogen-storage#:~:text=There%20are%20four%20standard%20types,cylinders%20with%20nonload%20bearing%20nonmetallic.

[653] U.S. Department of Energy, Fuel Cell Technologies Office. “Hydrogen Storage”. March 2017. Available online: https://www.energy.gov/sites/prod/files/2017/03/f34/fcto-h2-storage-fact-sheet.pdf.

[654] Houchins, Cassidy and Brian D. James. “2019 DOE Hydrogen and Fuel Cell Program Review: Hydrogen Storage Cost Analysis”. Strategic Analysis. May 2019. Available online: https://www.hydrogen.energy.gov/pdfs/review19/st100_james_2019_o.pdf.

[655] Basma, Hussein and Felipe Rodriquez. “Fuel cell electric tractor-trailers: Technology overview and fuel economy”. Working Paper 2022-23. International Council on Clean Transportation. July 2022. Available online: https://theicct.org/wp-content/uploads/2022/07/fuel-cell-tractor-trailer-tech-fuel-jul22.pdf.

[656] NextEnergy. “Hydrogen Heavy Duty Vehicle Industry Group to Standardize Hydrogen Refueling, Bringing Hydrogen Closer to Wide Scale Adoption”. October 8, 2021. Available online: https://nextenergy.org/hydrogen-heavy-duty-vehicle-industry-group-partners-to-standardize-hydrogen-refueling/.

[657] DOE suggests that 60 kg of H2 will be required to achieve a 750-mile range in a Class 8 tractor-trailer truck, assuming a fuel economy of 12.4 miles per kilogram. In the DOE lab, one fill (61.5 kg) was demonstrated from the fueling station into seven type-IV tanks of a HD vehicle simulator, and the second fill (75.9 kg) was demonstrated from the station into nine tanks.

[658] Marcinkoski, Jason et. al. “Hydrogen Class 8 Long Haul Truck Targets”. U.S. Department of Energy. October 31, 2019. Available online: https://www.hydrogen.energy.gov/pdfs/19006_hydrogen_class8_long_haul_truck_targets.pdf.

[659] Martineau, Rebecca. “Fast Flow Future for Heavy-Duty Hydrogen Trucks: Expanded Capabilities at NREL Demonstration High-Flow-Rate Hydrogen Fueling for Heavy-Duty Applications”. National Renewable Energy Lab. June 2022. Available online: https://www.nrel.gov/news/program/2022/fast-flow-future-heavy-duty-hydrogen-trucks.html.

longer distances without a stop for fuel.[660] Liquid hydrogen is emerging as a cost-effective onboard storage option for long-haul operations; however, the technology readiness of liquid storage and refueling technologies is still relatively low compared to compressed gas technologies.[661,662] Therefore, given our assessment of technology readiness, liquid storage tanks were not included in the potential compliance pathway that supports the feasibility and appropriateness of our standards.

Liquid hydrogen requires cryogenic storage at temperatures reaching -253 degrees Celsius at atmospheric pressure. Preparing hydrogen for storage as a liquid is more energy intensive than gaseous storage. For example, compression and cooling can require 10 kWh of energy per kg of hydrogen for liquid, compared to 3 to 5 kWh per kg of hydrogen for 700 bar compressed hydrogen and 2 kWh per kg hydrogen for 350 bar.[663,664] Nonetheless, companies like Daimler and Hyzon are pursuing onboard liquid hydrogen to minimize potential payload impacts and maintain the flexibility to drive up to 1,000 miles between refueling, comparable to today's diesel ICE vehicle refueling ranges.[665,666]

Cryo-compressed hydrogen, a hybrid storage system option that combines compressed hydrogen gas and liquid hydrogen, is under development but is even less ready for commercialization than liquid hydrogen.[667]

In the NPRM, we requested comment and data related to packaging space availability associated with FCEVs and projections for the development and application of liquid hydrogen in the HD transportation sector over the next decade. Only one comment was received on this issue, from a vehicle manufacturer, who stated that they believe liquid hydrogen is required to meet the packaging requirement for vehicles with a 500-mile range, consistent with our assessment at the proposal. The same commenter also included 90th percentile daily VMT estimates of 484 miles for Class 8 day cabs and 724 miles for sleeper cab tractors, based on an 18-day snapshot of telematics data, because they said they believe EPA is overestimating ZEV application suitability.

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[660] Basma, Hussein and Felipe Rodriquez. "Fuel cell electric tractor-trailers: Technology overview and fuel economy". Working Paper 2022-23. International Council on Clean Transportation. July 2022. Available online: https://theicct.org/wp-content/uploads/2022/07/fuel-cell-tractor-trailer-tech-fuel-jul22.pdf.

[661] Basma, Hussein and Felipe Rodriquez. "Fuel cell electric tractor-trailers: Technology overview and fuel economy". Working Paper 2022-23. International Council on Clean Transportation. July 2022. Available online: https://theicct.org/wp-content/uploads/2022/07/fuel-cell-tractor-trailer-tech-fuel-jul22.pdf.

[662] Gomez, Julian A. and Diogo M.F. Santos. "The Status of On-Board Hydrogen Storage in Fuel Cell Electric Vehicles". Designs 2023: 7(4). Available online: https://www.mdpi.com/2411-9660/7/4/97.

[663] At low heating value, one kg of H2 includes 33.3 kWh of useable energy, which is about the same amount of energy as a gallon of diesel.

[664] Gomez, Julian A. and Diogo M.F. Santos. "The Status of On-Board Hydrogen Storage in Fuel Cell Electric Vehicles". Designs 2023: 7(4). Available online: https://www.mdpi.com/2411-9660/7/4/97.

[665] Daimler Truck. "Development milestone: Daimler Truck tests fuel-cell truck with liquid hydrogen". June 2022. Available online: https://media.daimlertruck.com/marsMediaSite/en/instance/ko/Development-milestone-Daimler-Truck-tests-fuel-cell-truck-with-liquid-hydrogen.xhtml?oid=51975637.

[666] Hyzon. "Hyzon Motors, Chart Industries to Develop Liquid Hydrogen Fuel Cell-Powered Truck, Targeting 1000-Mile Range". July 2021. Available online: https://www.hyzonmotors.com/in-the-news/hyzon-motors-chart-industries-to-develop-liquid-hydrogen-fuel-cell-powered-truck-targeting-1000-mile-range.

[667] Basma, Hussein and Felipe Rodriquez. "Fuel cell electric tractor-trailers: Technology overview and fuel economy". Working Paper 2022-23. International Council on Clean Transportation. July 2022. Available online: https://theicct.org/wp-content/uploads/2022/07/fuel-cell-tractor-trailer-tech-fuel-jul22.pdf.

For the final rule, we contracted FEV Group to conduct a packaging analysis for Class 8 long-haul FCEVs that store 700-bar gaseous hydrogen onboard.[668] FEV found ways to package six hydrogen tanks to deliver up to a 500-mile range with a sleeper cab using a 265-inch wheelbase. All tanks could be at the back of the cab and the batteries mounted outside of the frame rails, or four of the tanks could be behind the cab and two tanks mounted to the side frame under the cab if the battery pack can be placed between the frame rails. This would allow a long-haul tractor to meet a daily operational VMT requirement of 420 miles. If a HD FCEV refuels once en-route, then it could cover a 90th percentile VMT requirement of as far as 724 miles in a day (essentially matching the 90th percentile VMT noted by the commenter). A refueling event during the day should not be a burden, given that refueling times are as short as 20 minutes or less and are considered a key benefit of HD FCEVs.[669]

Based on our review of the literature for the NPRM and after consideration of the comments received and additional information, our assessment is that most HD vehicles likely have sufficient physical space to package gaseous hydrogen storage tanks onboard,[670] including long-haul sleeper cabs that travel up to 420 miles per day, or longer if they refuel en-route.

1.7.4 Fuel Cell Electric Vehicle Safety Considerations

FCEVs have two potential risk factors that must be addressed through proper design, process, and training: hydrogen and electricity. Electricity risks are identical to those of BEVs and, thus, are discussed in Chapter 1.5.2. Hydrogen risks can occur throughout the process of fueling a vehicle. FCEVs must be designed so that hydrogen can be safely delivered to a vehicle and then transferred into a vehicle's onboard storage tanks and fuel cell stacks. Hydrogen is flammable across a wide range of concentrations and can cause explosions if it is not handled properly. If hydrogen escapes during a fueling operation or from a vehicle fueling system, it can form a combustible mixture with air. The flammability range of hydrogen, 4% to 75%, is much greater than other common fuels.[671] Hydrogen has a lower ignition energy than gasoline vapor of 0.02 mJ compared to 0.24 mJ, so hydrogen will ignite more easily. Hydrogen is colorless, odorless, and tasteless so detecting leaked hydrogen is difficult. Even when ignited, the hydrogen flames are almost invisible so visually detecting a hydrogen fire is difficult and flame detectors are highly recommended. Fortunately, hydrogen is light and quickly rises and diffuses into the atmosphere to the point where it is no longer flammable, so flammable concentrations are less likely to exist. In June 2023, the World Forum for Harmonization of Vehicle Regulations under the United Nations Economic Commission for Europe adopted the Phase 2 amendments to the Global Technical Regulation (GTR) No. 13, 'Hydrogen and fuel cell vehicles.' The amendments reflect extensive revisions to GTR No. 13, including improvements of test procedures, extension of the applicability of the regulation to heavy vehicles, and a better reflection of the state-of-the-

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[668] FEV Consulting. "Heavy Duty Commercial Vehicles Class 4 to 8: Technology and Cost Evaluation for Electrified Powertrains—Final Report". Prepared for EPA. March 2024.

[669] U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office. "The #H2IQ Hour. Today's Topic: Heavy-Duty Vehicle Decarbonization". September 21, 2023. Available online: https://www.energy.gov/sites/default/files/2023-10/h2iqhour-09212023.pdf.

[670] Kast, James et. al. "Designing hydrogen fuel cell electric trucks in a diverse medium and heavy duty market". Research in Transportation Economics: Volume 70. October 2018. Available online: https://www.sciencedirect.com/science/article/pii/S0739885916301639.

[671] Center for Hydrogen Safety. "Hydrogen Flammability". Accessed on February 2, 2023. Available online: https://www.aiche.org/sites/default/files/docs/pages/the_elemental_-_hydrogen_flammability.pdf.

art with respect to hydrogen vehicles. Acceptance of the draft amendments has put into place the first regulation for heavy-duty vehicles fueled by hydrogen.[672]

Components and systems that store and move hydrogen are designed to accommodate small hydrogen molecules that are challenging to contain. Even with properly designed systems, small leaks are common. The vehicles themselves may have minor leaks but must not leak hydrogen into areas that can capture the rising gas. If vehicles are indoors for storage or repair, proper passive ventilation must include outlet openings at the high point of the enclosure so the hydrogen can vent. Active ventilation is also an option as fans and actuators exist that are classified for use where hydrogen could be present. If a FCEV is outdoors under a roof, the roof design should ensure that rising hydrogen does not have the opportunity to accumulate in any traps.

Use of hydrogen in a FCEV drives design considerations and standard procedures that help ensure safety during and after a crash. In-tank solenoid valves[673] are used to turn off hydrogen flow if needed to prevent an uncontrolled release of hydrogen. The solenoid will close if a prescribed level of impact is detected. First responders can help ensure solenoid closure by turning the vehicle off or physically interrupting the 12V supply as the solenoid default (no power) is off. If the physical integrity of the hydrogen storage tank is at risk due to fire, a thermally activated pressure relief device (TPRD) will vent the hydrogen. FCEV designs protect the hydrogen handling components. Since a crash may cause physical damage that releases hydrogen, care is taken to avoid traps where hydrogen can accumulate. Training of first responders for unique FCEV dangers and protocol is crucial. Vehicle specific emergency response documentation that helps the first responders apply their training safely and efficiently should be made readily available to first responders. Finally, post-crash, an initial inspection should be completed to verify the vehicle can be safely removed from the crash site. The FCEV should then be stored in an isolated area where final inspection and risk remediation can be implemented.[674,675]

Hydrogen has been handled, used, stored, and moved in industrial settings for more than 50 years, and there are established methods for doing so safely.[676] There is also federal oversight and regulation throughout the hydrogen supply chain system.[677] Safety training and education are key for maintaining reasonable risk while handling and using hydrogen. For example, hydrogen-related fuel cell vehicle risks can be mitigated through:

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[672] International Energy Agency. “Global Hydrogen Review 2023”. December 2023. Available online: https://iea.blob.core.windows.net/assets/ecdfc3bb-d212-4a4c-9ff7-6ce5b1e19cef/GlobalHydrogenReview2023.pdf.

[673] A solenoid valve is a valve utilizing an electromagnet formed by a coil of wire in the shape of a cylinder. When it carries a current, it acts like a magnet and the movable core is drawn into the coil causing the valve to either open or close.

[674] SAE International J2990-1. “Gaseous Hydrogen and Fuel Cell Vehicle First and Second Responder Recommended Practice”. June 2016.

[675] SAE International. “WIP: Gaseous Hydrogen and Fuel Cell Vehilce First and Second Responder Recommended Practice J2990/1”. December 2, 2019. Available online: https://www.sae.org/standards/content/j2990/1/.

[676] Hydrogen Tools. “Best Practices Overview”. Pacific Northwest National Laboratory. Accessed on February 2, 2023. Available online: https://h2tools.org/bestpractices/best-practices-overview.

[677] Baird, Austin R. et. al. “Federal Oversight of Hydrogen Systems”. Sandia National Laboratories. SAND2021-2955. March 2021. Available online: https://energy.sandia.gov/wp-content/uploads/2021/03/H2-Regulatory-Map-Report_SAND2021-2955.pdf.

- proper no/low leak designs for: infrastructure, hydrogen fill equipment, vehicle connectors, and vehicle storage and supply;
- ambient hydrogen concentration monitoring and alarm;
- hydrogen pressure monitoring in the vehicle and infrastructure to indicate leaks;
- proper ventilation in and around hydrogen fueling equipment and fuel cell vehicles;
- vehicle controls to ensure the vehicle cannot be driven while fueling equipment is attached; and
- vehicle controls that isolate hydrogen storage in the case of an accident.[678]

The following codes and standards are in place to guide safe use of hydrogen:

- SAE J2578, Recommended Practice for General Fuel Cell Vehicle Safety
- SAE J2579, Standard for Fuel Systems in Fuel Cell and Other Hydrogen Vehicles
- SAE J2990, Hybrid and EV First and Second Responder Recommended Practice (with recommendations for hazards associated with hydrogen vehicles) OSHA standard 29 CFR 1910.103 on Hydrogen

Hydrogen risk is usually reduced due to its buoyancy and rapid dissipation. These physical aspects of hydrogen have less positive impact in enclosures like tunnels. DOE/Sandia National Laboratories is working with other authorities to evaluate safety in tunnels.[679] Per NHTSA, DOE is also working with local authorities to evaluate safety and travel of FCEV in tunnels like Boston and Baltimore harbor tunnels. If these studies find it prudent to restrict HD FCEV from the tunnels, HD FCEV would need to use the same alternative routes currently used by fuel tankers and the like.[680] FCEVs including their storage systems, like ICE vehicles, are required to meet the Federal Motor Vehicle Safety Standards (FMVSS) for crash safety so that the systems will maintain their integrity after the specified crash conditions. Additional FCEV safety information is available in RTC Section 4.9. EPA obtained additional NHTSA safety input regarding comments and updates for the final rulemaking.[681]

1.7.5 FCEV Market

The fuel cell market for heavy-duty vehicles is not as far along as the market for heavy-duty BEVs. When EPA conducted an analysis of manufacturer-supplied end-of-year production

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[678] Hydrogen Tools. “Hydrogen Infrastructure and Vehicle Safety”. Pacific Northwest National Laboratory. Accessed on February 2, 2023. Available online: https://h2tools.org/safety-hydrogen-vehicles-and-infrastructure-bulletin.

[679] Glover, et. al. "Hydrogen Fuel Cell Vehicles in Tunnels". Sandia National Laboratories. SAND2020-4507 R. April 2020. Available online: https://energy.sandia.gov/wp-content/uploads/2020/05/Hydrogen-Fuel-Cell-Vehicles-in-Tunnels_SAND2020-204507r.pdf.

[680] Cole, Matt. “Colorado DOT to study allowing hazmat trucks to travel through I-70’s Eisenhower Tunnel”. Overdrive. April 12, 2019. Available Online: https://www.overdriveonline.com/business/article/14896160/colorado-dot-to-study-allowing-hazmat-trucks-to-travel-through-i-70s-eisenhower-tunnel.

[681] Landgraf, Michael. Memorandum to docket EPA-HQ-OAR-2022-0985. Summary of NHTSA Safety Communications. February 14, 2024.

reports provided to us as a requirement of the process to certify HD vehicles to our GHG emission standards, based on the end-of-year production reports for MY 2019, there were no HD FCEVs certified through MY 2021. Some models are available now and others are still being developed and tested but are anticipated in the coming decade. According to the Global Commercial Vehicle Drive to Zero Zero-Emission Technology Inventory (ZETI), the following fuel cell vehicles are expected to become commercially available for production in the United States and Canada region by CY 2024, as shown in Table 1-29.[682]

Table 1-29 Current and Projected North American HD Fuel Cell Vehicles

OEM	Vehicle	Class	Range	Est. Payload	Energy Capacity	First Available Year
Hyzon	Hyzon	Class 8	500 mi		70 kg	2022
International	HD Hydrogen Fuel Cell Truck	Class 8	500 mi			2024
Kenworth/Toyota	T680	Class 8	400 mi	110,000 lbs		2023
Nikola	Tre	Class 8	500 mi	40,000 lbs		2023
Nikola	Two	Class 8	900 mi	40,000 lbs		2024
Toyota	Beta	Class 8	300 mi	88,185 lbs	40 kg	2023
Hyzon	Econic Refuse	Class 8	125 mi	2000 lbs	25 kg	2019
Unique Electric Solutions (UES)	FCCC MT-55 FC	Class 6	140 mi	4000 lbs		2021
UES	F-59 FC	Class 6	140 mi	4000 lbs		2021
UES	International 1652 FC	Class 6	150 mi	4000 lbs		2020
ElDorado National	AXESS FC 35 ft	Transit Bus	260 mi	42 seats		2020
ElDorado National	AXESS FC 40 ft	Transit Bus	260 mi	43 seats		2020
New Flyer	Xcelsior CHARGE H2 – 40 ft	Transit Bus	350 mi	40 seats	38 kg	2020
New Flyer	Xcelsior CHARGE H2 – 60 ft	Transit Bus	350 mi	52 seats	60 kg	2020
Cenntro Electric Group	LM864H	Class 7	186 mi	81,571 lbs	1680 L 40 kg @ 350 bar est.	2023
Hyundai	XCient	Class 8	249 mi	42,990 lbs	32 kg	2023

The Hydrogen Fuel Cell Partnership states that fuel cell electric buses have been in commercial development for 20 years and, as of May 2020, 60 buses are in operation or in planning in the U.S.[683] As of October 2022, California's Innovative Clean Transit program identified over 2000 FCEV transit bus potential future purchases throughout the state.[684]

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[682] CALSTART. "Drive to Zero's Zero-Emission Technology Inventory (ZETI) Tool Version 8.0". Accessed November 2023. Available online: https://globaldrivetozero.org/tools/zeti/.

[683] Hydrogen Fuel Cell Partnership. "Buses & Trucks". Available online: https://h2fcp.org/buses_trucks.

[684] California Air Resources Board. "Fuel Cell Electric Bus Deployment in California: FCEB-Deployment-Map.pdf". Last updated 10/22/2022. Available online: https://ww2.arb.ca.gov/sites/default/files/2022-10/FCEB-Deployment-Map.pdf.

Deployments have occurred so far, for example, in Los Angeles County, where Foothill Transit began operating 33 FCEV transit buses in 2023 and ordered 19 additional FCEV buses;[685] and in Orange County, where the Transportation Authority is operating 10 FCEB transit buses and has fueling station capacity to for up to 50 buses that is scalable to 100 buses with additional fuel storage and components.[686] In addition, the Regional Transportation Commission of Southern Nevada awarded a contract for seven FCEV transit buses with an option to purchase up to 100 additional buses over the duration of a five-year contract.[687] The Champagne-Urbana Transit District in Illinois has two FCEV transit buses that run on electrolysis powered by solar energy,[688] and a project in Montgomery County, Maryland, plans to follow suit with 13 buses.[689]

Several Class 6 to 8 HD FCEVs have been demonstrated in California. For example, there was successful testing of 10 Toyota-Kenworth Class 8 fuel cell tractors in the Port of Los Angeles and surrounding area through the Zero- and Near-Zero Emissions Freight Facilities "Shore to Shore" project (Spring 2019-2023);[690,691] four FCEV walk-in delivery vans (February 2019 to Fall 2022),[692] and then 15 more FCEV delivery vans (Winter 2019-2022).[693] A current project will build and deploy at least 30 fuel cell trucks at the Port of Oakland along with a hydrogen fueling station (August 2021 to Spring 2025).[694,695]

Additional Class 8 FCEVs are under development. Some may be for nonroad applications such as yard tractors at ports or are not expected for production until after 2024. For example:

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[685] Foothill Transit. "Greening Big". August 22, 2023. Available online: https://www.foothilltransit.org/greeningbig.

[686] Orange County Transportation Authority. "Hydrogen Fuel Cell Electric Bus". Available online: https://www.octa.net/about/about-octa/environmental-sustainability/fuel-cell/.

[687] NFI Group Inc. "NFI receives third zero-emission contract from RTC, for up to 107 New Flyer fuel cell-electric buses, expanding sustainable, high-capacity mobility in Southern Nevada". April 28, 2023. Available online: https://www.globenewswire.com/news-release/2023/04/28/2657341/0/en/NFI-receives-third-zero-emission-contract-from-RTC-for-up-to-107-New-Flyer-fuel-cell-electric-buses-expanding-sustainable-high-capacity-mobility-in-Southern-Nevada.html.

[688] Hays, Emily. "Hydrogen buses come to Champaign-Urbana mass transit". October 19, 2021. Available online: https://ipmnewsroom.org/hydrogen-buses-roll-out-from-urbana/.

[689] Gallucci, Maria. "This East Coast bus depot will make its own carbon-free fuel". May 18, 2023. Available online: https://www.canarymedia.com/articles/public-transit/this-east-coast-bus-depot-will-make-its-own-carbon-free-fuel.

[690] Heavy Duty Trucking. "FCEV Drayage Trucks Prove Themselves in LA Port Demonstration Project" September 22, 2022. Available online: https://www.truckinginfo.com/10181655/fcev-drayage-trucks-prove-themselves-in-la-port-demonstration-project.

[691] California Air Resources Board. "LCTI: Port of Los Angeles "Shore to Store" Project. Available online: https://ww2.arb.ca.gov/lcti-port-los-angeles-shore-store-project.

[692] California Air Resources Board. "LCTI: Next Generation Fuel Cell Delivery Van Deployment". Available online: https://ww2.arb.ca.gov/lcti-next-generation-fuel-cell-delivery-van-deployment.

[693] California Air Resources Board. "LCTI: Fuel Cell Hybrid Electric Delivery Van Deployment". Available online: https://ww2.arb.ca.gov/lcti-fuel-cell-hybrid-electric-delivery-van-deployment.

[694] Adler, Alan. "Hyundai's Xcient positioned for instant US fuel cell truck leadership". FreightWaves. November 29, 2022. Available online: https://www.freightwaves.com/news/hyundais-xcient-positioned-for-instant-us-fuel-cell-truck-leadership.

[695] California Air Resources Board. "LCTI: NorCAL Zero-Emission Regional ad Drayage Operations with Fuel Cell Electric Trucks. Available online: https://ww2.arb.ca.gov/lcti-norcal-zero-emission-regional-and-drayage-operations-fuel-cell-electric-trucks.

- Nikola commercially launched the MY2024 Tre FCEV at their manufacturing facility in Coolidge, Arizona, which has an expected production capacity of approximately 2,400 BEV and FCEV trucks per year.[696]
    - Nikola's Tre FCEV received eligibility for the California Air Resources Board (CARB) Hybrid and Zero Emission Truck and Bus Voucher Incentives Project (HVIP) program in California, which means that customers can receive a point-of-sale incentive starting at $240,000 per truck with warranty and service support.[697]
- Hyzon Motors has a Class 8 FCEV and a FCEV conversion that qualify for HVIP.
- Hyundai XCIENT Class 8 truck qualifies for HVIP.[698]
- PACCAR and Toyota are expanding efforts to develop and produce FCEV Kenworth T680 and Peterbilt 579 truck models with initial customer deliveries planned for 2024.[699]
    - Toyota received a Zero Emission Powertrain (ZEP) Executive Order from CARB for a new heavy-duty fuel cell electric powertrain kit that includes hydrogen fuel storage tanks, fuel cell stacks, batteries, and electric motors and transmission. This means the powertrain complies with CARB regulations for zero-emission powertrains.
- DTNA and Cummins are collaborating to validate Freightliner Cascadia trucks with Cummins fuel cell powertrains for use in North America in 2024, pending success.[700]
- Volvo and Daimler joined forces in the European Union to launch cellcentric to accelerate the use of hydrogen fuel cells in long-haul trucks.[701]
    - They completed successful road tests in the Arctic Circle in early 2023.[702]
    - Volvo Trucks is developing a Class 8 truck with a 600-mile range.[703]

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[696] Nikola. "Nikola Celebrates the Commercial Launch of Hydrogen Fuel Cell Electric Truck in Coolidge, Arizona". September 28, 2023. Available online: https://www.nikolamotor.com/press_releases/nikola-celebrates-the-commercial-launch-of-hydrogen-fuel-cell-electric-truck-in-coolidge-arizona/.

[697] Nikola Corporation. "Nikola Tre FCEV Receives CARB HVIP Incentive Eligibility". PR Newswire. February 7, 2023. Available online: https://www.prnewswire.com/news-releases/nikola-tre-fcev-receives-carb-hvip-incentive-eligibility-301740512.html.

[698] California HVIP. "Tractor". Accessed November 2023. Available online: https://californiahvip.org/vehicle-category/heavy-duty/.

[699] Toyota Newsroom. "PACCAR and Toyota Expand Hydrogen Fuel Cell Truck Collaboration to Include Commercialization. May 2, 2023. Available online: https://pressroom.toyota.com/paccar-and-toyota-expand-hydrogen-fuel-cell-truck-collaboration-to-include-commercialization/.

[700] AfterMarket News. "DTNA, Cummins Collaborate on Hydrogen Fuel Cell Trucks". May 16, 2022. Available online: https://www.aftermarketnews.com/dtna-cummins-collaborate-on-hydrogen-fuel-cell-trucks-forward-in-north-america/.

[701] OEM Off-Highway Magazine. "Daimler and Volvo Launch Strategy for Fuel Cell Joint Venture". April 29, 2021. Available online: https://www.oemoffhighway.com/electronics/power-systems/press-release/21403767/volvo-group-global-daimler-and-volvo-launch-strategy-for-fuel-cell-joint-venture.

[702] Fisher, John. "Volvo finding fuel cell success in Arctic conditions". FleetOwner. May 30, 2023. Available online: https://www.fleetowner.com/emissions-efficiency/article/21266721/volvo-testing-fuel-cell-tech-in-arctic-conditions.

[703] Edelstein, Stephen. "Volvo fuel-cell semi: 600 miles, 15-minute refueling with green hydrogen still not widely available". June 21, 2022. Available online: https://www.greencarreports.com/news/1136248_volvo-fuel-cell-semi-600-miles-15-minute-refueling-green-hydrogen.

- Isuzu and Honda announced a partnership in Japan to develop fuel cell technology for heavy-duty trucks for the market, scheduled to launch in 2027.[704]
- Hino built a Class 8 FCEV prototype.[705]
- Scania plans to deliver fuel cell trucks to customers in Switzerland in 2024 and 2025.[706]
- Quantron received an order for 500 Class 8 FCEVs in the U.S. for delivery by 2024.[707,708]
  - Quantron US is preparing to launch a 750-mile Class 8 FCEV tractor in North America in 2024 that can store 80 kg of hydrogen at 700 bar of pressure.[709]
- Symbio, a joint venture between Faurecia and Michelin, received a California Energy Commission grant to support establishment of a facility to assemble regional HD FCEV Class 8 trucks, medium-duty FCEVs, and fuel cell power systems. They are demonstrating a regional-haul Class 8 truck along a 400-mile route under the Symbio H2 Central Valley Express Project.[710]
- In December 2022, Air Liquide, Hyzon Motors, and the TALKE Group began a demonstration of a hydrogen fuel cell electric truck in the Port of Houston.[711]
- A zepp.solutions long-range sleeper truck called Europa is scheduled to enter operation in late 2023.[712]
- Autocar announced that they will be making Class 8 vocational FCEVs such as cement mixers and dump trucks using Hydrotec fuel cell "power cubes" made by

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[704] Honda. "Isuzu Selects Honda as Partner to Develop and Supply Fuel Cell System for its Fuel Cell-Powered Heavy-duty Truck Scheduled to be Launched in 2027". May 15, 2023. Available online: https://global.honda/en/newsroom/news/2023/c230515aeng.html.

[705] Hino Trucks. "Hino Trucks Reveals First XL8 Fuel Cell Electric Truck Prototype". August 31, 2021. Available online: https://www.hino.com/press20210831.html.

[706] Scania. "Scania to deliver fuel cell trucks in Switzerland". November 8, 2022. Available online: https://www.scania.com/group/en/home/newsroom/news/2022/scania-to-deliver-fuel-cell-trucks-to-switzerland.html#:~:text=We%20now%20develop%20Scania's%20first,Switzerland%20in%202024%20and%202025.

[707] FuelCellsWorks. "Quantron US Receives Order for 500 Class 8 Hydrogen Fuel Cell Powered Trucks". October 12, 2022. Available online: https://fuelcellsworks.com/news/quantron-us-receives-order-for-500-class-8-hydrogen-fuel-cell-powered-trucks/.

[708] Quantron AG. "Up to 500 QUANTRON Class 8 Fuel Cell Trucks for US-based TMP Logistics Group Ltd. PR Newswire. October 12, 2022. Available online: https://www.prnewswire.com/news-releases/up-to-500-quantron-class-8-fuel-cell-trucks-for-us-based-tmp-logistics-group-ltd-301647751.html.

[709] Crissey, Jeff. "Quantron has long-range ambitions for U.S. Class 8 hydrogen fuel cell truck". Clean Trucking. November 9, 2023. Available online: https://www.cleantrucking.com/hydrogen/article/15638212/quantron-has-longrange-ambitions-for-us-class-8-hydrogen-fuel-cell-truck?utm_source=email&utm_medium=email&utm_campaign=AD2023+CT+Quantron-to-enter-US-market_NL_Engaged&utm_term=AE311OCJC&ust_id=5634G4743101H9J&utm_content=11-21-2023.

[710] Symbio. "Symbio North America received grant award from California Energy Commission for manufacturing hydrogen fuel cell vehicle power systems and vehicle assembly". May 2, 2023. Available online: https://www.symbio.one/en/news-and-media/symbio-north-america-received-grant-award-california-energy-commission-manufacturing.

[711] Air Liquide. "Air Liquide fuels first hydrogen fuel cell truck demonstration at Port of Houston". January 12, 2023. Available online: https://usa.airliquide.com/hyzon-port-of-houston.

[712] FuelCellsWorks. "zepp.solutions Unveils Specifications of New Hydrogen-Powered Truck: 'Europa' to Launch in Q4 2023". February 7, 2023. Available online: https://fuelcellsworks.com/news/zepp-solutions-unveils-specifications-of-new-hydrogen-powered-truck-europa-to-launch-in-q4-2023/.

General Motors. They expect to start producing vehicles at a plant in Birmingham, Alabama, in 2026.[713]

- Hybot, a Chinese company, unveiled a gaseous FCEV sleeper cab called H49 with a range of over 600 miles, expected to be officially launched into mass production in 2025.[714]GM and Honda have started production of fuel cells in Brownstown, MI, to power commercial trucks and other applications.[715]

Fleets are also starting to purchase HD FCEVs:

- Nikola has agreements with fleets to purchase or lease over 200 Class 8 trucks upon satisfactory completion of demonstrations.[716,717,718,719]
    - In addition, AJR Trucking announced purchase of 50 Nikola Tre FCEVs, with deliveries expected through 2024.[720]
- Amazon signed an agreement with Plug Power,[721,722] a company building an end-to-end hydrogen ecosystem, to supply hydrogen for up to 800 HD long-haul trucks or 30,000 forklifts (which are commonly powered using hydrogen) starting in 2025 through 2040.[723]
- Walmart is purchasing hydrogen from Plug Power.[724] Walmart plans to expand pilots of fuel cell forklifts, yard trucks, and possibly HD long-haul trucks by 2040.[725]

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[713] HDT Truckinginfo. “Autocar, GM to Produce Fuel-Cell Electric Vocational Trucks”. December 8, 2023. Available online: https://www.truckinginfo.com/10211875/autocar-and-gm-announce-electric-truck-joint-venture.

[714] Collins, Leigh. “Chinese start-up unveils world’s first gaseous-hydrogen truck with 1,000km range”. HydrogenInsight. December 14, 2023. Available online:https://www.hydrogeninsight.com/transport/chinese-start-up-unveils-worlds-first-gaseous-hydrogen-truck-with-1-000km-range/2-1-1570968.

[715] Tingwall, Eric. “The Next Diesel? GM and Honda Start U.S. Production of Hydrogen Fuel Cells. January 25, 2024. Available online: https://www.motortrend.com/news/honda-general-motors-hydrogen-fuel-cell-production-start/.

[716] HDT Truckinginfo. “Pennsylvania Flatbed Carrier to Lease 100 Nikola Tre FCEVs.” October 14, 2021. Available online: https://www.truckinginfo.com/10153974/pennsylvania-flatbed-carrier-to-lease-100-nikola-tre-evs.

[717] Green Car Congress. “Covenant Logistics Group signs letter of intent for 10 Nikola Tre BEVs and 40 Tre FCEVs.” January 12, 2022. Available online: https://www.greencarcongress.com/2022/01/20220112-covenant.html.

[718] Adler, Alan. “Plug Power will buy up to 75 Nikola fuel cell trucks.” Freightwaves. December 15, 2022. Available online; https://www.freightwaves.com/news/plug-power-will-buy-up-to-75-nikola-fuel-cell-trucks.

[719] Nikola. “Nikola Corporation Reports Third Quarter 2023 Results.” November 2, 2023. Available online: https://www.nikolamotor.com/press_releases/nikola-corporation-reports-third-quarter-2023-results/.

[720] AJR Trucking. “AJR Trucking Announces Order for 50 Nikola Tre FCEVs”. May 2, 2023. Available online: https://www.ajrtrucking.com/blog/ajr-trucking-announces-order-for-50-nikola-tre-fcevs/.

[721] Plug Power. “About Us”. Available online: https://www.plugpower.com/about-us/.

[722] Adler, Alan. “Forklift-fueling hydrogen network holds long-haul trucking potential: Amazon, Walmart distribution centers could form a backbone”. FreightWaves. April 21, 2023. Available online: https://www.freightwaves.com/news/todays-forklift-fueling-hydrogen-network-holds-long-haul-trucking-potential.

[723] Amazon. “Amazon adopts green hydrogen to help decarbonize its operations”. August 25, 2022. Available online: https://www.aboutamazon.com/news/sustainability/amazon-adopts-green-hydrogen-to-help-decarbonize-its-operations.

[724] Plug Power. “Plug Supplies Walmart with Green Hydrogen to Fuel Retailer’s Fleet of Material Handling Lift Trucks”. April 19, 2022. Available online: https://www.ir.plugpower.com/press-releases/news-details/2022/Plug-Supplies-Walmart-with-Green-Hydrogen-to-Fuel-Retailers-Fleet-of-Material-Handling-Lift-Trucks/default.aspx.

[725] Proactive. “WalMart eyes benefits of hydrogen delivery vehicles in wider trials”. Proactive 13:17. June 8, 2022. Available online: https://www.proactiveinvestors.co.uk/companies/news/984360/walmart-eyes-benefits-of-hydrogen-delivery-vehicles-in-wider-trials-984360.html.

- Plug Power has agreed to purchase up to 75 Nikola Class 8 fuel cell trucks over the next three years in exchange for supplying the company with hydrogen fuel.[726]
- Performance Food Group, Inc. (PFG) entered an agreement with Hyzon for five FCEVs with 110 kW fuel cell systems, and possibly 15 or more FCEVs with 200 kW systems pending a successful vehicle trial.[727]

As the costs of components and hydrogen fuel decrease over time, we expect the HD FCEV market to grow.

1.7.5.1 FCEV Component Manufacturers

Currently, most of the components of a fuel cell vehicle are the same as components in a HD BEV. See Table 1-30 for an abbreviated list of manufacturers of HD FCEV-specific components that are additional to a HD BEV.

Table 1-30 FCEV Component Manufacturers

Component	Manufacturers
PEM Fuel Cell Stack[728]	Bosch, Ballard, Nuvera, Advent, Cummins, GM Hydrotec, Toyota
Hydrogen Tank[729]	Quantum, Hanwha Cimarron (Hanwha Solutions), Voith

This list includes Bosch, who announced an investment of $200 million in South Carolina to produce fuel cell stacks for hydrogen fuel cell trucks,[730] and General Motors, who announced

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[726] Adler, Alan. "Plug Power will buy up to 75 Nikola fuel cell trucks". Freightwaves. December 15, 2022. Available online: https://www.freightwaves.com/news/plug-power-will-buy-up-to-75-nikola-fuel-cell-trucks.

[727] HDT Truckinginfo. "Performance Food Group Plans to Buy Hyzon Fuel Cell Trucks". June 9, 2023. Available online: https://www.truckinginfo.com/10200499/performance-food-group-to-purchase-hyzon-fuel-cell-trucks.

[728] Advent. "Advent Fuel Cells: Digi-Tronic". Available online: https://www.advent.energy/advent-digi-tronic/.; Nuvera. "What distinguishes Nuvera fuel cell stacks?". Available online: https://www.nuvera.com/technology.; Ballard. "Heavy Duty Modules: FCmove". Available online: https://www.ballard.com/fuel-cell-solutions/fuel-cell-power-products/motive-modules.; Bosch. "Fuel-cell stacks: the recipe for success in mass manufacturing". Available online: https://www.bosch.com/stories/fuel-cell-stack/.; GM. "Hydrotec". Available online: https://www.gm.com/commitments/hydrotec.; accelera by Cummins. "Technologies: Fuel Cells". Available online: https://www.accelerazero.com/fuel-cells.; Shepard, Paul. "News: Cummins Acquires Hydrogenics for Fuel Cell and Hydrogen Production Tech". September 2019. Available online: https://eepower.com/news/cummins-acquires-hydrogenics-for-fuel-cell-and-hydrogen-production-tech/#.

[729] Quantum Fuel Systems. "Scalable Hydrogen Fuel Systems and Infrastructure". Available online: https://www.qtww.com/product/hydrogen/.; Hanwha Cimarron. "Hanwha Cimarron developed distinguished Type-4 technology that enables Hydrogen storing tanks for Fuel Cell". Available online: https://hanwhacimarron.com/on-vehicle/.; Voith. "Plug & Drive H2 Storage System". Available online: https://voith.com/corp-en/drives-transmissions/drive-h2.html.

[730] Ohnsman, Alan. "Bosch Is Investing $200 Million to Make Fuel Cells for Hydrogen Trucks in South Carolina". Forbes. August 31, 2022. Available online: https://www.forbes.com/sites/alanohnsman/2022/08/30/bosch-to-make-fuel-cells-for-hydrogen-trucks-in-south-carolina/?sh=3da3873b2242.

that it will supply fuel cells to Navistar.[731] Toyota also announced plans to assemble fuel cell modules for use in heavy-duty commercial trucks starting in 2023.[732]

1.7.6 FCEV Research and Development

DOE has a Hydrogen and Fuel Cell Technologies Office focused on research, development, and demonstration of hydrogen and fuel cell technologies across sectors, including transportation. Through the 21st Century Truck Partnership and SuperTruck 3, they are working with industry stakeholders to reduce emissions of freight transportation, [733] with the projects listed in Table 1-31 for 2022 through 2026 focused on fuel cell trucks.

Table 1-31 DOE Funded Hydrogen HDV Projects Awarded in 2022[734]

Company	Project Description	Award Amount*
Daimler Trucks North America, LLC	Develop and demonstrate two 2 Class-8 fuel cell trucks with 600-mile range, 25,000-hour durability, equivalent payload capacity and range to diesel.	$25,791,669
Ford Motor Company	Develop and demonstrate five hydrogen fuel cell electric Class-6 Super Duty trucks targeting cost, payload, towing, and refueling times that are equivalent to conventional gasoline trucks.	$24,952,314
General Motors, LLC	Develop and demonstrate four hydrogen fuel cell and four battery electric Class 4-6 trucks. The project will also focus on development of clean hydrogen via electrolysis and clean power for fast charging	$26,061,726

* Subject to appropriations.

DOE also works with industry through the Million Mile Fuel Cell Truck (M2FCT) multi-lab consortium to advance the efficiency and durability of PEM fuel cells at a pre-competitive level to enable their commercialization for heavy-duty vehicle applications with an initial focus on long-haul trucks.[735]

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[731] Eisenstein, Paul A. “GM Enters The Fuel Cell Business, Will Power Navistar Trucks”. Forbes: Wheels. October 4, 2021. Available online: https://www.forbes.com/wheels/news/gm-enters-fuel-cell-business-power-navistar-trucks/.

[732] Zurschmeide, Jeff. “Toyota Expands U.S. Fuel Cell Manufacturing for Heavy Trucks”. The Detroit Bureau. July 12, 2023. Available online: https://www.thedetroitbureau.com/2023/07/toyota-expands-u-s-fuel-cell-manufacturing-for-heavy-trucks/.

[733] U.S. Department of Energy. “DOE Projects Zero Emissions Medium- and Heavy-Duty Electric Trucks Will Be Cheaper than Diesel-Powered Trucks by 2035”. March 2022. Available online: https://www.energy.gov/articles/doe-projects-zero-emissions-medium-and-heavy-duty-electric-trucks-will-be-cheaper-diesel.

[734] U.S. Department of Energy. “DOE Announces Nearly $200 Million to Reduce Emissions From Cars and Trucks. November 1, 2021. Available online: https://www.energy.gov/articles/doe-announces-nearly-200-million-reduce-emissions-cars-and-trucks.

[735] Million Mile Fuel Cell Truck. “Zero-emission Fuel Cell Trucks powered by Hydrogen: Envisioning a future fleet of emission-free heavy-duty vehicles”. U.S. Department of Energy, Available online: https://millionmilefuelcelltruck.org/.

1.8 Overview of Hydrogen Industry and Infrastructure

This section provides a basic overview of hydrogen infrastructure and then discusses the status and outlook of an early market hydrogen refueling network for HD FCEVs.

1.8.1 Hydrogen Characteristics and Use

Hydrogen is the lightest and most abundant element in the universe, composed of one proton and one electron. It has low volumetric density, so it must be compressed or liquified for use, but high gravimetric density, with about 2.5 to 3 times the energy content per unit of mass than gasoline or diesel.[736]

Today, hydrogen is mainly used in oil refining and other industrial sectors such steel production, and as a feedstock to produce chemicals like methanol or ammonia for products such as fertilizer. As additional renewable electricity from wind and solar technologies is added to the grid, hydrogen could be used as an energy carrier to seasonally store excess energy to help balance intermittent supply with varying demand.[737] Hydrogen could also be used as a fuel for hard-to-decarbonize transportation modes like heavy-duty trucks, rail, and marine vessels.

In 2020, DOE began characterizing the growth potential of a diverse hydrogen industry in the United States through an H2@Scale initiative. The overarching vision highlights opportunities for hydrogen as an essential feedstock and energy carrier that can enable zero and near-zero emissions across multiple sectors, along with energy security and resiliency. Its expansive use can lead to economies of scale that can drive revenue prospects while making hydrogen more affordable.[738] The range of sectors that could participate in a larger H_2 economy are demonstrated in Figure 1-18.[739]

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[736] Chukwudi Tashie-Lewis, Bernard and Somtochukwu Godfrey Nnabuife. “Hydrogen Production, Distribution, Storage and Power Conversion in a Hydrogen Economy—A Technology Review”. Chemical Engineering Journal Advances, Volume 8. November 15, 2021. Available online: https://www.sciencedirect.com/science/article/pii/S2666821121000880#bib0012.

[737] In May 2022, renewable power exceeded demand for power in California for the first time in history. Satyapal, Sunita. “2022 AMR Plenary Session”. U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office. June 6, 2022. Available online: https://www.energy.gov/sites/default/files/2022-06/hfto-amr-plenary-satyapal-2022-1.pdf.

[738] U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office. “H2@Scale”. Available online: https://www.energy.gov/eere/fuelcells/h2scale.

[739] U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office. “H2@Scale”. Available online: https://www.energy.gov/eere/fuelcells/h2scale.

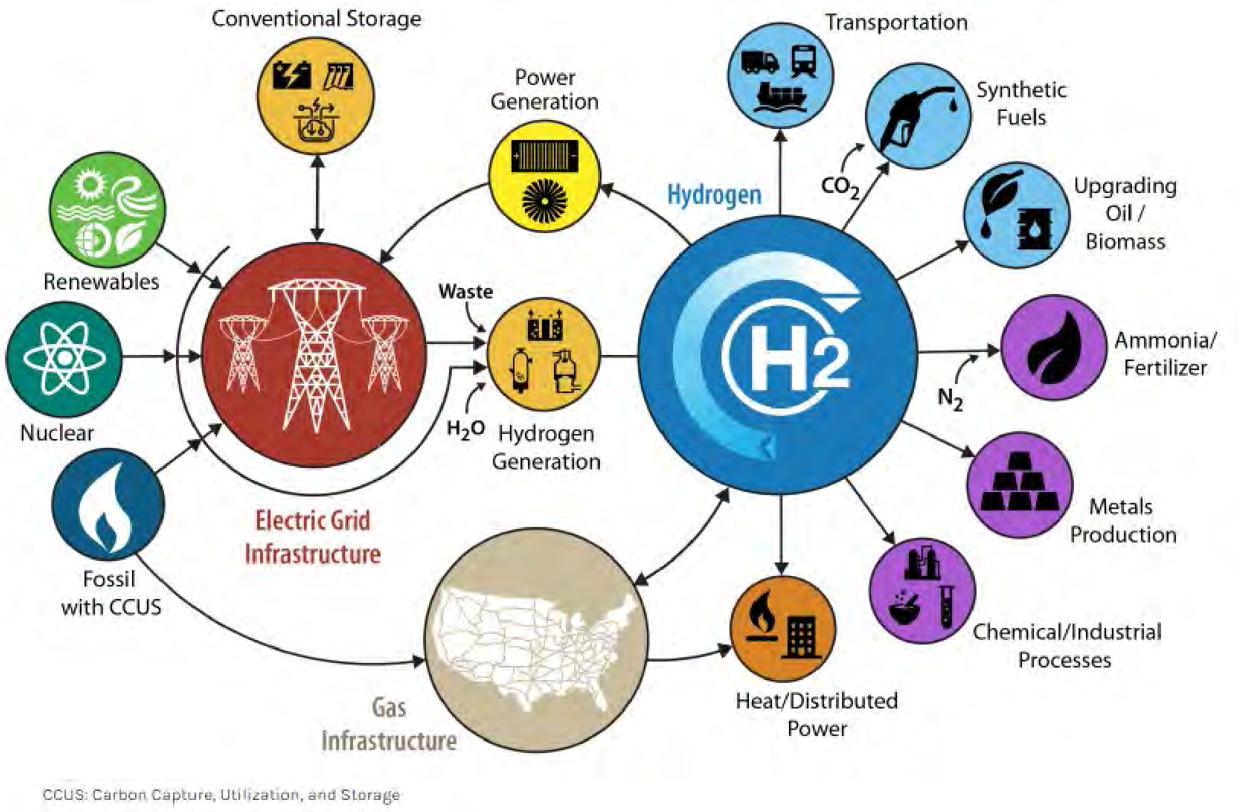

Figure 1-18 U.S. Department of Energy's H2@Scale Concept

1.8.2 Hydrogen Infrastructure Basics

As FCEV adoption grows, more hydrogen refueling infrastructure will be needed to support the HD FCEV fleet. Infrastructure is required during the production, distribution and storage, and dispensing of hydrogen fuel.

1.8.2.1 Hydrogen Production

Hydrogen can be produced using different feedstocks (e.g., natural gas, water), power sources, and production methods or processes, as listed in Table 1-32.

Table 1-32 Hydrogen Production Methods[740,741]

Power Source	Production Process
Coal	Gasification with or without carbon capture and storage (CCS)

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[740] Adapted from EPA's Office of Air Quality and Standards (OAQPS) draft Technical Support Document on Hydrogen in Combustion Turbine Electric Generating Units, which includes more detailed information about hydrogen production methods.

[741] U.S. Environmental Protection Agency, Office of Air and Radiation. "Hydrogen in Combustion Turbine Electric Generating Units: Technical Support Document". May 23, 2023. Available online: https://www.epa.gov/system/files/documents/2023-05/TSD%20-%20Hydrogen%20in%20Combustion%20Turbine%20EGUs.pdf.

Natural Gas	Steam Methane Reforming (SMR) and Autothermal Reforming (ATR) with or without CCS, Methane Pyrolysis
Nuclear	Thermal energy for gasification or SMR, Electrolysis (low and high temperature), and Thermochemical
Renewable	Electrolysis, Photoelectrochemical (PEC), Thermochemical
Others	Byproduct hydrogen and hydrogen derived from biomass, byproducts, and refuse; Electrolysis*

*Note that electrolysis can also be produced using grid electricity

Hydrogen production methods are at different levels of technology readiness and range in cost and carbon emissions intensity.[742] The U.S. Department of Energy supports clean hydrogen production from diverse resources and conducts well-to-gate analysis[743] to characterize the emissions of hydrogen production using state of the art tools, such as Argonne National Laboratory’s GREET model.

Figure 1-19 compares current well-to-gate carbon intensities of several domestic hydrogen production pathways.[744]

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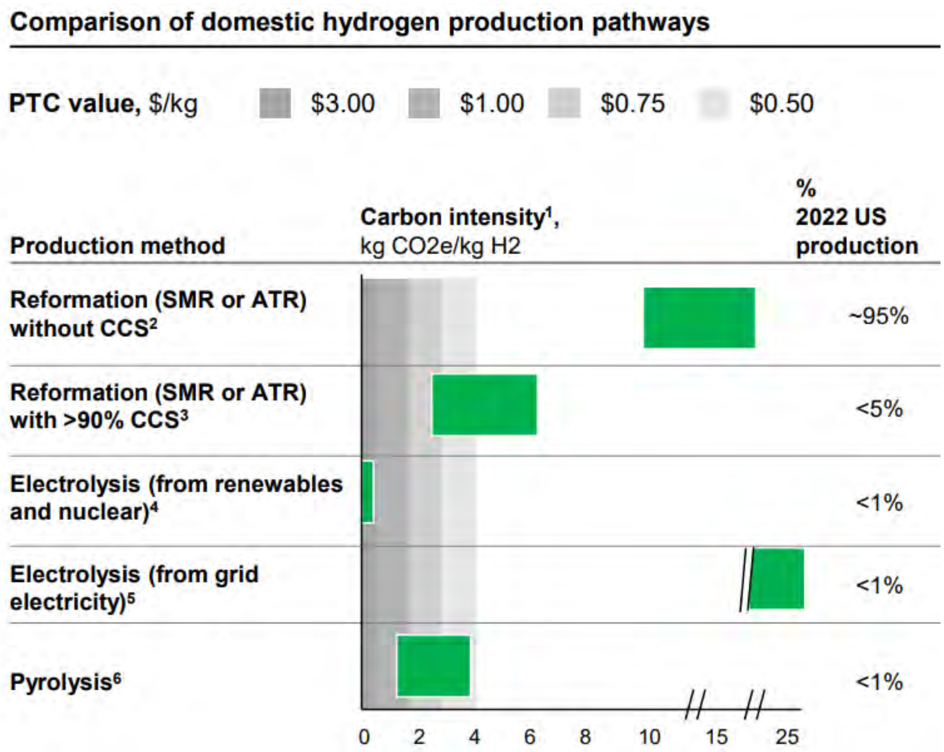
[742] U.S. Department of Energy, Hydrogen Program. “Clean Hydrogen Production Standard Guidance”. June 2023. Available online: https://www.hydrogen.energy.gov/library/policies-acts/clean-hydrogen-production-standard, https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/clean-hydrogen-production-standard-guidance.pdf.

[743] Well-to-gate is a system boundary used to evaluate lifecycle emissions from feedstock generation or extraction through to the point of production.

[744] U.S. Department of Energy. “Pathways to Commercial Liftoff: Clean Hydrogen”. March 2023. Available online: https://liftoff.energy.gov/wp-content/uploads/2023/03/20230320-Liftoff-Clean-H2-vPUB.pdf.



1 Excludes renewable natural gas feedstocks that would result in negative carbon intensities. Carbon intensities shown are well-to-gate
2 Capex: SMR facility capex (100k Nm3/h capacity): $215 million (current and 2030); reference case natural gas: $4.8/MMBtu (current), $3/MMBtu (2030); high case natural gas: $4.8/MMBtu (current), $3.3/MMBtu (2030); high case based on EIA Advanced Energy Outlook 2022 high oil price scenario. Range for current reformation costs based on +/- 25% natural gas price.
3 Unit costs assumptions are the same as (1), plus CCS capex (for 100k Nm3 / h SMR facility): $145 million (current), $135 million (2030). Currently operational projects with CCS may have lower than 90% capture rates. Negative values not shown but feasible with high percentages of RNG.
4 Assumes alkaline electrolyzer with installed capex: $1400/kW (current, 2MW electrolyzer, 450 Nm3/h), $425 / kW (2030, ~90MW electrolyzer, 20,000 Nm3/h); reference case based on NREL ATB Class 5 onshore wind: capacity factor: 42% (current), 45% (2030), LCOE: $31/MWh (current), $22/MWh (2030); low case based on NREL ATB Class 1 onshore wind: capacity factor: 48% (current), 54% (2030), LCOE: $27/MWh (current), $18/MWh (2030); high case based on NREL ATB Class 9 onshore wind: capacity factor: 27% (current), 30% (2030), LCOE: $48/MWh (current), $33/MWh (2030)
5 Electricity unit costs are based on median, top quartile, and bottom quartile 2030 grid LCOE by census region from EIA Annual Energy Outlook 2022; assumes the same electrolyzer installed capex as (5); median LCOE: $68/MWh (current), $63/MWh (2030); top quartile LCOE: $66/MWh (current), $62/MWh (2030); bottom quartile LCOE: $89/MWh (current), $80/MWh (2030); Grid carbon intensities are based on data from the Carnegie Mellon Power Sector Carbon Index as well as national averages in grid mix carbon intensity – in some states, grid carbon intensity can be as high as 40 kg CO2e / kg H2 (absent power import / export across sate lines that can lower the carbon intensity of consumption, relative to generation)
6 Values with RNG not shown (which could include negative carbon intensities)
Sources: Hydrogen Council, NREL Annual Technology Baseline 2022, EIA Annual Energy Outlook 2022

Figure 1-19 DOE Comparison of Domestic Hydrogen Production Pathways[745]

The figure shows that today in the United States, over 95 percent of hydrogen is produced from natural gas through a process called steam methane reforming (SMR). Auto-thermal reforming (ATR) is another gas reforming technology that is less prevalent today but has slightly better performance and economics when paired with carbon capture technologies.[746] The methane in natural gas reacts with high-temperature steam under pressure and in the presence of a catalyst to create hydrogen and carbon monoxide (CO). The CO then reacts with steam to create carbon dioxide and more hydrogen.[747] To reduce GHG impact, efforts are underway to test the potential of capturing the CO_2 created by SMR or ATR and either storing it underground or using it commercially. This potential strategy is commonly referred to as carbon capture and

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[745] U.S. Department of Energy. “Pathways to Commercial Liftoff: Clean Hydrogen”. March 2023. Available online: https://liftoff.energy.gov/wp-content/uploads/2023/03/20230320-Liftoff-Clean-H2-vPUB.pdf.

[746] Oni, A.O.,et. al. “Comparative assessment of blue hydrogen from steam methane reforming, autothermal reforming, and natural gas decomposition technologies for natural gas-producing regions”. Energy Conversion and Management, Volume 254. February 15, 2022. Available online: https://www.sciencedirect.com/science/article/pii/S0196890422000413.

[747] U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office. “Hydrogen Production: Natural Gas Reforming”. Available online: https://www.energy.gov/eere/fuelcells/hydrogen-production-natural-gas-reforming.

storage (CCS).[748] A concern with SMR or ATR and CCS is methane leakage, since methane is a greenhouse gas that is more potent than CO_2 at trapping heat in the atmosphere.[749] EPA finalized a rule in 2023 to reduce methane from both new and existing sources in the oil and natural gas industry that could help address this problem.[750]

Electrolysis, which does not involve methane, is the process of splitting water. Electrolyzers are viable today. They function like fuel cells in reverse: fuel cells consume hydrogen and oxygen to make electricity and water, while electrolyzers consume electricity and water to make hydrogen and oxygen. When powered using the standard electricity grid, lifecycle emissions can vary significantly by region across the country depending on the carbon intensity of the grid. Over time as the grid decarbonizes, grid electrolysis would get cleaner. When powered using renewable or nuclear energy, electrolyzers have low GHGs on a lifecycle emissions basis.[751,752]

Electrolysis is, however, energy intensive. DOE is investing in baseload energy resources including nuclear reactors to scale low-GHG hydrogen production quickly and reduce technology costs,[753] and in hydropower dams that can also offer baseload energy for hydrogen production.[754,755] Electricity production at large existing reactors and dams is difficult to ramp up and down. The desire to operate even when demand for electricity is low makes electricity storage systems such as electrolytic hydrogen attractive as additive technologies for these large generation assets in the near term. The potential for large-scale storage of excess hydrogen in underground salt or lined hard rock caverns for later use when needed is an area of active research.[756] In the longer term, the need to balance electrical load across non-emitting generation assets such as wind, solar, nuclear, and hydro will create additional opportunities for hydrogen storage technologies.

Pyrolysis is similar to biomass gasification (a process that uses heat, steam, and oxygen to convert biomass to hydrogen and other byproducts) but without the use of oxygen. Both processes can use methane generated from the decay of biomass, which can range from

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[748] When also discussing the possibility of using CO_2 commercially, this strategy is referred to as carbon capture, utilization, and storage (CCUS).

[749] The GHG intensities of hydrogen made using methane (SMR, ATR, and pyrolysis) also depend on the extent of methane leaks during the production and transportation of the natural gas feedstock.

[750] U.S. Environmental Protection Agency. “EPA’s Final Rule for Oil and Natural Gas Operations Will Sharply Reduce Methane and Other Harmful Pollution”. December 2, 2023. Available online: https://www.epa.gov/controlling-air-pollution-oil-and-natural-gas-operations/epas-final-rule-oil-and-natural-gas.

[751] Electrolysis powered by solar or wind energy can include indirect upstream emissions of GHGs associated with building the system components and potential land use impacts.

[752] U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office. “Hydrogen Production Pathways”. Available online: https://www.energy.gov/eere/fuelcells/hydrogen-production-pathways.

[753] U.S. Department of Energy, Office of Nuclear Energy. “3 Nuclear Power Plants Gearing Up for Clean Hydrogen Production”. November 9, 2022. Available online: https://www.energy.gov/ne/articles/4-nuclear-power-plants-gearing-clean-hydrogen-production.

[754] McCue, Dan. “IRA Expected to Be ‘Transformative’ for Hydropower Sector”. The Well News: Well Powered. August 22, 2022. Available online: https://www.thewellnews.com/energy/ira-expected-to-be-transformative-for-hydropower-sector/.

[755] Ashcroft, Nathan and Pietro Di Zanno. “Hydropower: A Cost-Effective Source of Energy for Hydrogen Production”. Power. November 1, 2021. Available online: https://www.powermag.com/hydropower-a-cost-effective-source-of-energy-for-hydrogen-production/.

[756] U.S. Department of Energy. “Bulk Storage of Gaseous Hydrogen: 2022 Workshop Summary Report”. February 10-11, 2022. Available online: https://www.energy.gov/sites/default/files/2022-05/bulk-storage-gaseous-hydrogen-2022_0.pdf.

agricultural crop or forest residues to organic municipal solid waste or animal-based wastestreams. These technologies do not involve combustion but may require the use of a catalyst.[757] Pyrolysis has other market dependences that drive uncertainty, so is considered to have lower potential as a low-GHG pathway than SMR with CCS and electrolysis.[758]

1.8.2.2 Hydrogen Distribution and Storage

Hydrogen can be commercially delivered today in either gaseous or liquid form. Through 2030, we expect that gaseous or liquid trucking to hydrogen refueling stations from central production facilities is likely to be a primary method of distributing hydrogen. Tube trailers that carry compressed hydrogen gas contain long cylinders that are stacked on a trailer, like those that carry compressed natural gas. They can carry up to 900 kg of hydrogen per trailer.[759] Gaseous delivery requires less capital than liquid delivery and can be cost-effective at smaller scales and shorter distances.[760] Delivery using cryogenic liquid tanker trucks is more economical for longer distances and higher volume demands, with the potential to carry roughly five times the amount of energy in a comparable truck of gaseous hydrogen.[761] Liquefaction requires about 30 percent more energy to cool the hydrogen below -253 degrees Celsius (-423 degrees Fahrenheit) and can result in boil-off during delivery, despite the quality of the insulation of the “dewar” or tank.[762]

An alternative to trucking hydrogen to a fueling station is to produce hydrogen onsite. This can be costly but can offer a solution for locations that require larger volumes of hydrogen on a regular basis. Consumers can purchase methane reformers or electrolyzers. Access to existing natural resources and feedstocks such as natural gas and water at low cost, the carbon intensity and cost of electricity, and other factors can be influential.[763]

On-site hydrogen storage is required throughout the supply chain such as at central hydrogen production facilities, transport terminals, and end-use refueling stations for HD FCEVs. There are common high-pressure gaseous storage vessels and super-insulated, low-pressure vessels to store liquid hydrogen. Hydrogen infrastructure can also require geologic or underground bulk storage to handle variations in demand throughout the year. There are few existing salt caverns

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[757] U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office. “Hydrogen Production: Biomass Gasification”. Available online: https://www.energy.gov/eere/fuelcells/hydrogen-production-biomass-gasification.

[758] U.S. Department of Energy. “Pathways to Commercial Liftoff: Clean Hydrogen”. March 2023. Available online: https://liftoff.energy.gov/wp-content/uploads/2023/03/20230320-Liftoff-Clean-H2-vPUB.pdf.

[759] U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office. “Hydrogen Tube Trailers”. Available online: https://www.energy.gov/eere/fuelcells/hydrogen-tube-trailers.

[760] U.S. Department of Energy. “Pathways to Commercial Liftoff: Clean Hydrogen”. March 2023. Available online: https://liftoff.energy.gov/wp-content/uploads/2023/03/20230320-Liftoff-Clean-H2-vPUB.pdf.

[761] Mulder, Brandon. “Liquid hydrogen seen as ‘holy grail’ for hydrogen uptake in the mobility sector: Linde COO”. S&P Global: Commodity Insights. November 16, 2021. Available online: https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/energy-transition/111621-liquid-hydrogen-seen-as-holy-grail-for-hydrogen-uptake-in-mobility-sector-linde-coo.

[762] U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office. “Liquid Hydrogen Delivery”. Available online: https://www.energy.gov/eere/fuelcells/liquid-hydrogen-delivery.

[763] Quimby, Tom. “Producing hydrogen on-site ‘gives flexibility now’”. CCJ. July 27, 2022. Available online: https://www.ccjdigital.com/alternative-power/hydrogen-fuel-cell/article/15294540/producing-hydrogen-onsite-gives-flexibility-now.

used for hydrogen storage today. The use of hydrogen stored underground for FCEVs requires further investigation due to the introduction of possible impurities.[764]

In the long term,[765] a dedicated hydrogen pipeline system could be cost-effective as hydrogen utilization and production volumes grow and provide economies of scale.[766] Dedicated hydrogen pipelines can move hydrogen from low-cost production regions to clusters of demand, which can make it easier to then truck hydrogen to individual stations in lower volumes.[767] In the U.S., there is a network of about 1,600 miles of existing pipeline networks that are concentrated in areas where hydrogen is currently produced and consumed, primarily in the Gulf Coast region.[768]

To fill gaps in distribution in the short term, mobile fueling is another option, where fuel providers can deliver a self-contained unit of product that can directly fuel a vehicle. Mobile fuelers can be deployed quickly and can help meet the immediate and initial fueling needs of smaller and growing fleets at lower capital costs than a permanent refueling station. Mobile fueling can be deployed during the construction of a fueling station, and may be viable for remote locations or for operations that require limited amounts of fuel.[769]

1.8.2.3 Hydrogen Fueling Stations

Once onsite, hydrogen may need to be conditioned for consumption in vehicles using compressors, dispensers, chillers, and the like. Fuel is typically dispensed into FCEVs as a pressurized gas. The development of HD refueling stations will necessitate the establishment of uniform measures (e.g., refueling protocols, purity standards, metering requirements, component standardization) to ensure that stations perform efficiently, effectively, and safely. Safety-related codes and standards associated with fueling FCEVs are discussed in Chapter 1.7.4.

As is the case with BEVs (see Chapter 1.6.1.3), fleets adopting fuel cell technologies may opt for a private depot fueling model. Many of today's diesel fleet vehicles are fueled at private depots and, upon conversion, may prefer to maintain this model. However, we considered FCEVs in our modeled potential compliance pathway for select applications, including some day cab and sleeper cab tractors, that travel longer distances. We project that these vehicle applications would be less likely to return to base for regular fueling and would likely need to use public en-route refueling on the way to their next location.

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[764] U.S. DOE EERE Hydrogen and Fuel Cell Technologies Office, On-Site and Bulk Hydrogen Storage, https://www.energy.gov/eere/fuelcells/site-and-bulk-hydrogen-storage.

[765] We do not anticipate long-distance pipelines in the near-term so do not address topics such as potential for metal embrittlement or hydrogen blending with natural gas.

[766] Ogden, Joan et. al. "Natural gas as a bridge to hydrogen transportation fuel: Insights from the literature". Energy Policy, Volume 115. April 2018. Available online: https://www.sciencedirect.com/science/article/pii/S0301421517308741.

[767] U.S. Department of Energy. "Pathways to Commercial Liftoff: Clean Hydrogen". March 2023. Available online: https://liftoff.energy.gov/wp-content/uploads/2023/03/20230320-Liftoff-Clean-H2-vPUB.pdf.

[768] U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office. "Hydrogen Pipelines". Available online: https://www.energy.gov/eere/fuelcells/hydrogen-pipelines#:~:text=Approximately%201%2C600%20miles%20of%20hydrogen,as%20the%20Gulf%20Coast%20region.

[769] U.S. Department of Energy, Alternative Fuels Data Center. "Hydrogen Fueling Stations". Available online: https://afdc.energy.gov/fuels/hydrogen_stations.html.

1.8.3 Status and Outlook of Hydrogen Refueling Infrastructure

Chapter 1.3.2 includes a description of numerous provisions in BIL and IRA designed to support the deployment of ZEVs and supportive infrastructure, including policies and incentives to reduce the cost of clean hydrogen production and jumpstart the hydrogen market in the United States. These programs are informed by demand scenarios to increase clean hydrogen production from nearly zero today to 10 million metric tons (MMT) per year by 2030, 20 MMT per year by 2040, and 50 MMT per year by 2050.[770]

EPA has seen progress on the implementation of BIL and IRA funding and other provisions to incentivize the establishment of clean hydrogen supply chain infrastructure. In June 2021, DOE launched a Hydrogen Shot goal to reduce the cost of clean hydrogen production by 80 percent to $1 per kilogram in one decade.[771] In March 2023, DOE released a Pathways to Commercial Liftoff Report on "Clean Hydrogen" to catalyze more rapid and coordinated action across the full technology value chain. Since the NPRM, the federal government has continued to deliver on BIL and IRA commitments. In June 2023, the U.S. National Clean Hydrogen Strategy and Roadmap was finalized, informed by extensive industry and stakeholder feedback, setting forth an all-of-government approach for achieving large-scale production and use of hydrogen and an assessment of the opportunity for hydrogen to contribute to national decarbonization goals across sectors over the next 30 years.[772] Also in June 2023, DOE updated Clean Hydrogen Production Standard (CHPS) guidance that establishes a target for lifecycle (defined as "well-to-gate") GHG emissions associated with hydrogen production, accounting for multiple requirements within the BIL provisions.[773] In October 2023, DOE announced the selection of seven Regional Clean Hydrogen Hubs (H2Hubs) in different regions of the country that will receive a total of $7 billion to kickstart a national network of hydrogen producers, consumers, and connective infrastructure while supporting the production, storage, delivery, and end-use of hydrogen. The investment will be matched by recipients to leverage a total of nearly $50 billion for the hubs, which are expected to reduce 25 million metric tons of carbon dioxide emissions each year from end uses ranging from industrial steel to HD transportation.[774]

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[770] U.S. Department of Energy. "U.S. National Clean Hydrogen Strategy and Roadmap". June 2023. Available online: https://www.hydrogen.energy.gov/library/roadmaps-vision/clean-hydrogen-strategy-roadmap, https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/us-national-clean-hydrogen-strategy-roadmap.pdf.

[771] Satyapal, Sunita. "2022 AMR Plenary Session". U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office. June 6, 2022. Available online: https://www.energy.gov/sites/default/files/2022-06/hfto-amr-plenary-satyapal-2022-1.pdf.

[772] U.S. Department of Energy. "U.S. National Clean Hydrogen Strategy and Roadmap". June 2023. Available online: https://www.hydrogen.energy.gov/library/roadmaps-vision/clean-hydrogen-strategy-roadmap, https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/us-national-clean-hydrogen-strategy-roadmap.pdf.

[773] U.S. Department of Energy, Hydrogen Program. "Clean Hydrogen Production Standard Guidance". June 2023. Available online: https://www.hydrogen.energy.gov/library/policies-acts/clean-hydrogen-production-standard, https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/clean-hydrogen-production-standard-guidance.pdf.

[774] U.S. Department of Energy. "Biden-Harris Administration Announces $7 Billion For America's First Clean Hydrogen Hubs, Driving Clean Manufacturing and Delivering New Economic Opportunities Nationwide". October 13, 2023. Available online: https://www.energy.gov/articles/biden-harris-administration-announces-7-billion-americas-first-clean-hydrogen-hubs-driving.

Several programs initiated by BIL and IRA investments that could influence the character of the emerging hydrogen production market are under ongoing development. In March 2023, DOE announced $750 million for research, development, and demonstration efforts to reduce the cost of clean hydrogen. This is the first phase of $1.5 billion in BIL funding dedicated to advancing electrolysis technologies and improving manufacturing and recycling capabilities.[775] In July 2023, DOE released a Notice of Intent to invest up to $1 billion in a demand-side initiative (to offer "demand pull") to support the H2Hubs.[776] In January 2024, DOE selected a consortium to design and implement the program.[777] (H2Hub negotiations are still underway.[778]) And in December 2023, the Treasury Department and Internal Revenue Service proposed regulations to offer income tax credit of up to $3 per kg for the production of qualified clean hydrogen at a qualified clean hydrogen facility (often referred to as the production tax credit, PTC, or 45V), as established in the IRA.[779] Final program designs are expected after this rule is finalized.[780,781] See Section 8.1 of the RTC for additional detail.

1.8.3.1 Current Refueling Network

Currently, DOE's Alternative Fuels Data Center (AFDC) lists 65 public retail hydrogen fueling stations in the United States, primarily for light-duty vehicles in California.[782] When

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[775] U.S. Department of Energy. "Biden-Harris Administration Announces $750 Million to Advance Clean Hydrogen Technologies". March 15, 2023. Available online: https://www.energy.gov/articles/biden-harris-administration-announces-750-million-advance-clean-hydrogen-technologies#:~:text=This%20funding%E2%80%94the%20first%20phase,the%20widespread%20use%20of%20clean.

[776] U.S. Department of Energy. "Biden-Harris Administration to Jumpstart Clean Hydrogen Economy with New Initiative to Provide Market Certainty and Unlock Private Investment". July 5, 2023. Available online: https://www.energy.gov/articles/biden-harris-administration-jumpstart-clean-hydrogen-economy-new-initiative-provide-market.

[777] U.S. Department of Energy, Office of Clean Energy Demonstrations. "DOE Selects Consortium to Bridge Early Demand for Clean Hydrogen, Providing Market Certainty and Unlocking Private Sector Investment". January 14, 2024. Available online: https://www.energy.gov/oced/articles/doe-selects-consortium-bridge-early-demand-clean-hydrogen-providing-market-certainty.

[778] U.S. Department of Energy, Office of Clean Energy Demonstrations. "Funding Notice: Regional Clean Hydrogen Hubs". Available online: https://www.energy.gov/oced/funding-notice-regional-clean-hydrogen-hubs.

[779] 88 FR 89220. Section 45V Credit for Production of Clean Hydrogen; Section 48(a)(15) Election To Treat Clean Hydrogen Production Facilities as Energy Property. December 26, 2023. Available online: https://www.federalregister.gov/documents/2023/12/26/2023-28359/section-45v-credit-for-production-of-clean-hydrogen-section-48a15-election-to-treat-clean-hydrogen.

[780] As the value of the PTC credit is based on lifecycle greenhouse gas emissions associated with the hydrogen production process, there is significant potential for the PTC to reduce overall GHG emissions associated with hydrogen production in the coming years. An analysis by Rhodium Group estimates that the proposed regulations could reduce between 8 and 236 million metric tons of CO2-equivalent emissions cumulatively between 2024 and 2035 because of the PTC, pending final decisions about the rule.

[781] King, et. al. "How Clean Will US Hydrogen Get? Unpacking Treasury's Proposed 45V Tax Credit Guidance". Rhodium Group. January 4, 2024. Available online: https://rhg.com/research/clean-hydrogen-45v-tax-guidance/.

[782] U.S. Department of Energy, Alternative Fuels Data Center. "Hydrogen Fueling Station Locations". See Advanced Filters, Fuel, "Hydrogen" checked (not "include non-retail stations"). Accessed February 15, 2024. Available online: https://afdc.energy.gov/fuels/hydrogen_locations.html#/analyze?fuel=HY.

including private, planned, and temporarily unavailable stations in a search, there are 99 refueling station locations nationwide.[783,784,785]

There are also several nationally designated corridor-ready or corridor-pending Alternative Fueling Corridors for hydrogen.[786] Corridor-ready designations have a sufficient number of fueling stations to allow for corridor travel. The designation requires that public hydrogen stations be no greater than 150 miles apart and no greater than five miles off the highway.[787] Corridor-pending designations may have public stations separated by more than 150 miles, but stations cannot be greater than five miles off the highway.[788] The purpose of the Alternative Fuel Corridors program is to support the needed changes in the transportation sector that assists in reducing greenhouse gas emissions and improves the mobility of vehicles that employ alternative fuel technologies across the U.S.[789] Figure 1-20 shows the most recent map of mostly "pending" hydrogen corridors, with two corridor-ready designations for hydrogen in California.

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[783] U.S. Department of Energy, Alternative Fuels Data Center. See Advanced Filters, Station, all "Access" and "Status" options checked. Accessed February 15, 2024. Available online: https://afdc.energy.gov/fuels/hydrogen_locations.html#/analyze?fuel=HY.

[784] When including non-retail stations, there are 132. Non-retail stations involve special permissions from the original equipment manufacturers to fuel along with pre-authorization from the station provider.

[785] U.S. Department of Transportation, Hydrogen and Fuel Cell Technologies Office. "Fact of the Month #18-01, January 29". 2018. Available online: https://www.energy.gov/eere/fuelcells/fact-month-18-01-january-29-there-are-39-publicly-available-hydrogen-fueling.

[786] U.S. Department of Transportation, Federal Highway Administration. HEPGIS. "Hydrogen (AFC Rounds 1-7)". Accessed January 2024. Available online: https://hepgis-usdot.hub.arcgis.com/apps/e1552ac704284d30ba8e504e3649699a/explore..

[787] U.S. Department of Transportation, Federal Highway Administration. "Memorandum, INFORMATION: Request for Nominations—Alternative Fuel Corridor (Round 7/2023)". May 18, 2023. Available online: https://www.fhwa.dot.gov/environment/alternative_fuel_corridors/nominations/2023_request_for_nominations_r7.pdf.

[788] U.S. Department of Transportation, Federal Highway Administration. "Alternative Fuel Corridors: Frequently Asked Questions FAST Act Section 1413—Alternative Fuel Corridor Designations Updated December 2020 to Support Round 5". Available online: https://www.fhwa.dot.gov/environment/alternative_fuel_corridors/resources/faq/.

[789] U.S. Department of Transportation, Federal Highway Administration. "Alternative Fuel Corridors". Available online: https://www.fhwa.dot.gov/environment/alternative_fuel_corridors/.

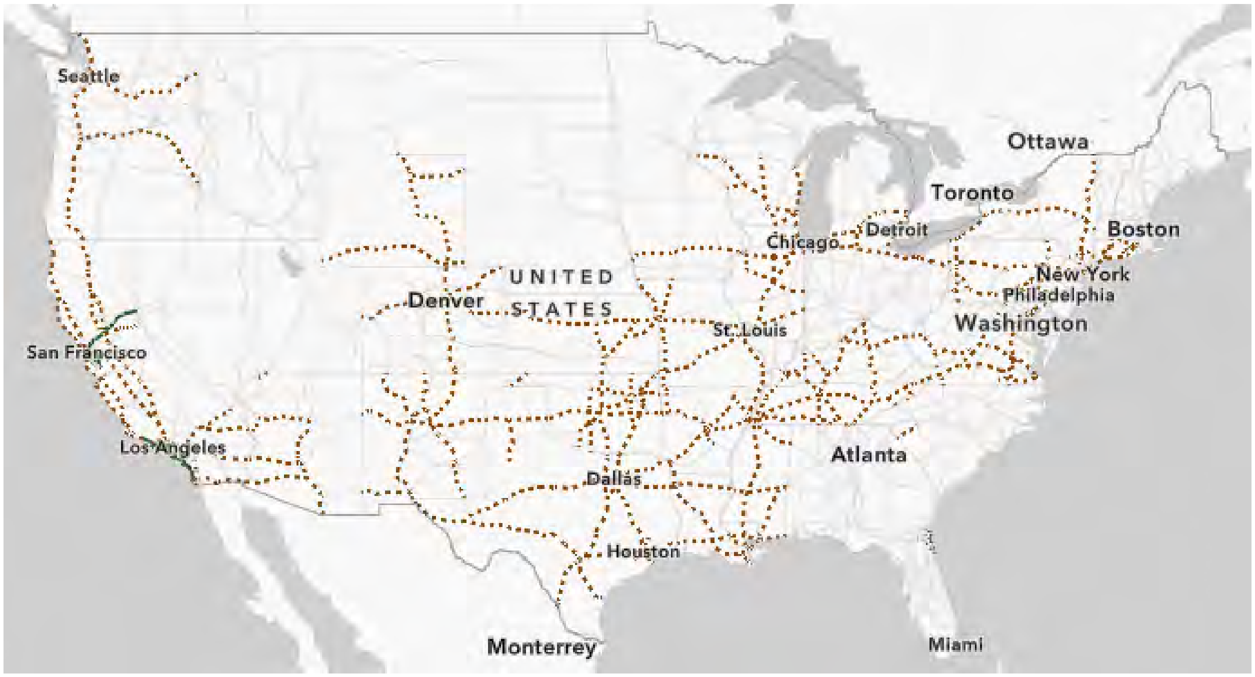

Figure 1-20 FHWA-Designated Alternative Fuel Corridors for Hydrogen[790] Hydrogen Round 1, 2, 3, 4, 5, 6 and 7: Ready (straight lines) and Pending (dotted lines)

1.8.3.2 The Evolving Hydrogen Market and Investment

While many companies produce hydrogen for their own internal use, the list of companies that produce and sell hydrogen in North America (i.e., "merchant" producers of hydrogen) is much smaller. Three companies—Air Products, Air Liquide, and Linde—produce a large majority of the merchant hydrogen for North American markets. Their products are predominantly produced via SMR.[791]

As government and commercial support for both low-GHG hydrogen as a transportation fuel and electrolytic hydrogen in general have grown in recent years, existing companies such as Siemens and Cummins and new participants such as Plug Power and Nel Hydrogen have emerged in this space to supply these products.[792] These companies have diverse business models. Some focus on production of hydrogen only, while others seek to become turnkey solutions for companies looking to source hydrogen for vehicle use. Production strategies vary as well, with some companies focusing on centralized production while others invest in onsite production models. It is too early to tell whether growth in hydrogen supply and demand will lead to a shifting landscape in the merchant hydrogen sector, or whether the established market

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[790] U.S. Department of Transportation, Federal Highway Administration. HEPGIS. "Hydrogen (AFC Rounds 1-7)". Accessed January 2024. Available online: https://hepgis-usdot.hub.arcgis.com/apps/e1552ac704284d30ba8e504e3649699a/explore.

[791] Hydrogen Tools. "Merchant Hydrogen Plant Capacities in North America". Pacific Northwest National Laboratory. January 2016. Available online: https://h2tools.org/hyarc/hydrogen-data/merchant-hydrogen-plant-capacities-north-america.

[792] Kearney Energy Transition Institute. "Hydrogen applications and business models". June 2020. Available online: https://www.kearney.com/documents/17779499/18269679/Hydrogen+FactBook+Final+-+June+2020.pdf/01ae498b-3d38-deca-2a61-6f107699dde1?t=1592252815706.

players will expand their portfolio to meet the need for low-GHG hydrogen as well. According to Cipher's Clean Technology Tracker, as of September 2023, there is $45.752 billion in total clean hydrogen production project investment in the United States,[793] with 1 percent in projects that are in operation (close to $500,000), 7 percent ($3.2 million) under construction, and a majority still classified as announced.[794] DOE has started tracking private sector announcements of domestic electrolyzers and fuel cell manufacturing facilities. So far, over $1.8 billion in new investments has been announced for over 10 new or expanded facilities with the capacity to manufacture approximately 10 GW of electrolyzers per year.[795] BIL and IRA programs are under ongoing development, but we anticipate that investment strategies (e.g., that connect producers of hydrogen with end users of fuel) will amplify and become clearer over time after the rule is finalized as policy and process details start to settle. We also expect this rule will provide greater certainty to the market to support timely development of hydrogen refueling stations.

DOE announced $98 million in grants to help build five hydrogen fueling stations for HD freight trucks in Texas and create a hydrogen corridor from California to Texas. They also announced grants for two public hydrogen fueling stations in California and three public stations in Colorado.[796] As of 2023, California expects to have at least seven stations capable of fueling HD vehicles by 2027.[797]

There is a broad awareness that, as hydrogen production scales, midstream (e.g., distribution and storage) and downstream (e.g., refueling station) infrastructure will need to expand to enable end users of hydrogen that are not co-located with production at hubs. Midstream and downstream infrastructure could account for half of the necessary investment through 2030 ($45-103 billion) to get to commercial liftoff of a clean hydrogen market.[798]

The following sampling of announcements to date indicate private sector involvement and interest in establishing a refueling station network for HD FCEVs:

- By the end of 2026, Nikola plans to have 60 hydrogen refueling stations in place.

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[793] According to the Clean Technology Tracker, clean hydrogen production refers to the production of hydrogen fuel with proton exchange membrane (PEM) electrolyzers and solid oxide electrolyzer cells (SOEC) or through other methods such as methane pyrolysis and natural gas with carbon capture.

[794] Cipher News. "Tracking a new era of climate solutions: Cleantech growth across the U.S." Accessed February 2024. Available online: https://ciphernews.com/cleantech-tracker/#definitions.

[795] U.S. Department of Energy. "Building America's Clean Energy Future—Hydrogen: Electrolyzers and Fuel Cells". Accessed February 2024. Available online: https://www.energy.gov/invest.

[796] U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office. "Biden-Harris Administration Announces $623 Million in Grants for EV Charging and Alternative Fueling—Including More Than $90 Million for Hydrogen Infrastructure". January 30, 2024. Available online: https://www.energy.gov/eere/fuelcells/articles/biden-harris-administration-announces-623-million-grants-ev-charging-and.

[797] Crowell, et. al. "Joint Agency Staff Report on Assembly Bill 8: 2023 Annual Assessment of the Hydrogen Refueling Network in California". CEC/CARB. December 2023. Available online: https://www.energy.ca.gov/sites/default/files/2023-12/CEC-600-2023-069.pdf.

[798] U.S. Department of Energy. "Pathways to Commercial Liftoff: Clean Hydrogen". March 2023. Available online: https://liftoff.energy.gov/wp-content/uploads/2023/03/20230320-Liftoff-Clean-H2-vPUB.pdf.

  - In August 2023, Nikola received a grant of $58.2 million to build six refueling stations for HD FCEVs in California.[799]
  - Nikola and Voltera formed a strategic partnership to develop 50 Hyla refueling stations for commercial vehicles throughout North America over five years (i.e., through 2027 to 2028).[800]
  - In February 2024, Nikola opened its first private hydrogen refueling station in Ontario, CA, that can fuel up to 40 Class 8 FCEVs every day.[801]

- Daimler Truck North America, LLC (DTNA), NextEra Energy Resources, LLC, and BlackRock Alternatives announced Greenlane, a $650 million joint venture to develop, design, and operate a nationwide public charging and hydrogen fueling network for MHDV BEVs and FCEVs.[802]
- Libertad Power, Hyundai Motor Company, and Diesel Direct partnered to develop a hydrogen-fueled Southwest Clean Freight Corridor, with plans to build an electrolysis plant by 2025 to produce 20 to 30 tons of hydrogen per day to start to supply stations in four states (i.e., Texas, New Mexico, Arizona, and California).[803]
- FirstElement is providing hydrogen fuel at 700 bar pressure through its True Zero network of liquid refueling stations in California to test Hyundai XCIENT truck.[804]

Mobile refueling can help fill initial temporary gaps in the refueling station network in the near-term as fleets transition to FCEVs:

- Under the Hyla brand, Nikola launched flexible mobile fueling trailers to support previously announced projects with Buckeye, AZ (150 tpd); Plug Power (up to 125

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[799] Balaraman, Kavya. “Nikola bags $58.2 million for hydrogen stations to fuel heavy-duty vehicles”. Pv Magazine. August 11, 2023. Available online: https://pv-magazine-usa.com/2023/08/11/nikola-bags-58-2-million-for-hydrogen-stations-to-fuel-heavy-duty-vehicles/.

[800] Ohnsman, Alan. “Nikola Partners With Voltera To Build Up To 50 Stations For Hydrogen Trucks. Forbes. May 2, 2023. Available online: https://www.forbes.com/sites/alanohnsman/2023/05/02/nikola-partners-with-voltera-to-build-up-to-50-stations-for-hydrogen-trucks/?sh=4dfcc722fb0d.

[801] Balaraman, Kavya. “Nikola opens hydrogen refueling station for heavy-duty vehicles in California”. PR Newswire. February 9, 2024. Available online: https://www.pv-magazine.com/2024/02/09/nikola-opens-hydrogen-refueling-station-for-heavy-duty-vehicles-in-california/.

[802] NextEra Energy Resources, LLC; Daimler Truck North America, LLC; BlackRock Alternatives. “Introducing Greenlane: Daimler Truck North America, NextEra Energy Resources and BlackRock Forge Ahead with Public Charging Infrastructure Joint Venture”. PR Newswire. April 28, 2023. Available online: https://www.prnewswire.com/news-releases/introducing-greenlane-daimler-truck-north-america-nextera-energy-resources-and-blackrock-forge-ahead-with-public-charging-infrastructure-joint-venture-301811101.html.

[803] Tank Storage News America. “NM to be Part of Clean Freight Corridor”. September 29, 2022. Available online: https://tankstoragenewsamerica.com/nm-to-be-part-of-clean-freight-corridor/.

[804] Williams, Bret. “FirstElement Fuel’s H2 refueling stations support Hyundai Motor’s fuel cell truck pilot program. Hydrogen Fuel News. March 16, 2023. Available online: https://www.hydrogenfuelnews.com/h2-refueling-firstelement-hyundai/8557730/.

tpd); Terre Haute, Indiana (50 tpd); Crossfield, Alberta, Canada (60 tpd); and Clinton County, Pennsylvania (100 tpd).[805]

  - Nikola signed purchase orders with Chart Industries, Inc, for multiple liquid hydrogen storage tanks, mobile and modular refueling stations, and liquid hydrogen transport trailers to support the quick deployment of HD FCEVs by meeting immediate and interim fueling needs.[806]

- Hyundai is partnering with FirstElement for high capacity mobile refuelers at 128 kg per hour to support HD FCEV OEM truck pilots.[807,808]
- Air Products offers portable fueling units that hold 150 kg of hydrogen for both short- and long-term deployments that can be delivered to customers with very short lead-times.[809]
- J.B. Hunt is piloting a Hydrogen Truck Ecosystem that includes General Motors Hydrotec Fuel Cell Power Cube technology, which uses Navistar and OneH2's modular, mobile, and scaleable hydrogen production and fueling capabilities.[810,811]

Some states have taken action:

- Illinois passed legislation to create a $1 per kg tax credit for end users of zero-carbon hydrogen in 2026 and 2027.[812]

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[805] Buckley, Julian. "Nikola launches Hyla to support hydrogen fuel distribution". Power Progress. January 26, 2023. Available online: https://www.powerprogress.com/news/nikola-launches-hyla-to-support-hydrogen-fuel-distribution/8026221.article.

[806] Nikola. "Chart Industries and Nikola Execute Strategic Partnership for Hydrogen-Related Equipment". March 30, 2023. Available online: https://www.nikolamotor.com/press_releases/chart-industries-and-nikola-execute-strategic-partnership-for-hydrogen-related-equipment/#:~:text=Nikola%20has%20recently%20signed%20purchase,advance%20the%20efforts%20to%20decarbonize.

[807] FirstElement Fuel. "FirstElement Fuel partners with Hyundai Motor on hydrogen refueling of class 8 fuel cell electric trucks, driving over 25K miiles with zero emissions". PR Newswire. March 14, 2023. Available online: https://www.prnewswire.com/news-releases/firstelement-fuel-partners-with-hyundai-motor-on-hydrogen-refueling-of-class-8-fuel-cell-electric-trucks-driving-over-25k-miles-with-zero-emissions-301770655.html.

[808] Williams, Bret. "FirstElement Fuel's H2 refueling stations support Hyundai Motor's fuel cell truck pilot program. Hydrogen Fuel News. March 16, 2023. Available online: https://www.hydrogenfuelnews.com/h2-refueling-firstelement-hyundai/8557730/.

[809] Air Products. "Portable Hydrogen Fueler". Available online: https://www.airproducts.com/services/portable-hydrogen-fueler.

[810] Navistar International Corporation. "Navistar Collaborates with General Motors and OneH2 To Launch Hydrogen Truck Ecosystem". PR Newswire. January 27, 2021. Available online: https://www.prnewswire.com/news-releases/navistar-collaborates-with-general-motors-and-oneh2-to-launch-hydrogen-truck-ecosystem-301216246.html.

[811] Navistar. "Hydrogen Fuel Cell: Modular, Mobile, and Scalable". Available online: https://www.navistar.com/en/our-path-forward/hydrogen-fuel-cell.

[812] Martin, Polly. "Illinois introduces tax credit for 'zero-carbon' hydrogen users in hard-to-abate sectors—for two years only". HydrogenInsight. July 26, 2023. Available online: https://www.hydrogeninsight.com/policy/illinois-introduces-tax-credit-for-zero-carbon-hydrogen-users-in-hard-to-abate-sectors-for-two-years-only/2-1-1491693.

- Colorado passed legislation to provide up to $1 per kg for the use of clean hydrogen in hard-to-decarbonize sectors.[813]
- Pennsylvania has a Regional Clean Hydrogen Hubs Tax Credit for qualified taxpayers who purchase clean hydrogen or natural gas for use in a manufacturing facility in the state. The credit offers $0.18 per kg of clean hydrogen from a H2Hub in the state and/or $0.47 per kg of natural gas.[814]
- California lawmakers passed Senate Bill 1291 in 2022 that requires all cities and counties in the state to develop an expedite streamlined permitting process for hydrogen fueling stations that meet certain criteria until 2030.[815]

Hydrogen refueling network investment plans and players will continue to evolve as programs spurred by federal investment through BIL and IRA are implemented.[816]

1.8.3.3 Hydrogen Hubs

As mentioned in Chapter 1.8.3, in October 2023, seven Regional Clean Hydrogen Hubs (H2Hubs) were awarded $7 billion in funding to launch a national hydrogen network:

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[813] Toor, Will. “A new Colorado law makes it a top site for clean hydrogen developers, but it’s not a model for federal rules”. UtilityDive. May 25, 2023. Available online: https://www.utilitydive.com/news/colorado-clean-hydrogen-tax-credit-incentives/651199/#:%7E:text=The%20use%20tax%20credit%20is,heavy%2Dduty%20trucking%20and%20aviation.

[814] Pennsylvania Department of Revenue. “Regional Clean Hydrogen Hubs Tax Credit”. Available online: https://www.revenue.pa.gov/IncentivesCreditsPrograms/PAEDGE/Pages/Regional-Clean-Hydrogen-Hubs-Tax-Credit.aspx.

[815] California Governor’s Office of Business and Economic Development. “Hydrogen Station Permit Streamlining Fact Sheet”. August 2023. Available online: https://business.ca.gov/wp-content/uploads/2023/08/SB-1291-Hydrogen-Station-Permit-Streamlining-Fact-Sheet.pdf.

[816] U.S. Department of Energy. “U.S. National Clean Hydrogen Strategy and Roadmap”. June 2023. Available online: https://www.hydrogen.energy.gov/library/roadmaps-vision/clean-hydrogen-strategy-roadmap, https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/us-national-clean-hydrogen-strategy-roadmap.pdf.

Figure 1-21 Map of Regional Clean Hydrogen Hubs[817]

H2Hubs were chosen based on technical merit and impact, including the ability to deploy infrastructure and produce at least 50 to 100 metric tons of clean hydrogen per day; financial and market viability; workplan (e.g., speed and project management details); management team and project partners; and community benefits plan.[818] Table 1-33 indicates the types of transportation-related interests per hub.

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[817] U.S. Department of Energy, Office of Clean Energy Demonstrations. “Regional Clean Hydrogen Hubs Selections for Award Negotiations”. Available online: https://www.energy.gov/oced/regional-clean-hydrogen-hubs-selections-award-negotiations.

[818] U.S. Department of Energy, Office of Clean Energy Demonstrations. “Regional Clean Hydrogen Hubs Selections for Award Negotiations”. Available online: https://www.energy.gov/oced/regional-clean-hydrogen-hubs-selections-award-negotiations.

Table 1-33 Transportation Highlights at H2Hubs

Hub Name	Location (Prime Contractor)	Total Federal Cost Share	Transportation Highlights*
Appalachian Regional Clean Hydrogen Hub (ARCH2)	West Virginia, Ohio, Pennsylvania (Battelle)	Up to $925 million	H2 pipelines, fueling stations Fuel cell electric mining trucks, HD vehicles
California's Alliance for Regional Clean Hydrogen Energy Systems (ARCHES)	California (Alliance for Renewable Clean Hydrogen Energy Systems LLC)	Up to $1.2 billion	Freight network between California and Pacific Northwest Hubs, fueling stations HD vehicles, port equipment, public transit
Gulf Coast's HyVelocity Hydrogen Hub (H2Hub)	Texas (HyVelocity, Inc.)	Up to $1.2 billion	H2 pipeline, refueling stations HD vehicles, marine fuel
Heartland Hydrogen Hub (HH2H)	Minnesota, North Dakota, South Dakota (Energy & Environmental Research Center)	Up to $925 million	Open access storage and pipeline infrastructure
Mid-Atlantic Clean Hydrogen Hub (MACH2)	Pennsylvania, Delaware, New Jersey (Mid-Atlantic Clean Hydrogen Hub, Inc.)	Up to $750 million	Expanded pipeline infrastructure, upgraded bus mechanic depots, refueling stations HD vehicles, refuse and sweeper trucks
Midwest Alliance for Clean Hydrogen (MachH2)	Illinois, Indiana, Michigan (MachH2)	Up to $1 billion	Refueling stations HD vehicles, sustainable aviation fuel
Pacific Northwest Hydrogen Hub (PNW H2)	Washington, Oregon, Montana (Pacific Northwest Hydrogen Association)	Up to $1 billion	Freight network between California and Pacific Northwest Hubs HD vehicles, ports

* Transportation highlights only represent a portion of proposed hub activity and, thus, would only receive a portion of H2Hubs funds.

H2Hubs would produce approximately three million metric tons of hydrogen per year. They may expand and are still subject to change, pending final negotiations in 2024.[819]

1.8.3.4 Projected Demand

Our potential compliance pathway for the final rule projects relatively modest hydrogen demand, even compared to amounts presently available. The final rule projects that hydrogen consumption from FCEVs will be a small proportion of total hydrogen currently produced (see

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[819] U.S. Department of Energy, Office of Clean Energy Demonstrations. "Regional Clean Hydrogen Hubs National Briefing: October 16, 2023". Available online: https://www.energy.gov/oced/regional-clean-hydrogen-hubs-selections-award-negotiations.

Table 1-34). Furthermore, as noted earlier in this section, programs under BIL and IRA are anticipated to potentially increase clean hydrogen production from 10 MMT per year by 2030 to 20 MMT per year by 2040. This represents an average growth in clean hydrogen production of 1 MMT per year in the 2030s, which far outpaces our projected growth of hydrogen consumption from FCEVs in the potential compliance pathway developed to support the feasibility of the final rule.

Table 1-34 Excerpt from Table 6-2 in RIA Chapter 6.5 on Estimated U.S. Oil Import Reductions and Electricity and Hydrogen Consumption Increases due to the Final Rule *

Calendar Year	Hydrogen Consumption (1000 metric tons per year)	% of 2020 U.S. Hydrogen Consumption*
2030	17	0.2%
2031	51	0.5%
2032	130	1.3%

*According to DOE, 10 million metric tons of hydrogen is produced annually.[820]

1.8.3.5 Assessment of Future Hydrogen Refueling Infrastructure Needs

As FCEV adoption grows, more hydrogen refueling infrastructure will be needed to support the HD FCEV fleet. Infrastructure is required during the production, distribution, storage, and dispensing of hydrogen fuel.

We reviewed literature that assesses hydrogen infrastructure needs for the HD transportation sector. The authors used differing analytical approaches and a large range of assumptions about the production, distribution and storage, and dispensing of hydrogen fuel to estimate hydrogen demand for HD FCEVs and the number of refueling stations required to meet that demand. Liu et. al[821] was one of the first to conduct a national assessment of hydrogen fueling needs to support the national long-haul trucking fleet. They found that at 10 percent HD FCEV penetration in 2025, 3553 small- and medium-sized hydrogen refueling stations would be needed along major corridors. Minjares et. al[822] evaluated infrastructure needed to support a goal of 100 percent sales of zero-emission tractor-trailers by 2040. They projected BEV charging stations along with over 220 hydrogen refueling stations by 2030, growing to close to 3000 by 2040. A Ricardo study for the Truck and Engine Manufacturers Association[823] investigated the feasibility of EPA's proposed Phase 3 GHG standards and found that about 10 percent of HD ZEV sales through 2032 would equate to around 128,000 FCEV and H2-ICE vehicles, or a hydrogen demand of about 0.9 million tons per year by 2032. FCEVs and H2-ICE would not start to ramp

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[820] Satyapal, Sunita. "U.S. DOE Hydrogen Program Annual Merit Review (AMR) Plenary Remarks". U.S. Department of Energy. June 5, 2023. Available online: https://www.energy.gov/sites/default/files/2023-06/h2amr-plenary-satyapal-2023_0.pdf.

[821] Liu, et. al. "Evaluating national hydrogen refueling infrastructure requirement and economic competitiveness of fuel cell electric long-haul trucks". Mitigation and Adaption Strategies for Global Change. November 21, 2019. Available online: https://link.springer.com/article/10.1007/s11027-019-09896-z

[822] Minjares, et. al. "Infrastructure to support a 100% zero-emission tractor-trailer fleet in the United States by 2040". International Council on Clean Transportation. September 2021. Available online: https://theicct.org/wp-content/uploads/2021/12/ze-tractor-trailer-fleet-us-hdvs-sept21.pdf.

[823] Kuhn et. al. "Feasibility study of EPA NPRM Phase 3 GHG standards for Medium Heavy-Duty Vehicles. Version: 3.0". Ricardo, prepared for Truck and Engine Manufacturers Association. July 19, 2023.

up until around 2030. They concluded that 696 hydrogen refueling stations would be needed to meet this demand, with 219 stations in Texas and California and 130 stations connected to these networks. The Coordinating Research Council (CRC)[824] evaluated infrastructure needs based on EPA's proposed rule along with other rules in California. They estimated that one percent of the total fleet would result in a demand of 0.89 million metric tons of hydrogen in 2035. They concluded that even with low FCEV penetration, HD FCEVs can play an important role in the long-haul sector. Based on their analysis, buildout of about 600 hydrogen refueling stations by 2030 (370 for HD trucks and buses and 230 for LD cars in California) would increase to about 1350 hydrogen refueling stations for trucks and buses and over 400 hydrogen refueling stations for LD cars in 2035. This review showed how station needs are likely to vary based on demand.

Several papers examined infrastructure costs in the 2030 timeframe, as discussed further in Chapter 2.5.3.1. In general, the authors concluded that economies of scale are important to reduce costs throughout the supply chain. Liu et. al recognized that fueling station availability and location (e.g., distance between stations) and capacity (i.e., station size) are key to determining station costs; when there are more trucks on the road and larger stations, fuel costs are lower. They found that HD FCEV costs and liquefaction costs are also important for cost-competitiveness.[825] Ricardo noted that HD hydrogen refueling station costs are likely to follow the cost reduction pattern of stations for LD vehicles due to economies of scale. They compared cumulative sales in the HD hydrogen market now to the early commercialization of LD FCEVs in 2016 and assumed station cost reductions of about 45 percent by 2032.[826] The Coordinating Research Council (CRC) suggested that station buildout could become faster and easier as economies of scale are achieved, among other factors, and applied a 70 percent reduction in station installation costs from a 2020 baseline by 2035. They recognized that economies of scale throughout the hydrogen supply chain, along with technology advancements and growth in use and demand, are needed to reduce the retail price of hydrogen.[827]

Most researchers of papers that we reviewed agree that it is not necessary to build a national infrastructure network for HD FCEVs all at once. Liu et. al recognized that FCEV technology may not be widely accepted in all regions of the U.S. at the same time. They found that station costs vary by region based on total hydrogen demand and suggested targeting regions with lower station costs (so high hydrogen demand) for initial station deployment. Though considering limited data, they found the West South Central and Pacific regions could potentially have some

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[824] Coordinating Research Council. "Assess the Battery-Recharging and Hydrogen-Refueling Infrastructure Needs, Costs, and Timelines Required to Support Regulatory Requirements for Light-, Medium-, and Heavy-Duty Zero-Emission Vehicles. Final Report". Prepared by ICF. CRC Report No. SM-CR-9. September 2023. Available online: https://crcao.org/wp-content/uploads/2023/09/CRC_Infrastructure_Assessment_Report_ICF_09282023_Final-Report.pdf.

[825] Liu, et. al. "Evaluating national hydrogen refueling infrastructure requirement and economic competitiveness of fuel cell electric long-haul trucks". Mitigation and Adaption Strategies for Global Change. November 21, 2019. Available online: https://link.springer.com/article/10.1007/s11027-019-09896-z

[826] Kuhn et. al. "Feasibility study of EPA NPRM Phase 3 GHG standards for Medium Heavy-Duty Vehicles. Version: 3.0". Ricardo, prepared for Truck and Engine Manufacturers Association. July 19, 2023.

[827] Coordinating Research Council. "Assess the Battery-Recharging and Hydrogen-Refueling Infrastructure Needs, Costs, and Timelines Required to Support Regulatory Requirements for Light-, Medium-, and Heavy-Duty Zero-Emission Vehicles. Final Report". Prepared by ICF. CRC Report No. SM-CR-9. September 2023. Available online: https://crcao.org/wp-content/uploads/2023/09/CRC_Infrastructure_Assessment_Report_ICF_09282023_Final-Report.pdf.

of the lowest station costs.[828] Ricardo identified California and Texas as the dominant states with the largest hydrogen demand by 2032. They noted that California's decarbonization policies and the large HD truck market and existing hydrogen resources in Texas could play roles. They called for investment and support for public refueling stations along Alternative Fuel Corridors and in key truck clusters such as ports, airports, railroads, warehouses, and freight hubs to support HD FCEV deployment.[829] CRC recognized a strategy laid out by CARB to start with smaller capacity stations to ensure adequate spatial coverage, and then gradually progress to larger capacity stations as demand increases. They suggested that California would lead in buildout due to existing policies, followed by other states starting in 2030 (i.e., a six-year lag, based on our proposed rule). According to their analysis, Texas would have the second largest need for refueling infrastructure based on estimated hydrogen demand.[830] Fulton et. al found that in California in the 2030 timeframe, smaller, lower-use hydrogen refueling stations could offer sufficient coverage and dominate a network in the near-term but then decline as demand grows and larger stations become more economical.[831] Ragon et. al noted that an infrastructure network does not need to be built all at once and should be prioritized in the near-term in areas with high energy needs from MHDV traffic flows. This conclusion was focused on BEV charging infrastructure in the 2030 timeframe but the high-level takeaway could also apply to the development of FCEV refueling stations. As the market develops, they suggested that infrastructure needs could expect to expand along freight corridors that connect priority hubs or industrial nodes.[832]

As discussed further in Chapter 2.5.3.1, we revised projections for HD FCEV adoption based on relatively low production volumes in the MY 2030 to 2032 timeframe, indicative of an early market technology rollout. As a result, hydrogen demand in the modeled potential compliance pathway in the final rule is smaller than projected in the NPRM and in these studies in the MY 2030 to 2032 timeframe. It is closer to about 130,000 metric tons of hydrogen per year by 2032, or 1.3% of current production. Our assessment is that early market buildout of a hydrogen refueling station network to support modest FCEV adoption levels in the modeled potential compliance pathway is feasible in the 2030 to 2032 timeframe.

We are not suggesting that a full national hydrogen infrastructure network needs to be in place by 2030 or 2032, and specifically note that a full national hydrogen infrastructure network is not necessary to accommodate the demand that we posit for HD FCEVs in our modeled potential

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[828] Liu, et. al. "Evaluating national hydrogen refueling infrastructure requirement and economic competitiveness of fuel cell electric long-haul trucks". Mitigation and Adaption Strategies for Global Change. November 21, 2019. Available online: https://link.springer.com/article/10.1007/s11027-019-09896-z

[829] Kuhn et. al. "Feasibility study of EPA NPRM Phase 3 GHG standards for Medium Heavy-Duty Vehicles. Version: 3.0". Ricardo, prepared for Truck and Engine Manufacturers Association. July 19, 2023.

[830] Coordinating Research Council. "Assess the Battery-Recharging and Hydrogen-Refueling Infrastructure Needs, Costs, and Timelines Required to Support Regulatory Requirements for Light-, Medium-, and Heavy-Duty Zero-Emission Vehicles. Final Report". Prepared by ICF. CRC Report No. SM-CR-9. September 2023. Available online: https://crcao.org/wp-content/uploads/2023/09/CRC_Infrastructure_Assessment_Report_ICF_09282023_Final-Report.pdf.

[831] Fulton, et. al. "California Hydrogen Analysis Project: The Future Role of Hydrogen in a Carbon-Neutral California—Final Synthesis Modeling Report". UC Davis Institute of Transportation Studies. April 19, 2023. Available online: https://escholarship.org/uc/item/27m7g841.

[832] Ragon, Pierre-Louis et al. "Near-term Infrastructure Deployment to Support Zero-Emission Medium- and Heavy-Duty Vehicles in the United States." May 2023. Available online: https://theicct.org/wp-content/uploads/2023/05/infrastructure-deployment-mhdv-may23.pdf.

compliance pathway. Through BIL and IRA incentives and private investment spurred by H2Hubs, we conclude there is opportunity to concentrate HD FCEV hydrogen demand from the modeled potential compliance pathway in priority areas. Secure and sufficient demand from local or regional anchor fleets would offer certainty that could help lower infrastructure costs in targeted regions and enable expansion over time. This strategy is supported in the literature, which include regional analyses that demonstrate that infrastructure buildout can start in targeted regions. The analyses also indicate that station financial prospects can vary by region and tend to be more favorable in areas with higher demand (i.e. high energy needs from HD traffic flows), while station costs are anticipated to drop with growth in demand and related economies of scale. Similar to BEVs, as explained in RTC Section 7.1, the infrastructure needed to meet this initial demand may be centered in a discrete sub-set of states and counties where freight activity is concentrated. Thus, the select vehicle applications for which we project FCEV adoption could start traveling within or between regional hubs in this timeframe where hydrogen development is prioritized initially.

Along these lines, in March 2024, the U.S. released a National Zero-Emission Freight Corridor Strategy,[833] released in March 2024, that, "sets an actionable vision and comprehensive approach to accelerating the deployment of a world-class, zero-emission freight network across the United States by 2040. The strategy focuses on advancing the deployment of zero-emission medium- and heavy-duty vehicle (ZE-MHDV) fueling infrastructure by targeting public investment to amplify private sector momentum, focus utility and regulatory energy planning, align industry activity, and mobilize communities for clean transportation."[834] The strategy has four phases. The first phase, from 2024-2027, focuses on establishing freight hubs defined "as a 100-mile to a 150-mile radius zone or geographic area centered around a point with a significant concentration of freight volume (e.g., ports, intermodal facilities, and truck parking), that supports a broader ecosystem of freight activity throughout that zone."[835] The second phase, from 2027-2030, will connect key ZEV hubs, building out infrastructure along several major highways. The third phase, from 2030-2045, will expand the corridors, "including access to charging and fueling to all coastal ports and their surrounding freight ecosystems for short-haul and regional operations."[836] The fourth phase, from 2035-2040, will complete the freight corridor network. This corridor strategy provides further support for the development of HD ZEV infrastructure that corresponds to the modeled potential compliance pathway for meeting the final standards.

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[833] Joint Office of Energy and Transportation. "National Zero-Emission Freight Corridor Strategy" DOE/EE-2816 2024. March 2024. Available at https://driveelectric.gov/files/zef-corridor-strategy.pdf.

[834] Joint Office of Energy and Transportation. "Biden-Harris Administration, Joint Office of Energy and Transportation Release Strategy to Accelerate Zero-Emission Freight Infrastructure Deployment." March 12, 2024. Available online: https://driveelectric.gov/news/decarbonize-freight.

[835] Joint Office of Energy and Transportation. "National Zero-Emission Freight Corridor Strategy" DOE/EE-2816 2024. March 2024. Available at https://driveelectric.gov/files/zef-corridor-strategy.pdf. See page 3.

[836] Joint Office of Energy and Transportation. "National Zero-Emission Freight Corridor Strategy" DOE/EE-2816 2024. March 2024. Available at https://driveelectric.gov/files/zef-corridor-strategy.pdf. See page 8.

1.8.3.6 Lead Time and Early Market Buildout

Hydrogen refueling infrastructure is currently limited in scope, so we evaluated the potential pace of buildout.

DOE's Liftoff Report identifies a path to scale hydrogen that involves three phases of potentially rapid market growth: near-term expansion (~2023-2026), industrial scaling (~2027-2034), and long-term growth (~2035+). The report acknowledges that there are both opportunities and challenges for sectors with few decarbonization alternatives like heavy-duty transportation end uses, including long-haul trucks.[837] It lays out a scenario where low-GHG hydrogen could be emerging for long-haul trucks during the timeframe of this rule (i.e., through 2032):

- Hydrogen will start getting cleaner:
    - By 2030, there is incentive to produce up to 10 MMT per year of hydrogen for new markets using low-GHG pathways (i.e., in addition to some portion of incumbent demand for conventional hydrogen).
        - Industry expects electrolyzer costs to drop significantly by 2030, though this is reliant on the availability of low-cost low-GHG electricity that also needs to scale.
    - This shift can start with existing end users that already have hydrogen infrastructure that connects production with end-use demand (e.g., industrial/chemicals).
    - New projects that receive hub funding are expected to break ground in the near-term and advance new networks of shared infrastructure.
- It will be challenging to establish regional infrastructure networks for end uses but doing so can start to lower the delivered cost of hydrogen:
    - During industrial scaling, privately funded hydrogen infrastructure projects will come online and start to build the midstream distribution and storage networks to connect greater numbers of producers and offtakers.
    - Increasing production volumes will reduce costs that drive adoption of hydrogen in new sectors like heavy-duty FCEVs.
    - Hydrogen will initially be dispersed through centralized regional hubs, and then eventually through a more distributed network of infrastructure, followed by anchors such as dedicated hydrogen pipelines and geologic storage in the long term.

The literature also supports our conclusion that there is sufficient lead time. Fulton et. al. noted that heavy-duty refueling station funding, design, and planning should start one to two

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[837] U.S. Department of Energy. "Pathways to Commercial Liftoff: Clean Hydrogen". March 2023. Available online: https://liftoff.energy.gov/wp-content/uploads/2023/03/20230320-Liftoff-Clean-H2-vPUB.pdf.

years before deployment.[838] CRC noted that full station development (i.e., design, permitting, construction, and commissioning) takes about two years, assuming no major hurdles. In California, they estimated that about 20 percent of more recent projects took up to 2.6 years to build.[839] The California Energy Commission has evaluated hydrogen refueling station development in California since 2010. Their planned network of 200 stations is mainly for light-duty vehicles but has at least 13 stations with the capability to serve HD FCEVs.[840] Station development times have generally decreased over time, from a median or typical time spent of around 1500 days in 2010 to about 500 days in 2019 (i.e., about two years if considering business days) for projects that have completed all phases of development.[841] They expect some increase in median development times as projects delayed by the COVID-19 pandemic are completed but regularly monitor progress and work to improve the deployment process.[842]

We note further, as one commenter points out, that hydrogen infrastructure development might have certain advantages over BEV infrastructure that favor its rapid deployment such as existing petroleum infrastructure that can be leveraged in some instances and fewer potential policy and process challenges (e.g., associated with utility commission regulations).

We recognize that these plans will require sustained support to come to fruition, and our assessment, in consultation with relevant federal agencies, is that our projections are supported and correspond to our measured approach in our modeled compliance pathway for FCEVs. There are many complex factors at play, and we have taken a close look at how the ramp-up period over the next decade is critical. In our modeled potential compliance pathway, we evaluated the existing and projected future hydrogen refueling infrastructure and considered FCEVs only in the MY 2030 and later timeframe to better ensure that our compliance pathway provides adequate time for early market infrastructure development. We conclude that a phased and targeted approach can offer sufficient lead time to meet the projected refueling needs that correspond to the technology packages for the final rule's potential compliance pathway, as further discussed in RIA Chapter 2.1. Additionally, EPA is committed to ensuring the Phase 3 program is successfully implemented and, as described in preamble Section II.B.2.iii, in consideration of concerns raised regarding inherent uncertainties about the future, we are including a commitment to monitor progress on infrastructure development in the final rule.

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[838] Fulton, et. al. "California Hydrogen Analysis Project: The Future Role of Hydrogen in a Carbon-Neutral California—Final Synthesis Modeling Report". UC Davis Institute of Transportation Studies. April 19, 2023. Available online: https://escholarship.org/uc/item/27m7g841.

[839] Coordinating Research Council, Inc. "Assess the Battery-Recharging and Hydrogen-Refueling Infrastructure Needs, Costs, and Timelines Required to Support Regulatory Requirements for Light-, Medium-, and Heavy-Duty Zero-Emission Vehicles: Final Report". Prepared by ICF. CRC Report No. SM-CR-9. September 2023. Available online: https://crcao.org/wp-content/uploads/2023/09/CRC_Infrastructure_Assessment_Report_ICF_09282023_Final-Report.pdf.

[840] The CEC has invested nearly $40 million in medium- and heavy-duty hydrogen infrastructure.

[841] Berner, et al. "Joint Agency Staff Report on Assembly Bill 8: 2022 Annual Assessment of Time and Cost Needed to Attain 100 Hydrogen Refueling Stations in California". California Energy Commission & California Air Resources Board. December 2022. Available online: https://www.energy.ca.gov/sites/default/files/2022-12/CEC-600-2022-064.pdf.

[842] Berner, et al. "Joint Agency Staff Report on Assembly Bill 8: 2022 Annual Assessment of Time and Cost Needed to Attain 100 Hydrogen Refueling Stations in California". California Energy Commission & California Air Resources Board. December 2022. Available online: https://www.energy.ca.gov/sites/default/files/2022-12/CEC-600-2022-064.pdf.

1.8.4 Environmental Considerations

As mentioned in RIA Chapters 1.8.2.1 and 1.8.3, the environmental impacts of different hydrogen pathways can vary. Recent investment and policy interest in hydrogen is rooted in its decarbonization potential and we expect that hydrogen production will become cleaner in the coming years. Depending on how the hydrogen market scales, additional considerations may need to be addressed.

Scientists are continuing to evaluate the potential of hydrogen to have indirect warming impacts. Hydrogen does not absorb and trap heat within the Earth's atmosphere and is therefore not considered a direct greenhouse gas. However, studies show that there are indirect radiative effects caused by the presence of emitted hydrogen in the troposphere.[843] Limited research suggests that hydrogen released to the troposphere may affect ozone concentrations and prolong the lifetime of methane.[844,845,846,847,848] The Intergovernmental Panel on Climate Change (IPCC) and United Nations Framework Convention on Climate Change (UNFCCC) have not identified and established a global warming potential[849] associated with hydrogen.[850] Its secondary impacts on warming should mitigate over time as methane emissions are controlled.[851]

Due to its extremely small molecular size, there can be leakage of gaseous hydrogen during production, transportation, storage, and dispensing into vehicles. It may need to be vented or purged when used in equipment. Such losses are presently expected to be small, due to the relatively small volumes of hydrogen in production today (e.g., 10 MMT produced per year in the United States and 90 MMT per year globally, compared to up to 660 MMT of global low-

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[843] Derwent, R., et al. "Global environmental impacts of the hydrogen economy". International Journal of Nuclear Hydrogen Production and Applications, 1(1), 57. May 2006. Available online: https://doi.org/10.1504/IJNHPA.2006.009869.

[844] Hydrogen gas released into the atmosphere can have climate and air quality effects through atmospheric chemical reactions. In particular, hydrogen is known to react with the hydroxyl radical, reducing concentrations of the hydroxyl radical in the atmosphere. Because the hydroxyl radical is important for the destruction of many other gases, a reduction in hydroxyl radical concentrations will lead to increased lifetimes of many other gases—including methane and tropospheric oxone. This means that hydrogen gas emissions can also indirectly contribute to warming through increased concentrations of methane and ozone.

[845] Forster, Piers, et al. "Changes in Atmospheric Constituents and in Radiative Forcing". IPCC. p. 106. February 2018. Available online: https://www.ipcc.ch/site/assets/uploads/2018/02/ar4-wg1-chapter2-1.pdf.

[846] Ocko, Ilissa B. and Steven P. Hamburg, Environmental Defense Fund. "Climate consequences of hydrogen emissions". Atmospheric Chemistry and Physics: 22. July 20, 2022. Available online: https://acp.copernicus.org/articles/22/9349/2022/.

[847] Sand, Maria, et. al. "A multi-modal assessment of Global Warming Potential of hydrogen". Communications Earth & Environment. June 7, 2023. Available online: https://www.nature.com/articles/s43247-023-00857-8.

[848] Warwick, Nicola J., et. al. "Atmospheric composition and climate impacts of a future hydrogen economy". Atmospheric Chemistry and Physics: Volume 23, Issue 20. October 25, 2023. Available online: https://acp.copernicus.org/articles/23/13451/2023/acp-23-13451-2023-discussion.html.

[849] A Global Warming Potential (GWP) is a quantified measure of the globally averaged relative radiative forcing impacts of a particular GHG relative to carbon dioxide.

[850] IPCC. "Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change". Geneva, Switzerland: IPCC. 2021. Available online: https://report.ipcc.ch/ar6/wg1/IPCC_AR6_WGI_FullReport.pdf

[851] U.S. Environmental Protection Agency." EPA's Final Rule for Oil and Natural Gas Operations Will Sharply Reduce Methane and Other Harmful Pollution". December 2, 2023. Available online: https://www.epa.gov/controlling-air-pollution-oil-and-natural-gas-operations/epas-final-rule-oil-and-natural-gas.

GHG hydrogen potential in 2050 to meet climate goals).[852] Even as hydrogen scales and much larger volumes are produced, with the attendant potential for emissions of hydrogen to oxidize in the atmosphere, we expect the benefits of low-GHG hydrogen as part of a low-carbon economy to outweigh any such effects in the future.[853] Furthermore, there is financial incentive to improve how to measure, monitor, evaluate, and manage hydrogen losses throughout the value chain.[854,855] Research is underway to understand ways to ensure that climate benefits of hydrogen can be maximized and any potential adverse effects minimized.[856]

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[852] Hydrogen Council and McKinsey & Company. “Hydrogen Insights 2022: An updated perspective on hydrogen market development and actions required to unlock hydrogen at scale”. September 2022. Available online: https://hydrogencouncil.com/wp-content/uploads/2022/09/Hydrogen-Insights-2022-2.pdf.

[853] Arrigoni, A. and Bravo Diaz, L. “Hydrogen emissions from a hydrogen economy and their potential global warming impact”. EUR 31188 EN, Publications Office of the European Union, Luxembourg, 2022, ISBN 978-92-76-55848-4, doi:10.2760/065589, JRC130362. Available online: https://publications.jrc.ec.europa.eu/repository/handle/JRC130362.

[854] Fan, Zhiyuan, et. al. “Hydrogen Leakage: A Potential Risk for the Hydrogen Economy”. Columbia SIPA, Center on Global Energy Policy. July 5, 2022. Available online: https://www.energypolicy.columbia.edu/publications/hydrogen-leakage-potential-risk-hydrogen-economy/.

[855] Koch blank, Thomas, et. al. “Hydrogen Reality Check #1: Hydrogen is Not a Significant Warming Risk”. Rocky Mountain Institute. May 9, 2022. Available online: https://rmi.org/hydrogen-reality-check-1-hydrogen-is-not-a-significant-warming-risk/.

[856] Frazer-Nash Consultancy. “Fugitive Hydrogen Emissions in a Future Hydrogen Economy”. March 2022. Available online: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1067137/fugitive-hydrogen-emissions-future-hydrogen-economy.pdf.

Chapter 2 Technology Assessment

2.1 Introduction

This chapter describes the operational characteristics and costs that we used to estimate heavy-duty technologies' feasibility and suitability and the analysis for the modeled potential compliance pathway's technology package that supports the feasibility of the final standards for MYs 2027 through 2032. For manufacturers, costs are typically direct manufacturing costs (DMC), but also retail price equivalents (RPE), which include DMC and indirect costs, in some cases as appropriate. We also evaluated purchaser upfront costs and operating costs. Additional discussion of DMC, indirect costs, and RPE, as well as purchaser upfront costs and operating costs, can be found in Chapter 3.2 of the RIA.

Many technologies have been demonstrated to reduce GHG emissions and are considered technically feasible for HD vehicles. Our analysis for this final rule further shows that a diverse range of HD vehicle technologies are feasible and may be used to comply with the final standards to reduce GHG emissions, including ICE (including alternative-fueled), hybrid, and plug-in hybrid vehicle technologies, hydrogen-fueled ICE technologies (H2 ICE), BEV technologies, and FCEV technologies. To conduct the portion of our analysis with regard to BEV and FCEV technologies, EPA developed a flexible spreadsheet-based framework called the Heavy-Duty Technology Resource Use Case Scenario (HD TRUCS) tool.[857] The tool in its current form is used to evaluate ICE vehicles, BEV, FCEVs, and PHEVs but could easily be adapted to evaluate other technologies.

While we acknowledge and are aware of other tools and models that perform related functions and have gathered important insights from them,[858,859,860,861] HD TRUCS has proven to be an excellent analytic tool for assessing heavy-duty vehicle suitability, cost, and payback comparisons between BEV and FCEV technologies (which we refer to as ZEVs collectively within this RIA) as compared to a comparable ICE vehicle, based on data and resources available to EPA at the time of the analysis. Because Clean Air Act section 202(a)(1)-(2) requires EPA to consider lead time and costs in establishing standards, and because manufacturers (and purchasers) of HD vehicles are profit-generating enterprises that are seeking to reduce costs, EPA then undertook an analysis to identify the technologies that would be most effective at

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[857] See Memorandum to docket EPA-HQ-OAR-2022-0985. "Heavy-Duty Technology Resource Use Case Scenario Tool (HD TRUCS). Final Rule." March 2024.

[858] For example, as cited in the endnotes: ACT Research's report mentions a proprietary Total Cost of Ownership model; Ledna et. al uses the National Renewable Energy Laboratory's Transportation Energy & Mobility Pathway Options Model (TEMPO) model; and California Air Resources Board's report refers to an assessment matrix developed by the Truck and Engine Manufacturers Association (EMA). Chapter 2.1.2 also discusses our use of Argonne National Laboratory's BEnefit ANalysis (BEAN) and Autonomie models.

[859] Mitchell, George. Memorandum to docket EPA-HQ-OAR-2022-0985. ACT Research Co. LLC. "Charging Forward" 2020-2040 BEV & FCEV Forecast & Analysis, updated December 2021.

[860] Ledna et. al. "Decarbonizing Medium- & Heavy-Duty On-Road Vehicles: Zero-Emission Vehicles Cost Analysis". U.S. Department of Energy, National Renewable Energy Laboratory. March 2022. Available online: https://www.nrel.gov/docs/fy22osti/82081.pdf.

[861] California Air Resources Board. Advanced Clean Trucks Regulation: Public Hearing Notice and Related Material, "Appendix E: Zero Emission Truck Market Assessment". Posted October 22, 2019. Available online: https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2019/act2019/appe.pdf

reducing GHG emissions and are feasible and cost-effective at doing so in the MYs 2027-2032 time frame to include in technology packages and model as a potential compliance pathway for the final standards. This analysis included using HD TRUCS. ZEV technologies for the heavy-duty sector have developed markedly since EPA promulgated the Phase 2 rule, and we anticipate future improvements and increase in use in the heavy-duty sector, as discussed in Chapter 1.[862] At the same time, EPA modeled other technologies (included in technology packages with different mixes of technologies as examples of other potential compliance pathways, as discussed in RIA Chapters 1.4.3 and 2.11) recognizing that OEMs can legally and practically choose many different ways to achieve CO_2 emissions reductions to comply with the final standards.

Regarding our approach to thoroughly analyze potential ZEV technologies, we used HD TRUCS to evaluate the design features needed to meet the energy and power demands of various HD vehicle types when using ZEV technologies. To assess these ZEV technologies using HD TRUCS, we created 101 representative vehicles in HD TRUCS that cover the full range of weight classes within the scope of the final standards (i.e., Class 2b through 8 vocational vehicles and tractors). The representative vehicles cover many aspects of work performed by the industry. This work was translated into total energy and power demands per vehicle type based on everyday use of HD vehicles, ranging from moving goods and people to mixing cement. We then identified the technical properties required for a BEV or FCEV to meet the operational needs of a comparable ICE vehicle.[863]

Since batteries can add weight and volume to a BEV,[864] we evaluated battery mass and physical volume required to package a battery pack. If the performance needs of a BEV resulted in a battery that was too heavy or large, then we did not consider the BEV for that application in our technology packages because of the impact on payload and, thus, potential work accomplished relative to a comparable ICE vehicle.[865]

To evaluate costs, including costs of compliance for manufacturers as well as purchaser costs related to purchasing and operating ZEVs, we sized vehicle components that are unique to ZEVs to meet the work demands of each representative vehicle. We determined the cost of each powertrain component based on sizing to assess the difference in total powertrain costs between the ICE and ZEV powertrains. We accounted for the IRA battery tax credit and vehicle purchase tax credit. We also compared operating costs due to fuel and electricity consumption as well as vehicle maintenance and repair, and we included the cost to procure, install, and support depot

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[862] BEVs and FCEVs may be well-suited to many heavy-duty applications because these technologies have high low-end torque, which may provide benefits for heavy vehicles at low speeds.

[863] Heavy-duty vehicles are typically powered by a diesel-fueled compression-ignition (CI) engine, though the heavy-duty market includes vehicles powered by gasoline-fueled spark-ignition (SI) engines and alternative-fueled ICEs. We selected diesel-powered ICE vehicles as the baseline vehicle for the assessment in HD TRUCS in our analysis because a diesel-fueled CI engine is broadly available for all of the 101 vehicle types and diesel engines are more efficient than SI engines.

[864] Smith, David et. al. "Medium- and Heavy-Duty Vehicle Electrification: An Assessment of Technology and Knowledge Gaps". U.S. Department of Energy: Oak Ridge National Laboratory and National Renewable Energy Laboratory. December 2019. Available online: https://info.ornl.gov/sites/publications/Files/Pub136575.pdf.

[865] This does not necessarily mean that a BEV with a large battery weight and volume would not be technically feasible for a given HD vehicle use, but rather this is an acknowledgement that we considered impacts of increased battery size on feasibility considerations like payload capacity as well as cost and payback within the selection of HD vehicle technologies for the technology packages.

charging infrastructure for BEVs (including accounting for the IRA EVSE tax credit). We have also assessed the cost of public charging infrastructure with respect to certain BEV applications, and analyzed that cost as part of the cost to charge (assessed as $/kWh of electricity), similar to ICE vehicles' infrastructure and fuel costs. For FCEVs, we likewise analyzed hydrogen infrastructure costs as part of the cost of hydrogen fuel.

We relied on research and findings discussed in RIA Chapter 1 and throughout this RIA Chapter 2 to conduct the HD TRUCS analysis. For MYs 2027 through 2029, our modeled compliance pathway's technology package focuses primarily on BEV technology using depot charging. Our modeling finds, and research supports, that BEV technologies can become cost-competitive for some duty cycles of HD vehicles by the late 2020s.[866,867,868] Given that there are many more BEV models available today compared to FCEV models (e.g., see RIA Chapters 1.7.5 and 1.7.6), we reasoned that BEV technology adoption is likely to happen sooner than the adoption of FCEV technology.

Starting in MY 2030, we also considered FCEV technology and BEVs using public charging for select applications in our HD TRUCS analysis. BEV technology is more efficient than FCEV technology but may not be as suitable for all applications, such as when the vehicle operating needs, such as long range, result in battery mass that may raise challenges in relation to the payload that the vehicle needs to carry. In cases like this, we considered either BEVs with smaller batteries (that may require enroute charging and the consequent use of public charging away from the depot) or FCEVs (which have shorter refueling times than BEVs with large batteries). FCEVs are more efficient than diesel vehicles and can have shorter refueling times than batteries.[869,870] We considered FCEVs and BEVs using public charging in the technology packages for applications that travel longer distances and/or carry heavier loads (i.e., for those that may be sensitive to refueling times or payload impacts). This included coach buses and tractors.

Though fuel cell technology is still emerging in HD vehicle applications, based on our review of the literature as well as information provided in public comments, FCEVs are a viable,

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[866] Ledna et. al. "Decarbonizing Medium- & Heavy-Duty On-Road Vehicles: Zero-Emission Vehicles Cost Analysis". U.S. Department of Energy, National Renewable Energy Laboratory. March 2022. Available online: https://www.nrel.gov/docs/fy22osti/82081.pdf.

[867] Hall, Dale and Nic Lutsey. "Estimating the Infrastructure Needs and Costs for the Launch of Zero-Emission Trucks". White Paper: The International Council on Clean Transportation. August 2019. Available online: https://theicct.org/wp-content/uploads/2021/06/ICCT_EV_HDVs_Infrastructure_20190809.pdf.

[868] Robo, Ellen and Dave Seamonds. Technical Memo to Environmental Defense Fund: Investment Reduction Act Supplemental Assessment: Analysis of Alternative Medium- and Heavy-Duty Zero-Emission Vehicle Business-As-Usual Scenarios. ERM. August 19, 2022. Available online: https://www.erm.com/contentassets/154d08e0d0674752925cd82c66b3e2b1/edf-zev-baseline-technical-memo-addendum.pdf.

[869] A technology is more energy efficient if it uses less energy to do the same amount of work. Energy can be lost as it moves through the vehicle's components due to heat and friction.

[870] Cunanan, Carlo et. al. "A Review of Heavy-Duty Vehicle Powertrain Technologies: Diesel Engine Vehicles, Battery Electric Vehicles, and Hydrogen Fuel Cell Electric Vehicles". *Clean Technol*. Available online: *https://www.mdpi.com/2571-8797/3/2/28*.

technically feasible ZEV technology for heavy-duty transportation.[871,872,873] FCEVs are available today with more models expected by the 2030 timeframe (see RIA Chapter 1.7.5).[874,875,876] Inclusion of FCEVs in the technology packages starting in MY 2030 takes into consideration additional lead time to allow manufacturers to design, develop, and manufacture HD FCEV models. Fuel cell technology in other sectors has been in existence for decades[877] and has been demonstrated to be technically feasible in heavy-duty transportation.[878] Interim research and development (R&D) technical targets and projects (see RIA Chapter 1.7.7) are in place to facilitate necessary improvements in the performance, durability, and costs of hydrogen-fueled long-haul HD tractors in 2030.[879] With substantial federal investment in low-GHG hydrogen production (see RIA Chapter 1.3.2), we anticipate that the price of hydrogen fuel will drop enough to make HD FCEVs cost-competitive with comparable ICE vehicles for some vehicle applications during the 10-year payback period. Hydrogen infrastructure is expected to need the additional time prior to MY 2030 to further develop, as discussed in greater detail in RIA Chapter 1.8, but we project the refueling needs can be met by MY 2030.[880] We also recognize the impact regulations (e.g., through regulatory certainty) can have on technology and refueling infrastructure development and deployment.

After considering operational characteristics and costs, the next step in our HD TRUCS analysis was determining the payback period, which is the number of years it will take to offset any incremental cost increase of a ZEV over a comparable ICE vehicle. Lastly, we assessed and

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[871] Mihelic, Rick et. al. “Making Sense of Heavy-Duty Hydrogen Fuel Cell Tractors”. North American Council for Freight Efficiency. December 16, 2020. Available online: https://nacfe.org/research/electric-trucks/making-sense-of-heavy-duty-hydrogen-fuel-cell-tractors/.

[872] Cunanan, Carlo et. al. “A Review of Heavy-Duty Vehicle Powertrain Technologies: Diesel Engine Vehicles, Battery Electric Vehicles, and Hydrogen Fuel Cell Electric Vehicles”. *Clean Technol*. Available online: *https://www.mdpi.com/2571-8797/3/2/28*.

[873] Cullen et. al. “New roads and challenges for fuel cells in heavy-duty transportation”. *Nature Energy*. March 25, 2021. Available online: *https://www.nature.com/articles/s41560-021-00775-z*.

[874] International Energy Agency. “Energy Technology Perspectives 2023”. January 2023. Available online: https://iea.blob.core.windows.net/assets/a86b480e-2b03-4e25-bae1-da1395e0b620/EnergyTechnologyPerspectives2023.pdf.

[875] McKinsey & Company, McKinsey Center for Future Mobility. “Preparing the world for zero-emission trucks”. September 2022. Available online: https://www.mckinsey.com/~/media/mckinsey/industries/automotive%20and%20assembly/our%20insights/preparing%20the%20world%20for%20zero%20emission%20trucks/preparing-the-world-for-zero-emission-trucks.pdf,

[876] Divis, Andrej, et. al. “Fuel for Thought: The commercial vehicle fleet accelerates toward ZEV adoption”. S&P Global Mobility. July 26, 2023. Available online: https://www.spglobal.com/mobility/en/research-analysis/fuel-for-thought-the-commercial-vehicle-fleet-accelerates.html.

[877] U.S. Energy Information Administration. “Hydrogen explained: Use of hydrogen”. Last updated January 20, 2022. Available online: https://www.eia.gov/energyexplained/hydrogen/use-of-hydrogen.php.

[878] Toyota. “Toyota, Kenworth Prove Fuel Cell Electric Truck Capabilities with Successful Completion of Truck Operations for ZANZEFF Project”. September 22, 2022. Available online: https://pressroom.toyota.com/toyota-kenworth-prove-fuel-cell-electric-truck-capabilities-with-successful-completion-of-truck-operations-for-zanzeff-project/.

[879] Marcinkoski, Jason et. al. “DOE Advanced Truck Technologies: Subsection of the Electrified Powertrain Roadmap—Technical Targets for Hydrogen-Fueled Long-Haul Tractor-Trailer Trucks. October 31, 2019. Available online: https://www.hydrogen.energy.gov/pdfs/19006_hydrogen_class8_long_haul_truck_targets.pdf.

[880] U.S. Department of Energy. “U.S. National Clean Hydrogen Strategy and Roadmap”. June 2023. Available online: https://www.hydrogen.energy.gov/library/roadmaps-vision/clean-hydrogen-strategy-roadmap, https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/us-national-clean-hydrogen-strategy-roadmap.pdf.

applied a payback schedule to the payback periods, which resulted in percentages of BEV technologies and FCEV technologies we then considered in the technology packages for the modeled potential compliance pathway to support the feasibility of the standards.

From a vehicle's emission standard compliance perspective, BEVs and FCEVs both emit zero grams of CO_2 per ton-mile at the tailpipe. Our HD TRUCS analysis discussed in this chapter focuses on these two technologies as part of one pathway for complying with the standards, but there are other technologies we included in technology packages with different mixes of technologies as examples of other potential compliance pathways as described in RIA Chapter 1 and Chapter 2.11 that can reduce CO_2 emissions, including H_2 fueled ICE vehicles that also emit 0 g CO_2 out of the engine.[881] Manufacturers may choose to utilize the technologies that work best for their business case and the operator's needs in meeting the final performance-based standards.

The remainder of RIA Chapter 2.1 provides an overview of the structure of the HD TRUCS tool. RIA Chapters 2.1 through 2.6 discuss tool inputs used to compare ZEV technologies to a comparable diesel ICE vehicle. RIA Chapter 2.2 explains how we established benchmark performance requirements for each HD TRUCS vehicle, independent of the powertrain. RIA Chapter 2.3 describes diesel vehicle components, upfront technology costs, diesel fuel consumption, and operational costs. RIA Chapter 2.4 describes BEV components, how components were sized in HD TRUCS to meet the performance requirements of heavy-duty vehicles, upfront technology costs, BEV energy consumption, and operational costs. RIA Chapter 2.5 describes FCEV components, how components were sized in HD TRUCS to meet the performance requirements of heavy-duty vehicles, upfront technology costs, FCEV energy consumption, and operational costs. RIA Chapter 2.6 contains a discussion of BEV charging and infrastructure. RIA Chapter 2.7 explains technology adoption approaches considered in the heavy-duty sector. RIA Chapter 2.8 summarizes the methodologies used in HD TRUCS to assess energy consumption of heavy-duty vehicles and ZEVs and evaluate technology feasibility, payback, and adoption rates in the technology packages for the modeled compliance pathway to support the final standards. RIA Chapter 2.9 shows the results of the analysis. RIA Chapter 2.10 summarizes the final standards. Chapter 2.11 describes three additional example potential compliance pathways. Chapter 2.12 describes a TCO (total cost to own) analysis that complements the HD TRUCs payback analysis.

The final version of HD TRUCS has a number of improvements to the proposal's version that were made based on consideration of stakeholder comments and additional information. These include both refinements to certain inputs and addressing a few minor errors in inputs, as described in the following sections and in RTC Section 3.

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[881] Hydrogen-powered internal combustion engines (H2-ICE) fueled with neat hydrogen emit zero engine-out CO_2 emissions (as well as zero engine-out HC, CH_4, CO emissions). We recognize that there may be negligible, but non-zero, CO_2 emissions at the tailpipe of H2-ICE that use selective catalytic reduction (SCR) aftertreatment systems and are fueled with neat hydrogen due to contributions from the aftertreatment system from urea decomposition. As further explained in preamble Section III, H2-ICE are considered to emit near zero CO_2 emissions under our part 1036 regulations and are deemed zero under out part 1037 regulations, consistent with our treatment of CO_2 emissions that are attributable to the aftertreatment systems in compression-ignition ICEs. H2-ICE also emit certain criteria pollutants. H2-ICE are not included in what we refer to collectively as ZEVs throughout this final rule. Note, NOx and PM emission testing is required under existing 40 CFR part 1036 for engines fueled with neat hydrogen.

Much of the material in this and other chapters of this RIA reflects EPA's long-standing expertise in the area of mobile source emissions and regulatory standards development. EPA’s Office of Transportation and Air Quality (OTAQ) has more than fifty years of experience in developing standards to reduce air pollution and greenhouse gas emissions from mobile sources. This work has historically involved not only broad stakeholder engagement and foundational work in regulatory design but also the development of deep scientific and technical expertise in the engineering and science surrounding the measurement, modeling, and control of mobile source emissions. This has included the development of sophisticated modeling tools to assess mobile source-related air quality problems; establishing national and international standards to reduce emissions; implementing standards through certification processes and in-use monitoring strategies; developing fuel efficiency programs and technologies; and researching, evaluating, and developing advanced technologies and new strategies for controlling emissions. Staff have a variety of technical, legal, policy, and communications backgrounds to work effectively with diverse stakeholders throughout this process. This includes employing well over a hundred staff with undergraduate and graduate degrees in mechanical engineering, electrical engineering, automotive engineering, computer science and engineering, chemical engineering, material science, physics, chemistry, and other engineering, science, and related fields, including economics.

OTAQ also staffs and operates the National Vehicle and Fuel Emissions Laboratory (NVFEL) in Ann Arbor, Michigan. For nearly 50 years, NVFEL has been a world-class, state-of-the-art testing facility that provides emission testing support for EPA programs related to light- and heavy-duty vehicles, heavy-duty engines, and nonroad engines, including testing of gasoline and diesel engines and vehicles, HEVs, PHEVs, BEVs, electric machines, and high-voltage batteries. EPA staff each year conduct hundreds of tests of vehicles and engines to measure emissions, fuel economy, and performance metrics. EPA also represents the United States Government at the United Nation’s World Forum for the Harmonization of Vehicle Regulations, and where EPA OTAQ employees have chaired several working groups that have developed Global Technical Regulations to establish international test procedures and emission standard for light-duty vehicles, motorcycles, heavy-duty engines and vehicles, and electric vehicles. EPA OTAQ staff also routinely works with major independent technical automotive laboratories and engineering contractors – the very same firms that are utilized by many of the light and heavy-duty engine and vehicle manufacturers. These include multi-year contracts with Southwest Research Institute and FEV North America. EPA utilize these contracts to expand our access to additional laboratory testing capabilities and expertise, including expertise in light and heavy-duty vehicle technology assessments. OTAQ has established Cooperative Agreements with major transportation research universities, including the University of Michigan, the University of California – Davis, and Michigan State University. EPA OTAQ has utilized interagency agreements with several of the Department of Energy and the Department of Transportation national laboratories to collaborate on transportation sources research investigations, and the National Vehicle and Fuel Emissions Laboratory has a long-standing, multi-decadal Cooperative Research and Development Agreement with the major U.S. car manufacturers and the California Air Resources Board to “identify, encourage, evaluate and envelope instrumentation and techniques to accurately and efficiently measure emission from motor vehicles.”

EPA OTAQ staff have authored and co-authored hundreds of peer reviewed articles in the engineering, scientific, and economic literature, including publications by the Society of

Automotive Engineers, the American Society of Mechanical Engineers, the Energy Policy journal, the International Review of Environmental and Resource Economics, the World Electric Vehicle Journal, Transportation Research, the International Journal of Environmental Research and Public Health, and many others. The EPA publications in the literature cover a wide range of topics, including the development of emission reduction technologies, new test vehicle and engine testing procedures, technology cost projections based on vehicle and sub-system tear-down assessments, vehicle and engine performance and emissions benchmarking, emission measurement programs, vehicle modeling techniques, vehicle fuel testing programs, and public health assessments of transportation emissions. EPA OTAQ employees have also frequently been asked to serve as peer reviewers for a number of these journals. EPA OTAQ employees working at the National Vehicle and Fuel Emissions Laboratory have also been granted over 100 U.S. patents covering a wide range of engine, and vehicle related technologies, including technologies for reducing criteria pollutant and GHG emissions, improving fuel efficiency, and technologies for the measurement of mobile source emissions.

2.1.1 HD TRUCS Vehicle Types

HD TRUCS includes 101 heavy-duty vehicle types that are representative of the wide range of duty cycles and use cases in the HD industry. These 101 categories encompass 22 different vehicle applications, which are further disaggregated by weight class, duty cycle, and daily vehicle miles traveled (VMT).

The initial list of HD TRUCS vehicles was based on work the Truck and Engine Manufacturers Association (EMA) and California Air Resources Board (CARB) conducted for CARB's Advanced Clean Trucks (ACT) Regulation.[882] That assessment contained 87 "market segments". We first consolidated the list, eliminated some of the more unique vehicles with fewer than 100 sales in California (like mobile laboratories), and assigned operational characteristics for the vocational vehicles that correspond to the urban, multi-purpose (MP), and regional duty cycles used in EPA's Greenhouse Gas Emissions Model (GEM).[883,884] Secondly, we added additional vehicles to reflect vehicle applications that were represented in EPA's 2019 Annual Production Volume (PV) Reports into Engine and Vehicle Compliance Information Systems.[885]

For the FRM version of HD TRUCS, EPA made certain refinements to the 101 vehicle types after consideration of comments on the proposal, including comments that said HD TRUCS

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[882] California Air Resources Board. Advanced Clean Trucks Regulation: Public Hearing Notice and Related Material, "Appendix E: Zero Emission Truck Market Assessment". Posted October 22, 2019. Available online: https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2019/act2019/appe.pdf.; California Air Resources Board, Final Regulation Order – Advanced Clean Trucks Regulation. Filed March 15, 2021. Available online: https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2019/act2019/fro2.pdf.

[883] GEM is an EPA vehicle simulation tool used to certify HD vehicles. HD TRUCS uses the version GEM2, which was developed for EPA's Phase 2 Greenhouse Gas rulemaking. A detailed description of GEM is beyond the scope of this document but can be found in the Phase 2 RIA or in GEM documentation on EPA's website. For more information about how GEM was used to simulate road load power requirements for various duty cycles over the default road load profiles to estimate work performed by HD vehicles, please see Miller, Neil. Memorandum to docket EPA-HQ-OAR-2022-0985. "Gem Inputs and Results". November 2023.

[884] U.S. Environmental Protection Agency. "Greenhouse Gas Emissions Model (GEM) for Medium- and Heavy-Duty Vehicle Compliance". Available online: https://www.epa.gov/regulations-emissions-vehicles-and-engines/greenhouse-gas-emissions-model-gem-medium-and-heavy-duty.

[885] US EPA, 2019 Annual Production Volume Reports into Engine and Vehicle Compliance Information System.

should include tractors that are designed to use public charging. First, because three of the 101 vehicle types in the proposal were redundant to three other vehicle types, we aggregated the sales of those vehicles into the corresponding vehicle types that remained. Second, we added three additional tractors vehicle types. This resulted in 101 vehicle types in HD TRUCS for the final rule.[886]. More specifically, we aggregated four light-heavy RVs from one vehicle type into two light-heavy RVs different vehicle types, and also aggregated two light-heavy shuttle buses from one vehicle type into one light-heavy shuttle bus vehicle type. We then reassessed all the tractors vehicle types, such that there are now four day cabs vehicle types and three sleeper cabs vehicle types that are modeled in our analysis to use public charging, starting in model year 2030. In addition, of the tractors vehicle types that were designed for public charging, one day cab and one sleeper cab were updated to reflect a more aerodynamic tractor design than the average tractor aerodynamics used in the technology assessment to support the Phase 2 standards; this is described in more detail in Chapter 2.2.2.1.Two day cabs and one sleeper cabs are assessed as FCEVs, and the tractors with the shortest daily VMT were generally assessed as BEVs with depot charging. For the final rule analysis, we evaluated the heavy-haul tractor with BEV technology instead of with fuel cell technology as we did in the NPRM. In addition, for the final rule analysis, we evaluated the coach buses with BEV technology in addition to fuel cell technology, recognizing that there are currently BEV coach buses in the market today.

Table 2-1 summarizes the 101 unique vehicle types represented in HD TRUCS and how they are categorized, each with a vehicle identifier (Vehicle ID), HD TRUCS vehicle application, vehicle weight class, MOVES[887] SourceTypeID and RegClassID, and GEM Energy ID.

Table 2-1 HD TRUCS Vehicle Types

Vehicle ID	Vehicle Application	Weight Class	MOVES source TypeID	MOVES regClassID	GEM Energy ID[888, a,]
01V_Amb_Cl4-5_MP	Ambulance	4-5	52	42	LHD_M
02V_Amb_Cl2b-3_MP	Ambulance	2b-3	52	42	LHD_M
03V_Amb_Cl4-5_U	Ambulance	4-5	52	42	LHD_U
04V_Amb_Cl2b-3_U	Ambulance	2b-3	52	42	LHD_U
05T_Box_Cl8_MP	Box Truck	8	52	47	HHD_M
06T_Box_Cl8_R	Box Truck	8	53	47	HHD_R
07T_Box_Cl6-7_MP	Box Truck	6-7	52	46	MHD_M
08T_Box_Cl6-7_R	Box Truck	6-7	53	46	MHD_R
09T_Box_Cl8_U	Box Truck	8	52	47	HHD_U

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[886] Note, while having exactly 101 vehicles is not meaningful to the analysis itself, maintaining the same overall 101 vehicle types made other updates to HD TRUCS easier as a practical matter. Before consolidating any vehicle types we first verified that no assessment insight was lost, through confirming that the vehicle types that were aggregated were effectively redundant.

[887] MOVES is EPA's MOtor Vehicle Emissions Simulator, a state-of-the-art emission modeling system that estimates emissions for mobile sources at the national, county, and project level for criteria air pollutants, greenhouse gases, and air toxics.

[888] For the proposal, each tractor in HD TRUCS was assigned a GEM Energy ID for a Low Roof Tractor. However, for the final rule, we have updated all tractors to use the high-roof default values in GEM. This update was made because we found that high-roof tractors were the most common certification configuration in MY 2021. Because the energy consumption rate for high roof tractors is typically higher than for low roof tractors, this is a conservative assumption.

Vehicle ID	Vehicle Application	Weight Class	MOVES source TypeID	MOVES regClassID	GEM Energy ID[888, a,]
10T_Box_Cl6-7_U	Box Truck	6-7	52	46	MHD_U
11T_Box_Cl2b-3_U	Box Truck	2b-3	52	42	LHD_U
12T_Box_Cl2b-3_R	Box Truck	2b-3	52	42	LHD_R
13T_Box_Cl2b-3_MP	Box Truck	2b-3	52	42	LHD_M
14T_Box_Cl4-5_U	Box Truck	4-5	52	42	LHD_U
15T_Box_Cl4-5_R	Box Truck	4-5	52	42	LHD_R
16T_Box_Cl4-5_MP	Box Truck	4-5	52	42	LHD_M
17B_Coach_Cl8_R	Coach Bus	8	41	47	Coach Bus
18B_Coach_Cl8_MP[b]	Coach Bus	8	41	47	Coach Bus
19C_Mix_Cl8_MP	Cement Mixer	8	52	47	Concrete Mixer
20T_Dump_Cl8_U	Dump Truck	8	52	47	HHD_U
21T_Dump_Cl8_MP	Dump Truck	8	52	47	HHD_M
22T_Dump_Cl6-7_MP	Dump Truck	6-7	52	46	MHD_M
23T_Dump_Cl8_U	Dump Truck	8	52	47	HHD_U
24T_Dump_Cl6-7_U	Dump Truck	6-7	52	46	MHD_U
25T_Fire_Cl8_MP	Fire Truck	8	52	47	HHD_M
26T_Fire_Cl8_U	Fire Truck	8	52	47	HHD_U
27T_Flat_Cl6-7_MP	Flatbed/Stake Truck	6-7	52	46	MHD_M
28T_Flat_Cl6-7_R	Flatbed/Stake Truck	6-7	52	46	MHD_R
29T_Flat_Cl6-7_U	Flatbed/Stake Truck	6-7	52	46	MHD_U
30Tractor_DC_Cl8	Tractor_DC	8	61	47	C8_DC_HR
31Tractor_DC_Cl7	Tractor_DC	7	61	46	C7_DC_HR
32Tractor_SC_Cl8	Tractor_SC	8	62	47	C8_SC_HR_CdA036
33Tractor_DC_Cl8	Tractor_DC	8	61	47	C8_DC_HR_CdA036
34T_Ref_Cl8_MP	Refuse	8	51	47	Refuse Truck
35T_Ref_Cl6-7_MP	Refuse	6-7	51	46	MHD_M
36T_Ref_Cl8_U	Refuse	8	51	47	Refuse Truck
37T_Ref_Cl6-7_U	Refuse	6-7	51	46	MHD_U
38RV_Cl8_R	RV	8	54	47	RV
39RV_Cl6-7_R	RV	6-7	54	46	MHD_R
40RV_Cl4-5_R	RV	4-5	54	42	LHD_R
41Tractor_DC_Cl7[b]	Tractor_DC	7	61	46	C7_DC_HR
42RV_Cl8_MP	RV	8	54	47	RV
43RV_Cl6-7_MP	RV	6-7	54	46	MHD_M
44RV_Cl4-5_MP	RV	4-5	54	42	LHD_M
45Tractor_DC_Cl8[b]	Tractor_DC	8	61	47	C8_DC_HR
46B_School_Cl8_MP	School Bus	8	43	47	HHD_M
47B_School_Cl6-7_MP	School Bus	6-7	43	46	School Bus
48B_School_Cl4-5_MP	School Bus	4-5	43	42	LHD_M
49B_School_Cl2b-3_MP	School Bus	2b-3	43	42	LHD_M
50B_School_Cl8_U	School Bus	8	43	47	HHD_U
51B_School_Cl6-7_U	School Bus	6-7	43	46	School Bus
52B_School_Cl4-5_U	School Bus	4-5	43	42	LHD_U
53B_School_Cl2b-3_U	School Bus	2b-3	43	42	LHD_U
54Tractor_SC_Cl8	Tractor_SC	8	62	47	C8_SC_HR

Vehicle ID	Vehicle Application	Weight Class	MOVES source TypeID	MOVES regClassID	GEM Energy ID[888, a,]
55B_Shuttle_Cl2b-3_MP	Shuttle Bus	2b-3	42	42	LHD_M
56B_Shuttle_Cl4-5_U	Shuttle Bus	4-5	41	42	LHD_U
57B_Shuttle_Cl2b-3_U	Shuttle Bus	2b-3	41	42	LHD_U
58B_Shuttle_Cl6-7_MP	Shuttle Bus	6-7	42	46	MHD_M
59B_Shuttle_Cl6-7_U	Shuttle Bus	6-7	41	46	MHD_U
60S_Plow_Cl6-7_MP	Snow Plow	6-7	52	46	MHD_M
61S_Plow_Cl8_MP	Snow Plow	8	52	47	HHD_M
62S_Plow_Cl6-7_U	Snow Plow	6-7	52	46	MHD_U
63S_Plow_Cl8_U	Snow Plow	8	52	47	HHD_U
64V_Step_Cl6-7_MP	Step Van	6-7	52	46	MHD_M
65V_Step_Cl4-5_MP	Step Van	4-5	52	42	LHD_M
66V_Step_Cl2b-3_MP	Step Van	2b-3	53	42	LHD_M
67V_Step_Cl6-7_U	Step Van	6-7	52	46	MHD_U
68V_Step_Cl4-5_U	Step Van	4-5	52	42	LHD_U
69V_Step_Cl2b-3_U	Step Van	2b-3	53	42	LHD_U
70S_Sweep_Cl6-7_U	Street Sweeper	6-7	52	46	MHD_U
71T_Tanker_Cl8_R	Tanker Truck	8	52	47	HHD_R
72T_Tanker_Cl8_MP	Tanker Truck	8	52	47	HHD_M
73T_Tanker_Cl8_U	Tanker Truck	8	52	47	HHD_U
74T_Tow_Cl8_R	Tow Truck	8	52	47	HHD_R
75T_Tow_Cl6-7_R	Tow Truck	6-7	52	46	MHD_R
76T_Tow_Cl8_U	Tow Truck	8	52	47	HHD_U
77T_Tow_Cl6-7_U	Tow Truck	6-7	52	46	MHD_U
78Tractor_SC_Cl8	Tractor_SC	8	62	47	C8_SC_HR
79Tractor_SC_Cl8[b]	Tractor_SC	8	62	47	C8_SC_HR
80Tractor_DC_Cl8	Tractor_DC	8	52	47	C8_HH
81Tractor_DC_Cl7	Tractor_DC	7	61	46	C7_DC_HR
82Tractor_DC_Cl8	Tractor_DC	8	61	47	C8_DC_HR
83Tractor_DC_Cl7	Tractor_DC	7	61	46	C7_DC_HR
84Tractor_DC_Cl8	Tractor_DC	8	61	47	C8_DC_HR
85B_Transit_Cl8_MP	Transit Bus	8	42	47	Transit Bus
86B_Transit_Cl6-7_MP	Transit Bus	6-7	42	46	MHD_M
87B_Transit_Cl8_U	Transit Bus	8	42	48	Transit Bus
88B_Transit_Cl6-7_U	Transit Bus	6-7	42	46	MHD_U
89T_Utility_Cl8_MP	Utility Truck	8	52	47	HHD_M
90T_Utility_Cl8_R	Utility Truck	8	52	47	HHD_R
91T_Utility_Cl6-7_MP	Utility Truck	6-7	52	46	MHD_M
92T_Utility_Cl6-7_R	Utility Truck	6-7	52	46	MHD_R
93T_Utility_Cl4-5_MP	Utility Truck	4-5	52	42	LHD_M
94T_Utility_Cl2b-3_MP	Utility Truck	2b-3	52	42	LHD_M
95T_Utility_Cl4-5_R	Utility Truck	4-5	53	42	LHD_R
96T_Utility_Cl2b-3_R	Utility Truck	2b-3	53	42	LHD_R
97T_Utility_Cl8_U	Utility Truck	8	52	47	HHD_U
98T_Utility_Cl6-7_U	Utility Truck	6-7	52	46	MHD_U
99T_Utility_Cl4-5_U	Utility Truck	4-5	52	42	LHD_U

Vehicle ID	Vehicle Application	Weight Class	MOVES source TypeID	MOVES regClassID	GEM Energy ID[888, a,]
100T_Utility_Cl2b-3_U	Utility Truck	2b-3	52	42	LHD_U
101Tractor_DC_Cl8	Yard Tractor	8	61	47	C8_DC_HR

[a] LHD is light heavy-duty, MHD is medium heavy-duty, HHD is heavy heavy-duty, U is urban, R is regional, M is multi-purpose, SC is sleeper cab, DC is day cab, HH is heavy haul, HR is high roof.

[b] These vehicle types were analyzed as FCEVs. The remaining vehicles were analyzed as BEVs.

It should be noted that while the vehicles are identified throughout this document using several different vehicle characteristics as well as vehicle performance metrics, we sometimes show the vehicles grouped in different ways. This is due to the differences in categorization among underlying data sources. For example, vehicles in MOVES are grouped differently than the GEM subcategories (or, for that matter, different than the regulatory subcategories in the Phase 3 standards). In most cases, we will show the results for the 101 HD TRUCS vehicle types listed in Table 2-1, and include additional aggregation as applicable.

2.1.2 HD TRUCS Inputs

Inputs to the analysis were chosen based on our assessment of available literature, analysis, engineering judgement, comments on the NPRM, and other information about vehicles in the HD market, as described in later chapters. We presume that values from literature represent calendar year (CY). However, because model year certification in the heavy-duty industry largely follows the calendar year, calendar year and model year values are typically the same.

Baseline energy consumption is based largely on results from EPA's GEM model (see RIA Chapter 2.2.2), and the targets to determine the peak power requirement are generally based on the ANL Autonomie model (see RIA Chapter 2.4.1.2). Activity data is based on multiple data sources, including National Renewable Energy Laboratory's (NREL) detailed FleetDNA data (see RIA Chapter 2.2.1). Vehicle sales estimates are generally based on EPA's MOVES 4.R3 (see RIA Chapter 2.2.3). Many of the cost estimates and BEV and FCEV technical assumptions originated from ANL's Autonomie[889] and BEAN[890] tools used for DOE's Vehicle Technologies Office (VTO) and Hydrogen and Fuel Cell Technologies Office (HFTO) Research and Development (R&D) Benefits Analysis of 2022;[891,892] however, some of these assumptions have been updated for the final version of HD TRUCS based on consideration of comments received and on new data. Table 2-2 shows the HD TRUCS vehicle ID mapping to ANL vehicle categories. In the proposal, most cost values that are derived from ANL's 2022 BEAN tool were

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[889] Autonomie is a vehicle system simulation tool used to assess the energy consumption, performance, and costs of multiple advanced vehicle technologies.

[890] BEAN was developed to quantify the impact of individual vehicle component technologies on costs. ANL has worked for years with industry stakeholders and other national laboratories to develop these tools.

[891] Islam, Ehsan Sabri, Ram Vijayagopal, Aymeric Rousseau. "A Comprehensive Simulation Study to Evaluate Future Vehicle Energy and Cost Reduction Potential", *Report to the U.S. Department of Energy, Contract ANL/ESD-22/6*, October 2022. Available online: https://anl.app.box.com/s/an4nx0v2xpudxtpsnkhd5peimzu4j1hk/file/1406494585829.

[892] Argonne National Laboratory. VTO HFTO Analysis Reports – 2022. "ANL – ESD-2206 Report – BEAN Tool – MD HD Vehicle Techno-Economic Analysis.xlsm". Available online: https://anl.app.box.com/s/an4nx0v2xpudxtpsnkhd5peimzu4j1hk/folder/242640145714.

incorrectly identified as being in 2019$, when in fact they are in 2020$. This has been corrected in the final rule.

Table 2-2 HD TRUCS Vehicle ID mapping to ANL vehicles

Vehicle ID	ANL Purpose	ANL RegCode	ANL Class
01V_Amb_Cl4-5_MP	Service	Medium	4
02V_Amb_Cl2b-3_MP	Van	Medium	3
03V_Amb_Cl4-5_U	Service	Medium	4
04V_Amb_Cl2b-3_U	Van	Medium	3
05T_Box_Cl8_MP	Vocational	Heavy	8
06T_Box_Cl8_R	Vocational	Heavy	8
07T_Box_Cl6-7_MP	Box	Medium	6
08T_Box_Cl6-7_R	Box	Medium	6
09T_Box_Cl8_U	Vocational	Heavy	8
10T_Box_Cl6-7_U	Box	Medium	6
11T_Box_Cl2b-3_U	Box	Medium	3
12T_Box_Cl2b-3_R	Box	Medium	3
13T_Box_Cl2b-3_MP	Box	Medium	3
14T_Box_Cl4-5_U	Box	Medium	4
15T_Box_Cl4-5_R	Box	Medium	4
16T_Box_Cl4-5_MP	Box	Medium	4
17B_Coach_Cl8_R	Transit	Heavy	8
18B_Coach_Cl8_MP	Transit	Heavy	8
19C_Mix_Cl8_MP	Vocational	Heavy	8
20T_Dump_Cl8_U	Vocational	Heavy	8
21T_Dump_Cl8_MP	Vocational	Heavy	8
22T_Dump_Cl6-7_MP	Vocational	Medium	7
23T_Dump_Cl8_U	Vocational	Heavy	8
24T_Dump_Cl6-7_U	Vocational	Medium	7
25T_Fire_Cl8_MP	Vocational	Heavy	8
26T_Fire_Cl8_U	Vocational	Heavy	8
27T_Flat_Cl6-7_MP	Vocational	Medium	7
28T_Flat_Cl6-7_R	Vocational	Medium	7
29T_Flat_Cl6-7_U	Vocational	Medium	7
30Tractor_DC_Cl8	Drayage	DayCab	8
31Tractor_DC_Cl7	Tractor	DayCab	7
32Tractor_SC_Cl8	Longhaul	Sleeper	8
33Tractor_DC_Cl8	Tractor	DayCab	7
34T_Ref_Cl8_MP	Refuse	Heavy	8
35T_Ref_Cl6-7_MP	Vocational	Medium	7
36T_Ref_Cl8_U	Refuse	Heavy	8
37T_Ref_Cl6-7_U	Vocational	Medium	7
38RV_Cl8_R	Transit	Heavy	8
39RV_Cl6-7_R	School	Medium	7
40RV_Cl4-5_R	StepVan	Medium	4
41Tractor_DC_Cl7	Tractor	DayCab	7
42RV_Cl8_MP	Transit	Heavy	8
43RV_Cl6-7_MP	School	Medium	7
44RV_Cl4-5_MP	StepVan	Medium	4
45Tractor_DC_Cl8	Regional	DayCab	8
46B_School_Cl8_MP	Transit	Heavy	8
47B_School_Cl6-7_MP	School	Medium	7
48B_School_Cl4-5_MP	StepVan	Medium	4

49B_School_Cl2b-3_MP	School	Medium	3
50B_School_Cl8_U	Transit	Heavy	8
51B_School_Cl6-7_U	School	Medium	7
52B_School_Cl4-5_U	StepVan	Medium	4
53B_School_Cl2b-3_U	School	Medium	3
54Tractor_SC_Cl8	Longhaul	Sleeper	8
55B_Shuttle_Cl2b-3_MP	School	Medium	3
56B_Shuttle_Cl4-5_U	StepVan	Medium	4
57B_Shuttle_Cl2b-3_U	School	Medium	3
58B_Shuttle_Cl6-7_MP	School	Medium	7
59B_Shuttle_Cl6-7_U	School	Medium	7
60S_Plow_Cl6-7_MP	Vocational	Medium	7
61S_Plow_Cl8_MP	Vocational	Heavy	8
62S_Plow_Cl6-7_U	Vocational	Medium	7
63S_Plow_Cl8_U	Vocational	Heavy	8
64V_Step_Cl6-7_MP	StepVan	Medium	6
65V_Step_Cl4-5_MP	StepVan	Medium	4
66V_Step_Cl2b-3_MP	Van	Medium	3
67V_Step_Cl6-7_U	StepVan	Medium	6
68V_Step_Cl4-5_U	StepVan	Medium	4
69V_Step_Cl2b-3_U	Van	Medium	3
70S_Sweep_Cl6-7_U	Vocational	Medium	7
71T_Tanker_Cl8_R	Vocational	Heavy	8
72T_Tanker_Cl8_MP	Vocational	Heavy	8
73T_Tanker_Cl8_U	Vocational	Heavy	8
74T_Tow_Cl8_R	Vocational	Heavy	8
75T_Tow_Cl6-7_R	Vocational	Medium	7
76T_Tow_Cl8_U	Vocational	Heavy	8
77T_Tow_Cl6-7_U	Vocational	Medium	7
78Tractor_SC_Cl8	Longhaul	Sleeper	8
79Tractor_SC_Cl8	Longhaul	Sleeper	8
80Tractor_DC_Cl8	Vocational	Heavy	8
81Tractor_DC_Cl7	Tractor	DayCab	7
82Tractor_DC_Cl8	Regional	DayCab	8
83Tractor_DC_Cl7	Tractor	DayCab	7
84Tractor_DC_Cl8	Beverage	DayCab	8
85B_Transit_Cl8_MP	Transit	Heavy	8
86B_Transit_Cl6-7_MP	School	Medium	7
87B_Transit_Cl8_U	Transit	Heavy	8
88B_Transit_Cl6-7_U	School	Medium	7
89T_Utility_Cl8_MP	Vocational	Heavy	8
90T_Utility_Cl8_R	Vocational	Heavy	8
91T_Utility_Cl6-7_MP	Vocational	Medium	7
92T_Utility_Cl6-7_R	Vocational	Medium	7
93T_Utility_Cl4-5_MP	Service	Medium	4
94T_Utility_Cl2b-3_MP	Van	Medium	3
95T_Utility_Cl4-5_R	Service	Medium	4
96T_Utility_Cl2b-3_R	Van	Medium	3
97T_Utility_Cl8_U	Vocational	Heavy	8
98T_Utility_Cl6-7_U	Vocational	Medium	7
99T_Utility_Cl4-5_U	Service	Medium	4
100T_Utility_Cl2b-3_U	Van	Medium	3
101Tractor_DC_Cl8	Beverage	DayCab	8

2.2 HD Vehicle Benchmark Characteristics

HD TRUCS is designed to evaluate future HD ZEVs that can meet the energy demands of many different types of HD ICE vehicles. To accomplish this, we have "benchmarked" HD vehicle activity and typical rates of energy consumption at the axle[893] for a wide range of vehicle applications, weight classes, and duty cycles. We also collected data that is used to assign new vehicle sales distributions for all HD TRUCS vehicle types.

RIA Chapter 2.2.1 describes key vehicle activity metrics in HD TRUCS which includes annual and daily vehicle miles traveled (VMT). Annual activity is primarily used for calculating operational costs, and daily activity[894] is important for sizing ZEV components.

RIA Chapter 2.2.2 describes the rate of energy consumption required of HD vehicles, including the demand of power take off units (PTOs) and the recovered energy from regenerative braking.

HD TRUCS also includes the sales distribution of new HD vehicles, so that each of the 101 vehicle types represented in HD TRUCS can be assigned a fraction of new vehicle sales. This allows us to create sales-weighted adoption rates for consideration for the technology packages. RIA Chapter 2.2.3 describes how the sales weighting distributions were estimated for each HD TRUCS vehicle category.

2.2.1 HD Vehicle Activity

In RIA Chapter 2.2.1, we describe how we used time-related assumptions and VMT considerations in HD TRUCS to establish performance benchmarks for HD ZEVs.

2.2.1.1 Time-Related Assumptions

2.2.1.1.1 Operating Days Per Year

In HD TRUCS, all vehicles, other than Recreational Vehicles (RVs), operate 250 days per year.[895] We are using 250 operating days per year based on 50 weeks of 5 working days. RVs, however, are assumed to operate only 8 days per year (see Chapter RIA 2.2.1.2 for additional explanation).

2.2.1.1.2 Operating Hours Per Day

In our HD TRUCS analysis, the vehicles operate for 8 hours a day. Daily operating hours are used to calculate the amount of energy needed per day for heating, ventilation, and air

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[893] RIA Chapter 2.2 generally describes HD vehicle energy consumption rates that do not include powertrain-specific losses and energy demands. The powertrain-specific diesel, BEV, and FCEV losses and demands are described in RIA Chapters 2.3, 2.4, and 2.5, respectively.

[894] While ICE vehicles may not require daily refueling, BEVs and FCEVs in HD TRUCS are assumed to re-charge or refuel every day; therefore, we size ZEV components to meet the daily energy and/or power demand that is needed to accommodate a day of work.

[895] North American Council for Freight Efficiency (NACFE). "Electric Trucks Have Arrived: The Use Case for Heavy-Duty Regional Haul Tractors—Run on Less Electric Report". May 5, 2022. Available online: https://nacfe.org/wp-content/uploads/edd/2022/05/HD-Regional-Haul-Report-FINAL.pdf. NACFE used 250 days per year for diesel and electric Class 8 tractors (regional haul) & vans and step vans.

conditioning (HVAC) based on the vehicles' power demand for HVAC, as described in RIA Chapters 2.4.1.1.1 through 2.4.1.1.3, and 2.5.1.2.2.

2.2.1.1.3 Year-by-Year Assessment

In the NPRM version of HD TRUCS, we used 10-year average values to assess operating costs; this approach was improved upon for the final version of HD TRUCS. For the final version for HD TRUCS, we have assessed each year of operation using the appropriate changes that occur over time for inputs such as VMT, maintenance and repair, and fuel costs. We have however, continued to show many 10-year average values in Chapter 2 of the RIA in order to provide the reader with values that are comparable to the proposal and DRIA.[896] Also, for values such as maintenance and repair that increase with vehicle age, an average value may be more informative, as a single value. This is discussed in greater detail in the VMT and operating costs sections, RIA Chapters 2.2.1.2, 2.3.4, 2.4.4, and 2.5.3 and in the payback analysis section, RIA Chapter 2.8.8, and Appendix A to this RIA shows VMT for each of the first ten years of operation.

2.2.1.2 Vehicle Miles Traveled (VMT)

Vehicle miles traveled, or VMT, is one way to consider heavy-duty vehicle activity. In HD TRUCS, VMT is used to determine the daily and yearly use or operation of a vehicle, to size BEV battery packs, H2 storage tanks for FCEVs, and other components, and to estimate depot infrastructure needs. We relied on multiple sources to determine the VMT applied in HD TRUCS for each vehicle. The sources for daily VMT we considered were based on our assessment of data availability. We have listed them in order of publication date, the level of detail included in the data, and whether the data was collected from in-use vehicles: NREL's FleetDNA[897] database, a University of California, Riverside[898] (UC-Riverside) database, the Department of Transportation's Bureau of Transportation Statistic's 2002 Vehicle Inventory and Use Survey[899] (2002 VIUS), California Air Resource Board (CARB) Large Entity Reporting[900], or independent sources, as discussed below. Values included in HD TRUCS by vehicle type are shown in Table 2-3.

2.2.1.2.1 Operational VMT

The 50th percentile daily VMT is used to estimate costs associated with operating HD vehicles such as the annual fuel or electricity costs and maintenance and repair costs (see RIA Chapters 2.3.4, 2.4.4, and 2.5.3). We used the 50th percentile daily VMT as a proxy for the average amount of work done by a vehicle during a normal workday. For the final rule, we are

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[896] Please note that the DRIA was generally presented in 2021$, and the final RIA is generally shown in 2022$, and the 2022 dollar basis is 7 percent higher than the 2021 dollar basis.

[897] NREL. Fleet DNA: Commercial Fleet Vehicle Operating Data. Available online https://www.nrel.gov/transportation/fleettest-fleet-dna.html

[898] Zhang, Chen, Karen Ficenec, Andrew Kotz, Kenneth Kelly, Darrell Sonntag, Carl Fulper, Jessica Brakora, Tiffany Mo, and Sudheer Ballare. 2021. Heavy-Duty Vehicle Activity Updates for MOVES Using NREL Fleet DNA and CE-CERT Data. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5400-79509. https://www.nrel.gov/docs/fy21osti/79509.pdf.

[899] United States Census Bureau. 2002 Vehicle Inventory and Use Survey. Available online https://www.census.gov/library/publications/2002/econ/census/vehicle-inventory-and-use-survey.html.

[900] CARB. Large Entity Fleet Reporting. Available online https://ww2.arb.ca.gov/sites/default/files/2022-02/Large_Entity_Reporting_Aggregated_Data_ADA.pdf.

continuing this approach as proposed, as our assessment is that an operational VMT at the 50th percentile is a conservative but reasonable means of evaluating payback. For VMT data sources that only included annual VMT, we used the 250 days per year described above to calculate an average daily VMT. We used the 50th percentile VMT to represent the daily VMT for vehicle age at year 0, the first year of operation, in HD TRUCS. A typical HD vehicle's VMT changes with age. See RIA Chapter 2.2.1.2.4 for the change in VMT we used in HD TRUCS.

2.2.1.2.2 Sizing VMT

A daily "Sizing VMT"[901] value was used to calculate the storage capacity needs of a BEV battery, number of BEV battery cycles, and the EVSE size requirements for depot-charged BEVs, as well as onboard hydrogen storage capacity for the FCEVs. For the proposal, we generally selected the 90th percentile VMT because we projected that manufacturers will design their ZEVs to meet most daily VMT needs, but not the most extreme operations. For the proposal, EPA's analysis assumed that all BEVs would be predominantly charged at a depot. For example, ZEVs designed for 100th percentile daily VMT needs are likely unnecessarily heavy and expensive for most operations, which may limit their appeal in the market. During the timeframe covered in this analysis, we took into consideration that the vehicles that require daily VMT greater than the 90th percentile could either be ICE powered or could also use en-route public charging or hydrogen refueling during the day to meet their needs. In the proposal, the 90th percentile VMT was also referred to as the "sizing VMT."

EPA received comments about the 90th percentile VMT that was used in the proposal version of HD TRUCS for sizing BEV batteries and FCEV hydrogen tanks.[902] The American Council for an Energy-Efficient Economy (ACEEE), Environmental Defense Fund (EDF), and California Air Resource Board (CARB) all commented that the sizing VMT was too high as manufacturers would provide multiple battery sizes for their vehicles to allow fleets to tailor the battery sizes to their routes and daily VMT rather than purchase a battery larger than they require which would negatively affect payload and the cost of the vehicle. Some commenters stated that the 90th percentile VMT was too low. Daimler Truck North America (DTNA) commented that the sizing VMT was too low and disputed both the choice of a 90th percentile and the mileage estimate of that 90th percentile, submitting 90th percentile data on day cabs and sleeper cabs, based on telematic data collected over 18 days in May of 2023, that showed higher 90th percentile daily VMT than the HD TRUCS proposal estimates for the 90th percentile daily VMT for long range sleeper and day cabs. POET commented that customers would not purchase vehicles with a range significantly lower than 100 miles.

Our assessment is that 1) the 90th percentile approach will cover the majority of fleet operations where fleets are using daily depot charging, 2) battery sizes to meet shorter daily VMTs (i.e. using a lower sizing VMT) would mean that these depot charged BEVs would be unavailable for some market segments in our analysis, and 3) battery sizes to meet longer daily VMTs (that is, using a sizing VMT greater than our 90th percentile) would be unnecessarily large for many applications where fleets are using daily depot charging. Thus, we disagree that fleets will not purchase a once per day depot charging BEV that can fulfill the 90th percentile of daily

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[901] Sizing VMT is an important part of calculating the overall storage capacity of a BEV's battery or a FCEV's hydrogen tank size in HD TRUCS, but there are also other factors that add battery capacity and increase hydrogen tank size. Those factors are described in RIA Chapters 2.4.1.1.3 and 2.5.1.2.

[902] See RTC Section 3.3.1 for more information about comments received on this topic.

use cases. However, as a conservative cost assumption, and in response to comment that purchasers may avoid purchasing vehicles with a sizing range below 100 miles, we are adding an additional constraint for minimum battery sizing, such that no vehicle in HD TRUCS is designed for less than 100 miles of range, i.e., any vehicle with 90th percentile VMT of less than 100 miles in our analysis has been assigned a sizing VMT of 100 miles. [903]

After consideration of comment, we updated our approach in this final rule in recognition that in some instances, notably when public charging is an option, maintaining sizing at the 90th percentile could lead to unnecessary expense (as these vehicles would have larger batteries than required to meet the majority of fleet needs) and may create potential payload impacts unnecessarily, which could lead some fleets to not purchase such vehicles. We thus agree with commenters who noted that if the 90th percentile VMT yields a battery that may negatively affect payload and adds unnecessary cost, then public charging may be the preferred option.

For the final rule, we sized batteries in BEVs that we expect to be charged en route using public charging starting in MY 2030 at the 50th percentile daily VMT.[904] For the longest range day cabs and sleeper cabs, on days when these vehicles are required to travel longer distances, we find that less than 30 minutes of mid-day charging at 1 MW is sufficient to meet the HD TRUCS 90th percentile VMT[905] assuming vehicles start the day with a full battery.[906] The MY 2030-MY 2032 vehicles that are expected to charge publicly, have a higher charging cost assigned to their operating cost calculations (see RIA Chapter 2.4.4.2) and do not include an EVSE as part of their up-front purchase costs because they are expected to use public charging. Similarly, the FCEV tractor with the longest range is also sized at the 50th percentile VMT to ensure that there is room for packaging of the hydrogen tanks and because we expect they can refuel once mid-route per day. For the final rule, we assigned all BEV sleeper cabs and long range day cab tractors to use public charging, rather than depot charging. The ability to charge publicly means that the batteries of long-range vehicles can be sized more appropriately for typical use. Therefore, we sized the batteries such that their range is equal to the 50th percentile VMT (i.e., the average daily operating VMT) at year zero.[907] This does not mean that BEV tractors in our HD TRUCS analysis cannot drive a higher percentile daily VMT; it just means that they would have to stop and charge in order to cover a longer distance day.

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[903] See the next section and RIA Chapter 2.9.1 discussing applications for which certain HD TRUCS representative vehicles were modified for the final rule in ways that also increased the battery sizing assumptions and/or limited projected utilization of ZEV technologies in our modeled compliance pathway, and further discussing why EPA regards these modifications as reasonably conservative.

[904] The publicly-charged coach bus, 17B_Coach_Cl8_R, and the FCEV coach bus, 18B_Coach_Cl8_MP, however, are sized to the 90th percentile as described below.

[905] The HD TRUCS 90th percentile for the long-range publicly-charged BEV or FCEV day cab and sleeper cab vehicles are as follows: 32Tractor_SC_Cl8, 54Tractor_SC_Cl8, and 79Tractor_SC_Cl8 have a 571 mile 90th percentile VMT; 33Tractor_DC_Cl8, 81Tractor_DC_Cl7, and 82Tractor_DC_Cl8 have a 349 mile 90th percentile VMT. Note that the long-range sleeper cab 90th percentile VMT has been updated from the proposal estimate of 550 miles to 571 miles. Long-range sleeper cabs were assigned a 571 mile 90th percentile value to match the 90th percentile of the UC Riverside data for their Class 8 long haul tractor.

[906] See RIA Chapter 2.6.3 for more information on 2C or 1 MW charging times for publicly-charged vehicle types.

[907] The "50th percentile VMT at Year 0" means the 50th percentile daily VMT when the vehicle is new. This specification is needed for clarity, because operational VMT decreases as vehicles age.

See the next section (RIA Chapter 2.2.1.2.3) for more information about EPA's analysis for sizing publicly charged BEVs and long-range sleeper cab FCEVs.[908]

Concerning the 90th percentile VMT value, DTNA submitted 90th percentile data on day cabs and sleeper cabs, based on telematic data collected over 18 days in May of 2023, that showed higher 90th percentile daily VMT than the HD TRUCS proposal estimates for the 90th percentile daily VMT for long range sleeper and day cabs. As DTNA points out, building batteries to meet the 90th percentile of the data they presented would increase upfront costs and have greater payload impacts than EPA had projected for these vehicles. We did not use these data to calculate the 90th percentile sizing VMT. We discuss the data we did use in the following section, but note here that we regard these data as more representative than DTNA's because the data sets are for periods considerably longer than several weeks. Moreover, DTNA's comment was (properly) directed at EPA's assumption at proposal that all BEVs would be depot charged and was designed to show that depot charging would be inadequate for certain longer haul tractor types. As noted above, we agree. As stated above, and as explained in detail in the following Chapter 2.2.1.2.3, we project that public charging is available for certain day and sleeper cab tractors, therefore we assigned a 50th percentile sizing VMT for such vehicles. For the long range tractors, the sizing VMT is generally consistent with the DTNA telematics data -- i.e. that the sizing VMT with one additional en-route charge or hydrogen re-fuel is similar to the 90th percentile of the DTNA telematics data.[909] For example, the long range publicly-charged BEV sleeper cabs have a sizing (and operational) VMT of 420 miles; therefore, a mid-route charge will generally allow the driver to exceed the 90th percentile data submitted by DTNA at 724 miles. [910] The long range fuel cell vehicles have a sizing VMT of 349 miles, and could therefore travel beyond DTNA's 90th percentile data for day cabs with one hydrogen re-fuel.

2.2.1.2.3 VMT Data Sources and Final Rule Updates

For values available in the NREL and UC-Riverside databases, EPA assigned each vehicle a 50th percentile daily VMT and a 90th percentile daily VMT.[911] As described above, the 50th percentile VMT is used to calculate "operational VMT," as described in RIA Chapter 2.2.1.2.1. The 90th percentile VMT is generally used for "sizing VMT" for vehicles that are expected to use depot charging, with a few exceptions just noted above for ZEVs that are expected to charge using public charging or which may refuel once mid-route per day with hydrogen and which instead use the 50th percentile VMT (at year 0) for sizing, as described in RIA Chapter 2.2.1.2.2.

Not all vehicle applications were reflected in the NREL or UC-Riverside databases. In these instances, we used 2002 VIUS data. This data was reported as yearly VMT, which we divided by the assumed 250 operating days per year to estimate the 50th percentile daily VMT. We then applied factors to the VIUS 50th percentile daily VMT to estimate the 90th percentile daily VMT

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[908] Moreover, under our modeled potential compliance pathway, ICE vehicles are available to accommodate applications requiring extremes of sizing VMT.

[909] See Comments from Daimler Trucks North America. Docket # EPA-HQ-OAR-2022-0985-1555-A1. Page 23.

[910] Designing for a VMT of 420 miles allows the required size tanks to package behind the sleeper cab with a standard wheelbase length. This is further explained in Chapter 2.9.1.2.

[911] If data existed in both the Fleet DNA database and the UC Riverside database, we typically averaged the two values.

for vehicles.[912] In our final analysis, all factors applied to the VIUS data are unchanged from the NPRM factors. (Note, however, that some vehicle types that have been updated to a 100 mile minimum sizing VMT as described in Chapter 2.2.1.2.2).[913]

For the vehicle applications where VMT was not included in the NREL, UC-Riverside, or 2002 VIUS databases, we relied on consideration of independent sources or comments received to estimate daily VMT. For coach buses, we have increased the FCEV coach bus sizing VMT to 450 miles, based on consideration of comments received from motor coach companies about typical daily VMT during multi-day trips. For the BEV coach bus that is expected to be charged publicly, we have increased the sizing VMT to 300 miles. This value reflects the fact that there are existing BEV coach buses with an advertised range of 125[914]-240[915] miles but also considers that as utilization of ZEV technologies increase for coach buses, the demand for longer range between charging events will also increase.[916] For coach bus operational VMT, we have continued to use annual VMT from motorcoach census data for 2017, divided by 250 operational days.[917] See RTC 2.2.1 for comments received from the motor coach industry and our responses. For RVs, we used average yearly VMT from a 2009 Federal Highway Administration survey,[918] divided by the average number of camping trips per year from a Coleman Company, Inc. report,[919] and multiplied by two (for two driving days per camping trip). For school buses and shuttle buses, we used DOE's Alternative Fuels Data Center (AFDC) information for Average Annual Vehicle Miles Traveled by Major Vehicle Category.[920]

For the final version of HD TRUCS, we corrected the 50th and 90th percentile VMT formulas for six vehicles to address errors that were raised in comments. EPA made additional changes after consideration of comments. These include the following and are described in more detail in this section: the sizing VMT was increased for some utility vehicles and all snow plows. As noted earlier, for BEV tractors that are projected to charge publicly (32Tractor_SC_Cl8, 33Tractor_DC_Cl8, 54Tractor_SC_Cl8, 78Tractor_SC_Cl8, 81Tractor_DC_Cl7 , 82Tractor_DC_Cl8, 84Tractor_DC_Cl8), and the FCEV sleeper cab (79Tractor_SC_Cl8) were sized such that their sizing VMT is equal to their operating VMT at year 0.

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[912] See Miller, Neil. Memorandum to docket EPA-HQ-OAR-2022-0985. "Estimating 90th Percentile VMT for Vehicles using 2002 VIUS Data". October 2023. Document ID: EPA-HQ-OAR-2022-0985-1044.

[913] See Miller, Neil. Memorandum to docket EPA-HQ-OAR-2022-0985. "Estimating 90th Percentile VMT for Vehicles using 2002 VIUS Data". October 2023. Document ID: EPA-HQ-OAR-2022-0985-1044.

[914] BYD. C8MS. Available online: https://en.byd.com/bus/bus-c8ms/

[915] Motor Coach Industries. J4500 Charge. Available online: https://www.mcicoach.com/site-content/uploads/2023/12/MCI-J4500-CHARGE%E2%84%A2-brochure.pdf

[916] See RIA Chapter 2.9.1 for a discussion about the potential for ZEV packaging impacts on coach bus luggage space and EPA's commensurate limit on utilization of ZEV technologies for coach buses in HD TRUCS.

[917] American Bus Association Foundation. "Motorcoach Census: A Study of the Size and Activity of the Motorcoach Industry in the United States and Canada in 2017". June 5, 2019. Available online: https://www.buses.org/assets/images/uploads/pdf/FINAL_2017_Census_1.pdf.

[918] Federal Highway Administration. 2009 National Household Travel Survey: Average Annual Vehicle Miles of Travel Per Vehicle (Best Estimate) By Vehicle Age and Type. Available online: https://nhts.ornl.gov/tables09/fatcat/2009/best_VEHAGE_VEHTYPE.html.

[919] Coleman Company, Inc., and the Outdoor Foundation. "2016 American Camper Report". Available online: https://outdoorindustry.org/wp-content/uploads/2017/05/2016-Camper-Report_FINAL.pdf.

[920] U.S. Department of Energy, Alternative Fuels Data Center. "Average Annual Vehicle Miles Traveled by Major Vehicle Category". Last updated, February 2020; printed October 19, 2022. Available online: https://afdc.energy.gov/data/widgets/10309.

The sizing VMT for all snow plows including 60S_Plow_Cl6-7_MP, 61S_Plow_Cl8_MP, 62S_Plow_Cl6-7_U, 63S_Plow_Cl8_U and the Class 8 regional utility vehicle 90T_Utility_Cl8_R has been increased. This was done after consideration of comments that snow plows may need to operate for longer periods of time during adverse winter weather conditions. For the proposal, we had assumed that snow plows were a unique vehicle, but for the final rule, we have determined that snow plows are off season dump trucks in parts of the country that experience harsh winter weather. We therefore increased the sizing VMT of snow plows to match the sizing VMT of dump trucks.[921] After consideration of comments that raised concerns about the sizing VMT of utility trucks being used in prolonged power-outage situations, we have increased the sizing VMT to the maximum recorded value in the NREL Fleet DNA database for the Class 8 regional utility vehicles. We have also limited consideration of the utilization of ZEV technologies for all regional utility vehicles (of all weight classes) to 0 percent in MY 2027 and 14 percent in MY 2032, as described in RIA Chapter 2.9.1.

As noted above, we now are projecting that all BEV sleeper cabs would charge publicly, rather than at depots, and we set the sizing VMT equal to the daily operating VMT at year 0. In addition, we divided the sleeper cab tractors into four configurations to represent several sizing and technology approaches. For the sleeper cab tractors with the longest daily operating range, 32Tractor_SC_Cl8, 54Tractor_SC_Cl8, and 79Tractor_SC_Cl8, we used MOVES data to set the 50th percentile operational VMT at 420 miles.[922] Sleeper cab, 78Tractor_SC_Cl8, represents sleeper cabs with a shorter operating range. For the proposal, this vehicle had a 200 mile daily operating range; however, for the final rule, we updated this tractor to a 300 mile operating range. Based on CARB's "Large Entity Fleet Reporting,"[923] we used a sales volume share for the sleeper cab with a shorter range that is consistent with the sum of the percent of total sleeper cabs that have an estimated daily mileage up to 300 miles, totaling to a 28 percent sales share.

There was one comment related to packaging space availability associated with FCEVs. One industry commenter stated they believe liquid hydrogen is required to meet the packaging requirement for vehicles with a 500-mile range. We did not include onboard liquid hydrogen storage tanks in the final rule due to low technology maturity and our assessment is that there is adequate space for onboard compressed gaseous hydrogen tanks for the FCEVs that we modeled. We contracted FEV to independently conduct a packaging analysis for Class 8 long-haul tractors in support of the rule, and then we conducted an external peer review of the final FEV report. FEV found ways to package a tractor with six onboard gaseous hydrogen tanks plus a sleeper cab that is able to travel up to 500 miles.[924] Therefore, for the FCEV sleeper cab, 79Tractor_SC_Cl8, we set the sizing VMT equal to the daily operating VMT of 420 miles to ensure that packaging is possible. This does not mean the FCEV tractors in our HD TRUCS analysis cannot travel further than 420 miles in a day; it just means they would have to stop to refuel to travel a longer distance. Furthermore, manufacturers could design tractors to hold additional hydrogen tank

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[921] Pennsylvania DOT. "What do you really know about snowplows?". February 2021. Available online: https://www.penndot.pa.gov/PennDOTWay/pages/Article.aspx?post=396

[922] As noted in Chapter 0, and further described in Chapter 2.2.2.1, one of the long range publicly-charged BEV sleeper cabs, 32Tractor_SC_Cl8, was updated to reflect a lower coefficient of aerodynamic drag.

[923] California Air Resources Board. "Large Entity Fleet Reporting: Statewide Aggregated Data." Reported in 2021 on 2019 fleet data. Available online: https://ww2.arb.ca.gov/sites/default/files/2022-02/Large_Entity_Reporting_Aggregated_Data_ADA.pdf.

[924] FEV Consulting. "Heavy Duty Commercial Vehicles Class 4 to 8: Technology and Cost Evaluation for Electrified Powertrains—Final Report". Prepared for EPA. March 2024.

capacity and achieve even longer distances than we modeled for the final rule. Other factors that affect battery sizing for BEVs and hydrogen tank sizing for FCEVs are discussed in RIA Chapters 2.4.1.1.3 and 2.5.1.2.

The day cab tractors in the final rule HD TRUCS analysis are also divided into several operational distances, technology approaches, and charging strategies. Similar to the proposal, we relied on the Fleet DNA and UC Riverside data to establish a short-range day cabs (97 miles of daily operational VMT), mid-range day cabs (120 miles of daily operational VMT), and long-range day cabs (216 miles of daily operational VMT); however, for the final rule, we ensured that there were medium heavy-duty and heavy heavy-duty tractors represented for each range category. The short-range day cabs, 30Tractor_DC_Cl8 and 31Tractor_DC_Cl6-7, are depot charged and have a 90th percentile sizing VMT. The medium heavy-duty mid-range day cab, 83Tractor_DC_Cl7, is depot charged and uses the 90th percentile sizing VMT, and the heavy heavy-duty mid-range day cab, 84Tractor_DC_Cl8, is assumed to be charged publicly, starting in model year 2030, and uses the 50th percentile VMT for sizing, consistent with the other en-route charging tractors. There are five long-range day cabs. The long-range medium heavy-duty and heavy heavy-duty fuel cell vehicles, 41Tractor_DC_Cl7 and 45Tractor_DC_Cl8 both use the 90th percentile VMT for sizing. These fuel cell day cab tractors can accommodate the hydrogen tanks required for 90th percentile VMT. There are also both medium heavy-duty and heavy heavy-duty BEV long-range day cab tractors, 33Tractor_DC_Cl8,[925] 81Tractor_DC_Cl7, and 82Tractor_DC_Cl8 that rely on public charging in our analysis, starting in model year 2030; consistent with all en-route charging sleeper cabs, these tractors have a daily sizing VMT that is equal to the operating VMT.

The heavy-haul tractor, 80Tractor_DC_Cl8_HH, is unchanged from the proposal in that we continue to rely on FleetDNA data for operational VMT (50th percentile) and sizing VMT (90th percentile).

Table 2-3 lists the operational VMT for vehicles when they are new and the sizing VMT, along with the data source for these values for each of the 101 vehicles in HD TRUCS.

Table 2-3 Operational and Sizing VMT[926] in HD TRUCS

Vehicle ID	Refueling Location	VMT Source	Operational VMT for year 1 of Operation (mi/day)	Sizing VMT (mi/day)
01V_Amb_Cl4-5_MP	Depot	FleetDNA & UCR	34	100
02V_Amb_Cl2b-3_MP	Depot	FleetDNA & UCR	49	100
03V_Amb_Cl4-5_U	Depot	FleetDNA	39	100
04V_Amb_Cl2b-3_U	Depot	FleetDNA	40	100
05T_Box_Cl8_MP	Depot	2002 VIUS	66	100
06T_Box_Cl8_R	Depot	2002 VIUS	66	100
07T_Box_Cl6-7_MP	Depot	FleetDNA & UCR	40	100
08T_Box_Cl6-7_R	Depot	FleetDNA & UCR	40	100
09T_Box_Cl8_U	Depot	2002 VIUS	66	100

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[925] Similar to sleeper cab, 32Tractor_SC_Cl8, the day cab, 33Tractor_DC_Cl8, was updated to reflect a lower coefficient of aerodynamic drag. For more details, see RIA Chapter 2.2.2.1.

[926] The Operational VMT, shown in Table 2 2, are the daily miles that are assumed for the first year of new vehicle ownership, as operational VMT changes over time (see RIA Chapter 2.2.1.2.4). See Appendix A to this RIA for a 10-year schedule of operational VMT.

Vehicle ID	Refueling Location	VMT Source	Operational VMT for year 1 of Operation (mi/day)	Sizing VMT (mi/day)
10T_Box_Cl6-7_U	Depot	FleetDNA	39	105
11T_Box_Cl2b-3_U	Depot	FleetDNA & UCR	59	100
12T_Box_Cl2b-3_R	Depot	FleetDNA & UCR	59	100
13T_Box_Cl2b-3_MP	Depot	FleetDNA & UCR	59	100
14T_Box_Cl4-5_U	Depot	FleetDNA & UCR	38	100
15T_Box_Cl4-5_R	Depot	FleetDNA & UCR	38	100
16T_Box_Cl4-5_MP	Depot	FleetDNA & UCR	38	100
17B_Coach_Cl8_R	Public	Independent	158	300
18B_Coach_Cl8_MP	H2 Station	Independent	158	450
19C_Mix_Cl8_MP	Depot	NREL UCR	89	100
20T_Dump_Cl8_U	Depot	2002 VIUS	40	111
21T_Dump_Cl8_MP	Depot	2002 VIUS	40	111
22T_Dump_Cl6-7_MP	Depot	FleetDNA & UCR	56	156
23T_Dump_Cl8_U	Depot	2002 VIUS	40	111
24T_Dump_Cl6-7_U	Depot	FleetDNA & UCR	56	156
25T_Fire_Cl8_MP	Depot	2002 VIUS	40	111
26T_Fire_Cl8_U	Depot	2002 VIUS	40	111
27T_Flat_Cl6-7_MP	Depot	FleetDNA & UCR	40	100
28T_Flat_Cl6-7_R	Depot	FleetDNA & UCR	40	100
29T_Flat_Cl6-7_U	Depot	FleetDNA & UCR	40	100
30Tractor_DC_Cl8	Depot	FleetDNA & UCR	97	136
31Tractor_DC_Cl7	Depot	FleetDNA & UCR	97	147
32Tractor_SC_Cl8	Public	Independent	420	420
33Tractor_DC_Cl8	Public	FleetDNA	216	216
34T_Ref_Cl8_MP	Depot	FleetDNA & UCR	52	118
35T_Ref_Cl6-7_MP	Depot	2002 VIUS	94	118
36T_Ref_Cl8_U	Depot	FleetDNA & UCR	52	118
37T_Ref_Cl6-7_U	Depot	2002 VIUS	94	118
38RV_Cl8_R	Depot	Independent	335	335
39RV_Cl6-7_R	Depot	Independent	335	335
40RV_Cl4-5_R	Depot	Independent	335	335
41Tractor_DC_Cl7	H2 Station	FleetDNA & UCR	216	349
42RV_Cl8_MP	Depot	Independent	335	335
43RV_Cl6-7_MP	Depot	Independent	335	335
44RV_Cl4-5_MP	Depot	Independent	335	335
45Tractor_DC_Cl8	H2 Station	FleetDNA & UCR	216	349
46B_School_Cl8_MP	Depot	Independent	48	100
47B_School_Cl6-7_MP	Depot	FleetDNA & UCR	51	100
48B_School_Cl4-5_MP	Depot	Independent	48	100
49B_School_Cl2b-3_MP	Depot	Independent	48	100
50B_School_Cl8_U	Depot	Independent	48	100
51B_School_Cl6-7_U	Depot	FleetDNA & UCR	51	100
52B_School_Cl4-5_U	Depot	Independent	48	100
53B_School_Cl2b-3_U	Depot	Independent	48	100
54Tractor_SC_Cl8	Public	Independent	420	420
55B_Shuttle_Cl2b-3_MP	Depot	Independent	118	150
56B_Shuttle_Cl4-5_U	Depot	Independent	118	150
57B_Shuttle_Cl2b-3_U	Depot	Independent	118	150
58B_Shuttle_Cl6-7_MP	Depot	Independent	118	150
59B_Shuttle_Cl6-7_U	Depot	Independent	118	150
60S_Plow_Cl6-7_MP	Depot	NREL UCR	40	111

Vehicle ID	Refueling Location	VMT Source	Operational VMT for year 1 of Operation (mi/day)	Sizing VMT (mi/day)
61S_Plow_Cl8_MP	Depot	NREL UCR	44	156
62S_Plow_Cl6-7_U	Depot	NREL UCR	40	111
63S_Plow_Cl8_U	Depot	NREL UCR	44	156
64V_Step_Cl6-7_MP	Depot	FleetDNA	61	101
65V_Step_Cl4-5_MP	Depot	FleetDNA & UCR	38	100
66V_Step_Cl2b-3_MP	Depot	FleetDNA & UCR	59	100
67V_Step_Cl6-7_U	Depot	FleetDNA	61	101
68V_Step_Cl4-5_U	Depot	FleetDNA & UCR	38	100
69V_Step_Cl2b-3_U	Depot	FleetDNA & UCR	59	100
70S_Sweep_Cl6-7_U	Depot	2002 VIUS	50	100
71T_Tanker_Cl8_R	Depot	2002 VIUS	52	100
72T_Tanker_Cl8_MP	Depot	2002 VIUS	52	100
73T_Tanker_Cl8_U	Depot	2002 VIUS	52	100
74T_Tow_Cl8_R	Depot	2002 VIUS	64	157
75T_Tow_Cl6-7_R	Depot	FleetDNA & UCR	56	157
76T_Tow_Cl8_U	Depot	2002 VIUS	64	157
77T_Tow_Cl6-7_U	Depot	FleetDNA & UCR	56	157
78Tractor_SC_Cl8	Public	Independent	300	300
79Tractor_SC_Cl8	H2 Station	Independent	420	420
80Tractor_DC_Cl8	Depot	Independent	106	180
81Tractor_DC_Cl7	Public	FleetDNA & UCR	216	216
82Tractor_DC_Cl8	Public	FleetDNA & UCR	216	216
83Tractor_DC_Cl7	Depot	FleetDNA	120	214
84Tractor_DC_Cl8	Public	Independent	120	120
85B_Transit_Cl8_MP	Depot	FleetDNA	136	203
86B_Transit_Cl6-7_MP	Depot	FleetDNA	80	219
87B_Transit_Cl8_U	Depot	FleetDNA	136	203
88B_Transit_Cl6-7_U	Depot	FleetDNA	80	219
89T_Utility_Cl8_MP	Depot	FleetDNA & UCR	27	100
90T_Utility_Cl8_R	Depot	FleetDNA & UCR	27	100
91T_Utility_Cl6-7_MP	Depot	2002 VIUS	49	100
92T_Utility_Cl6-7_R	Depot	2002 VIUS	49	100
93T_Utility_Cl4-5_MP	Depot	2002 VIUS	49	100
94T_Utility_Cl2b-3_MP	Depot	FleetDNA	23	100
95T_Utility_Cl4-5_R	Depot	2002 VIUS	49	100
96T_Utility_Cl2b-3_R	Depot	2002 VIUS	49	100
97T_Utility_Cl8_U	Depot	FleetDNA	27	100
98T_Utility_Cl6-7_U	Depot	2002 VIUS	49	100
99T_Utility_Cl4-5_U	Depot	2002 VIUS	49	100
100T_Utility_Cl2b-3_U	Depot	FleetDNA	23	100
101Tractor_DC_Cl8	Depot	FleetDNA	60	127

2.2.1.2.4 Vehicle Age Impact on VMT

The VMT of HD vehicles varies with the age of the vehicle. Typically, newer vehicles are driven more, while older vehicles are driven less. In the NPRM, two schedules were applied to all vehicles, one for vocational vehicles and one for tractors. For the FRM, we aligned the rate of change in VMT in HD TRUCS with those in MOVES which allows for additional disaggregation using the MOVES sourceType ID. There are nine different VMT schedules applied in HD TRUCS for each of the MOVES source types as shown in Table 2-4 and Figure 2-1.[927] The factors are applied to the operational VMT which is assumed to be the operational VMT for vehicle age at year 0.

Table 2-4 Relative Change in VMT to Vehicle Age of Year 0 for each MOVES Source Type ID

sourceType ID	sourceType Name	Vehicle Age (Year)									
		0	1	2	3	4	5	6	7	8	9
41	Other Buses	1.00	0.97	0.94	0.91	0.88	0.85	0.82	0.80	0.77	0.75
42	Transit Bus	1.00	0.97	0.94	0.91	0.88	0.85	0.82	0.80	0.77	0.75
43	School Bus	1.00	0.97	0.94	0.91	0.88	0.85	0.82	0.80	0.77	0.75
51	Refuse Truck	1.00	1.00	1.00	1.00	0.96	0.91	0.87	0.82	0.78	0.73
52	Single Unit Short-haul Truck	1.00	1.00	1.00	1.00	0.95	0.90	0.83	0.78	0.73	0.69
53	Single Unit Long-haul Truck	1.00	1.00	1.00	1.00	0.95	0.88	0.81	0.74	0.69	0.64
54	Motor Home	1.00	1.00	1.00	1.00	1.00	0.99	0.97	0.95	0.95	0.93
61	Combination Short-haul Truck	1.00	1.00	1.00	1.00	0.93	0.87	0.80	0.73	0.67	0.60
62	Combination Long-haul Truck	1.00	1.00	1.00	1.00	0.95	0.89	0.84	0.79	0.74	0.68

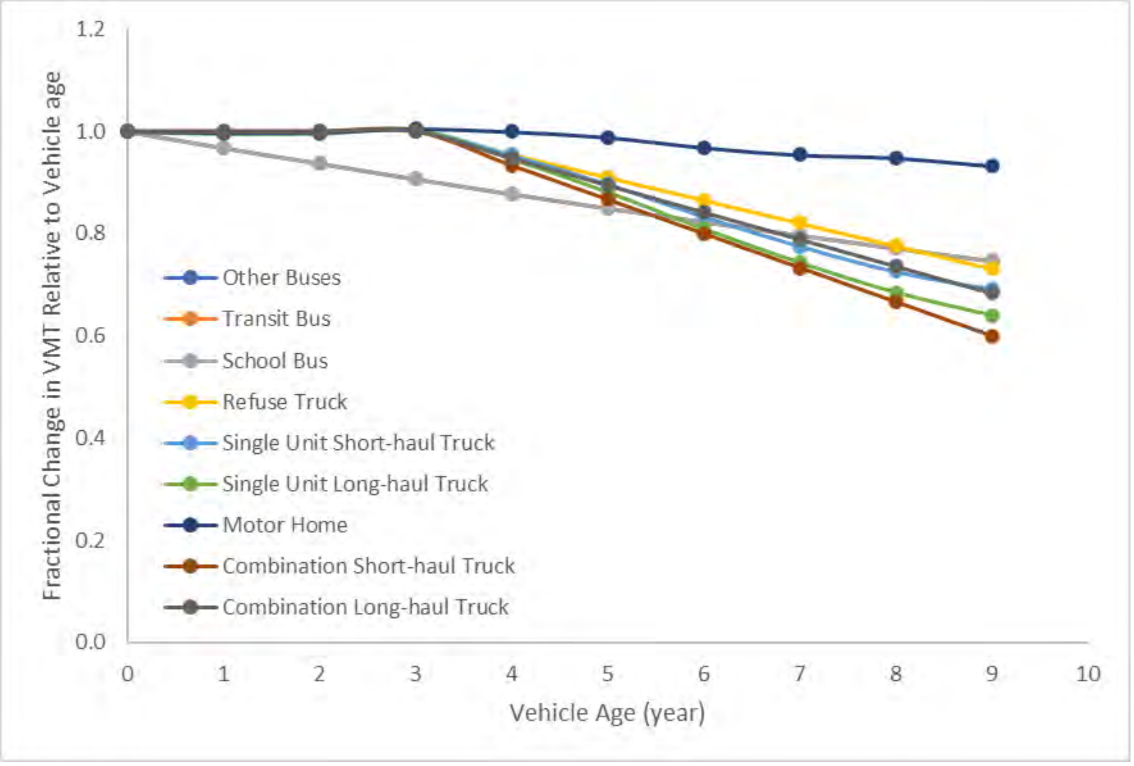

Figure 2-1 Relative Change in VMT from Vehicle Age in Year 0 to Age in Year 9

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[927] Murray, Evan. Memorandum to Docket EPA-HQ-OAR-2022-0985. "MOVES4.0.0 Technical Reports". February 2024.

2.2.2 HD Vehicle Energy Consumption

In this section, we describe how we evaluated HD vehicle energy consumption requirements, independent of the powertrain, to better understand how ZEVs could be designed to meet technical performance requirements.

For each HD TRUCS vehicle type, we determined the baseline energy consumption requirement that will be needed for ZEVs. We used EPA's GEM model to simulate road load power requirements for various duty cycles using the default road load profiles to estimate work performed by HD vehicles (as described in more detail in RIA Chapter 2.2.2.1.1). ZEV baseline energy includes the energy at the vehicle axle required to move the vehicle down the road (as described in more detail in RIA Chapter 2.2.2.1.2), the impact of regenerative braking[928] (as described in more detail below in RIA Chapter 2.2.2.1.3), and PTO energy (as described in more detail in RIA Chapter 2.2.2.1.4). The resulting ZEV baseline energy requirements are shown in Table 2-5 for each of the HD TRUCS vehicle types.

Other factors can impact energy consumption and power in a manner that may be different among ICE vehicles, BEVs, and FCEVs. The energy demand for heating, ventilation, and air conditioning (HVAC) is discussed in RIA Chapter 2.2.2.2. Additional powertrain-specific impacts on energy consumption and power are described in RIA Chapters 2.3.3, 2.4.1.1, and 2.5.1.2.

Table 2-5 Energy Requirements of HDVs

Vehicle ID	ZEV Baseline Energy Requirements			
	Axle (kWh/mi)	Regen Braking (kWh/mi)	PTO (kWh/mi)	ZEV Baseline Energy (kWh/mi)
01V_Amb_Cl4-5_MP	0.86	-0.08	0.00	0.78
02V_Amb_Cl2b-3_MP	0.86	-0.08	0.00	0.78
03V_Amb_Cl4-5_U	0.82	-0.13	0.00	0.68
04V_Amb_Cl2b-3_U	0.82	-0.13	0.00	0.68
05T_Box_Cl8_MP	2.07	-0.23	0.00	1.84
06T_Box_Cl8_R	2.07	-0.09	0.00	1.97
07T_Box_Cl6-7_MP	1.36	-0.14	0.00	1.23
08T_Box_Cl6-7_R	1.45	-0.06	0.00	1.39
09T_Box_Cl8_U	2.07	-0.37	0.00	1.70
10T_Box_Cl6-7_U	1.31	-0.22	0.00	1.09
11T_Box_Cl2b-3_U	0.82	-0.13	0.00	0.68
12T_Box_Cl2b-3_R	0.91	-0.03	0.00	0.88
13T_Box_Cl2b-3_MP	0.86	-0.08	0.00	0.78
14T_Box_Cl4-5_U	0.82	-0.13	0.00	0.68
15T_Box_Cl4-5_R	0.91	-0.03	0.00	0.88
16T_Box_Cl4-5_MP	0.86	-0.08	0.00	0.78
17B_Coach_Cl8_R	1.91	-0.09	0.00	1.82
18B_Coach_Cl8_MP	1.91	-0.09	0.00	1.82
19C_Mix_Cl8_MP	2.02	-0.36	1.48	3.14
20T_Dump_Cl8_U	2.07	-0.37	0.14	1.84
21T_Dump_Cl8_MP	2.07	-0.23	0.11	1.95

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[928] Regenerative braking is the process of slowing down a moving vehicle by using the vehicle's electric motor as a brake. This process allows the vehicle's electric motor to generate electricity which is then stored in the vehicle's battery and increases the net efficiency of the vehicle.

Vehicle ID	ZEV Baseline Energy Requirements			
	Axle (kWh/mi)	Regen Braking (kWh/mi)	PTO (kWh/mi)	ZEV Baseline Energy (kWh/mi)
22T_Dump_Cl6-7_MP	1.36	-0.14	0.09	1.32
23T_Dump_Cl8_U	2.07	-0.37	0.14	1.84
24T_Dump_Cl6-7_U	1.31	-0.22	0.10	1.19
25T_Fire_Cl8_MP	2.07	-0.23	0.22	2.06
26T_Fire_Cl8_U	2.07	-0.37	0.27	1.96
27T_Flat_Cl6-7_MP	1.36	-0.14	0.00	1.23
28T_Flat_Cl6-7_R	1.45	-0.06	0.00	1.39
29T_Flat_Cl6-7_U	1.31	-0.22	0.00	1.09
30Tractor_DC_Cl8	2.18	-0.15	0.00	2.03
31Tractor_DC_Cl7	1.80	-0.11	0.00	1.69
32Tractor_SC_Cl8	1.74	-0.10	0.00	1.63
33Tractor_DC_Cl8	1.86	-0.17	0.00	1.69
34T_Ref_Cl8_MP	2.01	-0.36	0.54	2.19
35T_Ref_Cl6-7_MP	1.35	-0.14	0.61	1.83
36T_Ref_Cl8_U	2.01	-0.36	0.54	2.19
37T_Ref_Cl6-7_U	1.28	-0.22	0.67	1.74
38RV_Cl8_R	1.36	-0.05	0.00	1.31
39RV_Cl6-7_R	1.45	-0.06	0.00	1.39
40RV_Cl4-5_R	0.91	-0.03	0.00	0.88
41Tractor_DC_Cl7	1.80	-0.11	0.00	1.69
42RV_Cl8_MP	1.36	-0.05	0.00	1.31
43RV_Cl6-7_MP	1.36	-0.14	0.00	1.23
44RV_Cl4-5_MP	0.86	-0.08	0.00	0.78
45Tractor_DC_Cl8	2.18	-0.15	0.00	2.03
46B_School_Cl8_MP	2.07	-0.23	0.00	1.84
47B_School_Cl6-7_MP	1.22	-0.21	0.00	1.02
48B_School_Cl4-5_MP	0.86	-0.08	0.00	0.78
49B_School_Cl2b-3_MP	0.86	-0.08	0.00	0.78
50B_School_Cl8_U	2.07	-0.37	0.00	1.70
51B_School_Cl6-7_U	1.22	-0.21	0.00	1.02
52B_School_Cl4-5_U	0.82	-0.13	0.00	0.68
53B_School_Cl2b-3_U	0.82	-0.13	0.00	0.68
54Tractor_SC_Cl8	2.05	-0.09	0.00	1.96
55B_Shuttle_Cl2b-3_MP	0.86	-0.08	0.00	0.78
56B_Shuttle_Cl4-5_U	0.82	-0.13	0.00	0.68
57B_Shuttle_Cl2b-3_U	0.82	-0.13	0.00	0.68
58B_Shuttle_Cl6-7_MP	1.36	-0.14	0.00	1.23
59B_Shuttle_Cl6-7_U	1.31	-0.22	0.00	1.09
60S_Plow_Cl6-7_MP	1.36	-0.14	0.09	1.32
61S_Plow_Cl8_MP	2.07	-0.23	0.09	1.93
62S_Plow_Cl6-7_U	1.31	-0.22	0.10	1.19
63S_Plow_Cl8_U	2.07	-0.37	0.11	1.81
64V_Step_Cl6-7_MP	1.36	-0.14	0.00	1.23
65V_Step_Cl4-5_MP	0.86	-0.08	0.00	0.78
66V_Step_Cl2b-3_MP	0.86	-0.08	0.00	0.78
67V_Step_Cl6-7_U	1.31	-0.22	0.00	1.09
68V_Step_Cl4-5_U	0.82	-0.13	0.00	0.68
69V_Step_Cl2b-3_U	0.82	-0.13	0.00	0.68
70S_Sweep_Cl6-7_U	1.31	-0.22	0.20	1.29
71T_Tanker_Cl8_R	2.07	-0.09	0.14	2.12
72T_Tanker_Cl8_MP	2.07	-0.23	0.16	2.00

Vehicle ID	ZEV Baseline Energy Requirements			
	Axle (kWh/mi)	Regen Braking (kWh/mi)	PTO (kWh/mi)	ZEV Baseline Energy (kWh/mi)
73T_Tanker_Cl8_U	2.07	-0.37	0.20	1.90
74T_Tow_Cl8_R	2.07	-0.09	0.12	2.09
75T_Tow_Cl6-7_R	1.45	-0.06	0.09	1.48
76T_Tow_Cl8_U	2.07	-0.37	0.16	1.86
77T_Tow_Cl6-7_U	1.31	-0.22	0.10	1.19
78Tractor_SC_Cl8	2.05	-0.09	0.00	1.96
79Tractor_SC_Cl8	2.05	-0.09	0.00	1.96
80Tractor_DC_Cl8	3.12	-0.26	0.00	2.86
81Tractor_DC_Cl7	1.80	-0.11	0.00	1.69
82Tractor_DC_Cl8	2.18	-0.15	0.00	2.03
83Tractor_DC_Cl7	1.80	-0.11	0.00	1.69
84Tractor_DC_Cl8	2.18	-0.15	0.00	2.03
85B_Transit_Cl8_MP	1.99	-0.36	0.00	1.63
86B_Transit_Cl6-7_MP	1.35	-0.14	0.00	1.21
87B_Transit_Cl8_U	1.99	-0.36	0.00	1.63
88B_Transit_Cl6-7_U	1.28	-0.22	0.00	1.06
89T_Utility_Cl8_MP	2.07	-0.23	0.08	1.93
90T_Utility_Cl8_R	2.07	-0.09	0.07	2.05
91T_Utility_Cl6-7_MP	1.36	-0.14	0.12	1.35
92T_Utility_Cl6-7_R	1.45	-0.06	0.12	1.51
93T_Utility_Cl4-5_MP	0.86	-0.08	0.09	0.86
94T_Utility_Cl2b-3_MP	0.86	-0.08	0.04	0.82
95T_Utility_Cl4-5_R	0.91	-0.03	0.08	0.96
96T_Utility_Cl2b-3_R	0.91	-0.03	0.08	0.96
97T_Utility_Cl8_U	2.07	-0.37	0.11	1.80
98T_Utility_Cl6-7_U	1.31	-0.22	0.14	1.22
99T_Utility_Cl4-5_U	0.82	-0.13	0.10	0.78
100T_Utility_Cl2b-3_U	0.82	-0.13	0.04	0.73
101Tractor_DC_Cl8	2.18	-0.15	0.00	2.03

2.2.2.1 ZEV Baseline Energy Consumption

ZEV baseline energy is the minimum energy required for the HD vehicle to perform its required work. Here, ZEV baseline energy includes the energy at the axle required to move the vehicle, impacts of regenerative braking (for vehicles with an electric motor), and the additional energy required from power take-off (PTO) units, if applicable.

We used EPA's GEM model to simulate road load power requirements for various duty cycles using the default road load profiles to estimate work performed by HD vehicles. GEM does this by modeling physical characteristics of a vehicle that include vehicle mass, frontal area, tire rolling resistance, tire size, gear ratio, accessory loads, as well as reductions in power demand for weight reduction and other technologies that reduce demand from the vehicle. We used the engine fuel maps and the vehicle technology inputs to GEM developed to support the MY 2027 HD GHG Phase 2 vehicle standards[929] (see the Phase 2 MY 2027 standards in Table 2-

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[929] U.S. Environmental Protection Agency and Department of Transportation. Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles - Phase 2 Regulatory Impact Analysis (October 25, 2016). Pages 2-136, 2-137, 2-158, 2-159.

109 for tractors, and in Table 2-110 for vocational vehicles for a list of the regulatory subcategories, including the vocational optional chassis subcategories) except for the BEVs 32Tractor_SC_Cl8 and 33Tractor_DC_Cl8.[930] For those vehicles we used the GEM inputs for C8_SC_HR and C8_DC_HR, respectively, except we applied a lower coefficient of drag area for the BEV vehicles (see GEM IDs C8_SC_HR_CdA036 and C8_DC_HR_CdA036) to represent trucks with a more aerodynamically optimized tractor design. To calculate the new value, we benchmarked the Tesla Semi which has the lowest coefficient of drag in the market today of 0.36.[931,932] We then multiplied the nominal frontal area (9.8 square meters) of these tractors by the Tesla Semi coefficient of drag, to determine the coefficient of drag area. The GEM input values also include default mechanical and electrical accessory loads (see Table 2-10 and Table 2-11).[933]

We used a tool developed in-house to evaluate hybrid vehicle performance to calculate a weighted percent of energy recovery due to regenerative braking.[934] This tool is like GEM in that it models physical vehicle properties over the Phase 2 duty cycles and uses the Phase 2 weighting for each regulatory subcategory to calculate the weighted energy recovered. We used the same Phase 2 vehicle GEM inputs for this tool as we used for the GEM simulations to maintain consistency in our calculations.

We incorporated PTO calculations into the ZEV baseline energy because they are the key aspect of work from some HD vehicles. In HD TRUCS, PTO is converted into kilowatt-hour (kWh) per mile (mi) using the operational hours and operational VMT for vehicles that have a PTO unit. We recognize that the presentation of PTO in terms of kWh/mi may suggest that all PTO loads are consumed while the vehicle is moving, but this is not the case for several vehicle types. Nonetheless, PTO is presented in terms of kWh/mi to help facilitate different calculations in HD TRUCS.

The total ZEV baseline energy is the summation of axle, regenerative braking, and PTO load energies, as shown in Table 2-5. Detailed descriptions of these values as well as inputs to GEM are discussed in RIA Chapters 2.2.2.1.1–2.2.2.1.4.[935]

2.2.2.1.1 GEM Inputs

Table 2-1 shows the GEM Energy ID that is assigned to each of the 101 vehicles in HD TRUCS. The tables in this RIA Chapter 2.2.2.1.1 show the GEM input values for each GEM

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[930] Note that GEM values are sometime applicable to a broader grouping of regulatory subcategories, so we will generally show GEM values at the regulatory subcategory grouping level that is appropriate. The vocational optional chassis subcategories are assigned a vocational vehicle services class and duty cycle for GEM simulations, as described in 40 CFR.1037.105(h).

[931] Inside EVs. “Tesla Semi: Details on Truck Aerodynamics and Drag Coefficient”. April 2019. Available online: https://insideevs.com/news/345710/tesla-semi-details-on-truck-aerodynamics-and-drag-coefficient/

[932] Fleetowner. “Musk touts Tesla Semi's range days before first fleet gets EV truck.” November 28, 2022. Available online: https://www.fleetowner.com/emissions-efficiency/article/21255400/musk-touts-tesla-semis-range-before-first-truck-deliveries-to-pepsico

[933] Note that the HVAC loads are subsequently removed to determine ZEV baseline energy consumption because HVAC loads differ among different powertrain technologies. See RIA Chapter 2.2.2.1.2 for more detail on the removal of HVAC loads for ZEV baseline energy.

[934] Miller, Neil. Memorandum to docket EPA-HQ-OAR-2022-0985. “Simple Hybrid Model”. March 2023.

[935] See also Miller, Neil. Memorandum to docket EPA-HQ-OAR-2022-0985. “GEM Inputs and Results”. November 2023.

Energy ID that are used to estimate energy demand at the axle. In the NPRM version of HD TRUCS, most MHD and HHD vehicles that could be optionally certified under an optional custom chassis category used GEM input default values for its corresponding optional custom chassis category; however, for the final version of HD TRUCS, we only used the optional custom chassis GEM default values for vehicles that are in the same weight class that is assigned to the Optional Chassis Category. This creates a more accurate estimate of energy consumption. An example of this is vehicle 46B_School_Cl8_MP, which was assigned the school bus optional chassis GEM Energy ID values (for a MHD vehicle) for the NPRM version of HD TRUCS. For the final version of HD TRUCS, we updated vehicle 46B_School_Cl8_MP to use GEM Energy ID values for a heavy heavy-duty multipurpose (HHD_M) vocational vehicle which is more representative of the energy consumption for a Class 8 school bus.

Table 2-6 through Table 2-9 show the engine, drivetrain, tire, and other GEM input parameters. Any GEM input parameters not listed have a value of zero.

Table 2-6 Model Year 2027 GEM Engine Parameters

GEM Energy ID	Engine File Name	Engine Power
C8_SC_HR	Engines\EPA_2027_D_SC_GENERIC_455_TCA_SIM_GEMv351.csv	455
C8_DC_HR	Engines\EPA_2027_D_SC_GENERIC_455_TCA_SIM_GEMv351.csv	455
C7_DC_HR	Engines\EPA_2027_D_GENERIC_350_TCA_SIM_GEMv351.csv	350
C8_HH	Engines\EPA_2018_D_GENERIC_600_TCA_SIM_GEMv351.csv	600
HHD_R	Engines\EPA_2027_D_Voc_GENERIC_455_TCA_SIM_GEMv351.csv	455
HHD_M	Engines\EPA_2027_D_Voc_GENERIC_350_TCA_SIM_GEMv351.csv	350
HHD_U	Engines\EPA_2027_D_Voc_GENERIC_350_TCA_SIM_GEMv351.csv	350
MHD_R	Engines\EPA_2027_D_GENERIC_270_TCA_SIM_GEMv351.csv	270
MHD_M	Engines\EPA_2027_D_GENERIC_270_TCA_SIM_GEMv351.csv	270
MHD_U	Engines\EPA_2027_D_GENERIC_270_TCA_SIM_GEMv351.csv	270
LHD_R	Engines\EPA_2027_D_GENERIC_200_TCA_SIM_GEMv351.csv	200
LHD_M	Engines\EPA_2027_D_GENERIC_200_TCA_SIM_GEMv351.csv	200
LHD_U	Engines\EPA_2027_D_GENERIC_200_TCA_SIM_GEMv351.csv	200
RV	Engines\EPA_2027_D_GENERIC_270_TCA_SIM_GEMv351.csv	270
School Bus	Engines\EPA_2027_D_GENERIC_270_TCA_SIM_GEMv351.csv	270
Coach Bus	Engines\EPA_2027_D_Voc_GENERIC_350_TCA_SIM_GEMv351.csv	350
Emergency	Engines\EPA_2027_D_Voc_GENERIC_350_TCA_SIM_GEMv351.csv	350
Mixer	Engines\EPA_2027_D_Voc_GENERIC_350_TCA_SIM_GEMv351.csv	350
Transit Bus	Engines\EPA_2027_D_Voc_GENERIC_350_TCA_SIM_GEMv351.csv	350
Refuse Truck	Engines\EPA_2027_D_Voc_GENERIC_350_TCA_SIM_GEMv351.csv	350

Table 2-7 Model Year 2027 GEM Drivetrain Parameters

GEM Energy ID	Transmission File Name	Drive Axle Config	Drive Axle Ratio
C8_SC_HR	Transmissions\EPA_MT_10_C78_4490_hires.csv	6X4	3.16
C8_DC_HR	Transmissions\EPA_MT_10_C78_4490_hires.csv	6X4	3.21
C7_DC_HR	Transmissions\EPA_MT_10_C78_4490_hires.csv	4X2	3.21
C8_HH	Transmissions\EPA_MT_18_HH_hires.csv	6X4	3.70
HHD_R	Transmissions\EPA_MT_10_HHD_4490_hires.csv	6X4	3.76
HHD_M	Transmissions\EPA_AT_6_HHD.csv	6X4	4.33
HHD_U	Transmissions\EPA_AT_5_HHD_1020_hires.csv	6X4	5.29
MHD_R	Transmissions\EPA_AT_6_MHD.csv	4X2	5.50
MHD_M	Transmissions\EPA_AT_6_MHD.csv	4X2	5.29
MHD_U	Transmissions\EPA_AT_5_MHD_803_hires.csv	4X2	5.29
LHD_R	Transmissions\EPA_AT_6_LHD.csv	4X2	4.33
LHD_M	Transmissions\EPA_AT_6_LHD.csv	4X2	4.56
LHD_U	Transmissions\EPA_AT_5_LHD_803_hires.csv	4X2	4.56
RV	Transmissions\EPA_AT_6_MHD.csv	4X2	5.50
School Bus	Transmissions\EPA_AT_5_MHD_803_hires.csv	4X2	5.29
Coach Bus	Transmissions\EPA_AT_6_HHDBus.csv	4X2	4.33
Emergency	Transmissions\EPA_AT_5_HHD_1020_hires.csv	6X4	5.29
Mixer	Transmissions\EPA_AT_5_HHDMixer.csv	6X4	5.29
Transit Bus	Transmissions\EPA_AT_5_HHD_1020_hires.csv	4X2	5.29
Refuse Truck	Transmissions\EPA_AT_5_HHD_1020_hires.csv	6X4	5.29

Table 2-8 Model Year 2027 GEM Vehicle Input Parameters

GEM Energy ID	Coef. of Drag Area (m2)	Steer Axle Tire Rolling Resistance Coefficient (N/kN)	Drive Axle 1 Tire Rolling Resistance Coefficient (N/kN)	Drive Axle 2 Tire Rolling Resistance Coefficient (N/kN)	Drive Axle Tire Size (rev/mile)
C8_SC_HR	5.26	5.6	5.8	5.8	512
C8_SC_HR_CdA036	3.53	5.6	5.8	5.8	512
C8_DC_HR	5.67	5.6	5.8	5.8	512
C8_DC_HR_CdA036	3.53	5.6	5.8	5.8	512
C7_DC_HR	5.67	5.6	5.8	NA	512
C8_HH	6.21	5.8	6.2	6.2	512
HHD_R	NA	7.7	7.7	7.7	496
HHD_M	NA	7.7	7.7	7.7	496
HHD_U	NA	7.7	7.7	7.7	496
MHD_R	NA	7.7	7.7	NA	517
MHD_M	NA	7.7	7.7	NA	557
MHD_U	NA	7.7	7.7	NA	557
LHD_R	NA	7.7	7.7	NA	670
LHD_M	NA	7.7	7.7	NA	670
LHD_U	NA	7.7	7.7	NA	660
RV	NA	5.8	5.8	NA	517
School Bus	NA	5.9	6.3	NA	557
Coach Bus	NA	5.8	5.8	5.8	496
Emergency	NA	6.4	8.1	8.1	496
Mixer	NA	6.7	7.2	7.2	496
Transit Bus	NA	6.7	6.8	NA	517
Refuse Truck	NA	6.7	6.8	6.8	496

Table 2-9 Model Year 2027 Additional Technology GEM Inputs

GEM Energy ID	Idle Speed (RPM)	Weight Reduction	Intelligent Controls (% Effectiveness)	Accessory Load (% Effectiveness)	Extended Idle Reduction (% Effectiveness)	Tire Pressure System (% Effectiveness)	Other Techs (% Effectiveness)
C8_SC_HR	600	0	0.8	0.5	3	1.1	5.5
C8_SC_HR_CdA036	600	0	0.8	0.5	3	1.1	5.5
C8_DC_HR	600	0	0.8	0.5	0	1.1	5.7
C8_DC_HR_CdA036	600	0	0.8	0.5	0	1.1	5.7
C7_DC_HR	650	0	0.8	0.5	0	1.1	5.1
C8_HH	600	0	0.8	0.5	0	1.1	9.5
HHD_R	600	0	NA	0.0	NA	0.0	0.0
HHD_M	650	0	NA	0.0	NA	0.0	0.0
HHD_U	650	0	NA	0.0	NA	0.0	0.0
MHD_R	750	0	NA	0.0	NA	0.0	0.0
MHD_M	750	0	NA	0.0	NA	0.0	0.0
MHD_U	750	0	NA	0.0	NA	0.0	0.0
LHD_R	750	0	NA	0.0	NA	0.0	0.0
LHD_M	750	0	NA	0.0	NA	0.0	0.0
LHD_U	750	0	NA	0.0	NA	0.0	0.0
RV	750	0	NA	0.0	NA	0.0	0.0
School Bus	750	0	NA	0.0	NA	0.0	0.0
Coach Bus	650	0	NA	0.0	NA	0.0	0.0
Emergency	650	0	NA	0.0	NA	0.0	0.0
Mixer	650	0	NA	0.0	NA	0.0	0.0
Transit Bus	650	75	NA	0.0	NA	0.0	0.0
Refuse Truck	650	0	NA	0.0	NA	0.0	0.0

We used the default values in GEM for the characteristics such as vehicle mass, rotational inertia, coefficient of drag (for vocational vehicles), tire rolling resistance (for trailers and vocational vehicles), payload, and electrical and mechanical accessory power (to account for additional loads related to accessories such as lights, radio, HVAC, and cooling fans) for each weight class and vehicle type. Table 2-10 contains values for tractors and Table 2-11 contains values for vocational vehicles. Additional details about model defaults can be found in the Phase 2 GEM documentation.[936]

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[936] U.S. Environmental Protection Agency. “Greenhouse Gas Emissions Model (GEM) v4.0 User Guide”. July 2022. Available online: https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P1015AND.pdf.

Table 2-10 GEM Tractor Default Values

Regulatory Class	Characteristic	Roof Height		
		High Roof	**Mid Roof**	**Low Roof**
C8_DC	Total Weight (kg)	31,297	29,529	29,710
	Tire Rolling Resistance (N/kN)	6.2		
	Rotational Mass (kg)	794		
	Payload (tons)	19		
	Electrical Acc Power (W)	1200		
	Mechanical Acc Power (W)	2300		
C8_SC	Total Weight (kg)	31,978	30,277	30,390
	Tire Rolling Resistance (N/kN)	6.2		
	Rotational Mass (kg)	794		
	Payload (tons)	19		
	Electrical Acc Power (W)	1200		
	Mechanical Acc Power (W)	2300		
C7_DC	Total Weight (kg)	22,679	20,910	21,091
	Tire Rolling Resistance (N/kN)	6.2		
	Rotational Mass (kg)	340		
	Payload (tons)	12.5		
	Electrical Acc Power (W)	1200		
	Mechanical Acc Power (W)	2300		
C8_HH	Total Weight (kg)	53750		
	Coefficient of Drag(m^2)	6.21		
	Tire Rolling Resistance (N/kN)	6.2		
	Rotational Mass (kg)	794		
	Payload (tons)	43		
	Electrical Acc Power (W)	1200		
	Mechanical Acc Power (W)	2300		

Table 2-11 GEM Vocational Vehicle Default Values

Regulatory Class	Total Weight (kg)	Coefficient of Drag (m^2)	Tire Rolling Resistance (N/kN)	Rotational Mass (kg)	Payload (tons)	Electrical Acc Power (W)	Mechanical Acc Power (W)
HHD	19,051	6.86	7.7	794	7.50	1200	2300
MHD	11,408	5.40	7.7	340	5.60	900	1600
LHD	7,257	3.40	7.7	340	2.85	500	1000
Emergency Vehicles	19,051	6.86	7.7	794	7.50	1200	2300
Cement Mixers	19,051	6.86	7.7	794	7.50	1200	2300
Refuse Trucks	19,051	6.86	7.7	794	7.50	1200	2300
Coach Buses	19,051	6.86	7.7	794	7.50	1200	2300
Transit Buses	19,051	6.86	7.7	794	7.50	1200	2300
Motor Homes	11,408	5.40	7.7	340	5.60	900	1600
School Buses	11,408	5.40	7.7	340	5.60	900	1600

2.2.2.1.2 GEM Energy Consumption at the Axle

To determine energy consumption per mile, we first calculated work performed, or energy consumed, at the axle (kWh) and CO_2 emissions (grams) for each duty cycle as shown in Table 2-12; this was determined for the constant cruise at 55 and 65 miles per hour (MPH) cycles as well as the transient cycle. The cruise cycles include road grade. The road grade profile for both the 55 mph and 65 mph duty cycles is based on statistical analysis of the United States' national distribution of road grades. The minimum grade in these cycles is –5 percent and the maximum grade is 5 percent. The cycle spends 46 percent of the distance in grades of ± 0.5 percent. Overall, the cycle spends approximately 66 percent of the time in relatively flat terrain with road gradients of ± 1 percent.[937]

We also removed the air conditioning compressor portion of the HVAC loads from axle work because HVAC loads differ across the range of HD vehicle powertrain technologies such as ICE, BEV, and FCEV. Therefore, we considered HVAC loads separately from the ZEV baseline energy consumption that is used for ZEVs. The energy consumption at the axle, as shown in Table 2-12, was determined by subtracting this HVAC power demand, weighted by GEM duty cycle, from the GEM output. The power consumption of the HVAC load during the duty cycle that we removed was 1.0 kilowatt (kW) for LHD and MHD vehicles and 1.5 kW for remainder of the vehicles based on the mechanical accessory loads developed for HD GHG Phase 2 version of GEM.[938] The HVAC load is calculated assuming that the HVAC system is operating at a constant load during the entire duty cycle.

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[937] 81 FR 73633.

[938] U.S. Environmental Protection Agency. "Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Truck – Regulatory Impact Analysis." August 2016. EPA 420-R-16-900. See Chapters 4.4.1.9 and 4.4.1.10.

Table 2-12 Model Year 2027 GEM Axle Work and CO_2 Emissions[939] (HVAC load has been removed)

GEM Energy ID	Cruise 55 MPH		Cruise 65 MPH		Transient Cycle	
	Axle Work (kWh)	Grams of CO_2	Axle Work (kWh)	Grams of CO_2	Axle Work (kWh)	Grams of CO_2
C8_SC_HR	23.5	13855	27.2	15687	8.2	6124
C8_SC_HR_CdA036	20.4		22.7		8.0	
C8_DC_HR	24.0	14712	28.0	16860	8.0	6286
C8_DC_HR_CdA036	20.1		22.5		7.8	
C7_DC_HR	20.0	12662	24.1	14950	5.9	5169
C8_HH	34.0	21058	37.6	23394	13.4	9982
HHD_R	23.5	16537	29.2	20266	5.5	5046
HHD_M	23.5	17704	29.0	21596	5.5	5748
HHD_U	23.5	21563	28.4	27897	5.5	5736
MHD_R	16.7	14321	21.1	17409	3.4	4016
MHD_M	16.7	14447	21.1	17465	3.4	4026
MHD_U	16.7	14980	21.2	18443	3.4	4043
LHD_R	10.5	9626	13.3	11514	2.1	2763
LHD_M	10.5	9836	13.4	11868	2.1	2808
LHD_U	10.5	10513	13.3	12974	2.1	2820
RV	15.5	13506	19.9	16534	3.2	3854
School Bus	15.6	14247	20.1	17729	3.1	3794
Coach Bus	21.5	15859	27.0	19539	5.1	5423
Emergency	23.4	21493	28.3	27834	5.4	5722
Mixer	22.9	21149	27.8	27525	5.4	5651
Transit Bus	22.6	20628	27.4	26948	5.3	5495
Refuse Truck	22.6	20971	27.5	27363	5.3	5614

The values for work performed during each duty cycle were then divided by the distance of each duty cycle to determine the energy demand per mile. The distance and duration of each duty cycle are listed in Table 2-13.

Table 2-13 GEM Duty Cycle Distance and Time

GEM Test Cycle	Distance (miles)	Time (s)
Transient	2.84	668
55 Cruise	13.43	879
65 Cruise	13.43	744

Energy required per mile was then weighted by the applicable Phase 2 weighting factor for each test cycle and respective regulatory class to adjust consumption based on GEM distance weighting (by duty cycle) and time weighting (by percent at idle) factors, as well as average speed during non-idle cycles, as shown in Table 2-14. (Note that the regulatory subcategories that use the same weight factors are aggregated in the table.)

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[939] There are two tractors, 33Tractor_DC_Cl8 and 32Tractor_SC_Cl8, which when assessed as BEVs were simulated in GEM with lower aerodynamic drag than their diesel counterparts. This is because typical engine packaging for diesel vehicles precludes the type of aerodynamic reductions that are available to BEVs. These two vehicles, when assessed as BEVs, are assigned Gem Energy IDs, BEV, C8_DC_HR_CdA036, and C8_SC_HR_CdA036, respectively. We did not calculate grams of CO_2 for these two GEM Energy IDs because these are only assessed as BEV vehicles and therefore do not have CO_2 emissions.

Table 2-14 GEM Test Cycle Weighting Factors and Average Speed

Regulatory Class	Distance-weighted Factor (%)			Time-weighted Factor (%)			Average speed (MPH)
	Transient	55 Cruise	65 Cruise	Drive idle	Parked idle	Non-idle	
Sleeper Cab	5	9	86				
Day Cab	19	17	64				
Heavy-haul tractors	19	17	64				
Vocational – Regional	20	24	56	0	25	75	28.41
Vocational – Multi-Purpose (2b-7)	54	29	17	17	25	58	23.18
Vocational – Multi-Purpose (8)	54	23	23	17	25	58	23.27
Vocational – Urban (2b-7)	92	8	0	15	25	60	16.25
Vocational – Urban (8)	90	10	0	15	25	60	16.51

The values were summed to calculate the energy consumption by regulatory class. The resulting values for weighted energy consumption per mile at the axle are shown in Table 2-15. As described above, HVAC loads have been removed, and neither PTO loads nor regenerative braking benefits are included in Table 2-15.

For the final rule, we updated the tractor energy consumption values. The updates were made for two distinct reasons. The first update was made to correct an error in the proposal that occurred when summing the weighted energy of the three duty cycles. We had added the weighted value at the transmission for the 65-mph cruise cycle into the tractors rather than using the weighted value at the axle. This correction had the effect of lowering the tractor energy consumption values. The second update was to use high-roof tractor Phase 2 inputs. For the proposal, each tractor in HD TRUCS was assigned a GEM Energy ID for a low roof tractor. However, for the final rule, we have updated all tractors to use the high-roof default values in GEM because we found that high-roof tractors were the most common configuration in the MY 2021 Phase 2 vehicle GHG emission certifications. Because the energy consumption rate for high roof tractors is typically higher than for low roof tractors, this is a conservative approach and had the effect of raising the energy consumption values. The net effect of both updates resulted in values that are 3 to 6 percent lower than the proposal for the impacted tractors.

Table 2-15 Weighted Energy Consumption per Mile

GEM Energy ID	Weighted Axle Work per Mile (kWh/mi)
C7_DC_HR	1.83
C8_DC_HR	2.21
C8_DC_HR_CdA036	1.89
C8_HH	3.15
C8_SC_HR	2.07
C8_SC_HR_CdA036	1.76
HHD_R	2.09
HHD_M	2.11
HHD_U	2.14
MHD_R	1.46
MHD_M	1.39
MHD_U	1.36
LHD_R	0.93
LHD_M	0.89
LHD_U	0.87
RV	1.38
School Bus	1.30
Coach Bus	1.94
Emergency	2.13
Concrete Mixer	2.10
Transit Bus	2.07
Refuse Truck	2.08

2.2.2.1.3 Regenerative Braking

Regenerative braking is utilized on BEVs and FCEVs, but the amount of potential energy recovery is dependent on the vehicle properties and drive cycle. The details for calculating our projections for regenerative (sometimes referred to as “regen”) braking energy are in RIA Chapter 2.8.1. In summary, to calculate percent energy recovery available, we estimated the braking energy and divided by the total tractive energy (i.e., the energy required to move the vehicle) for each drive cycle and then weighted the results using the respective GEM test cycle weighting factors from Table 2-14. We then multiplied these values by the weighted energy consumption per mile to get energy recovered per mile from regenerative braking. The results are shown in Table 2-16. This table in the proposal contained incorrect values in the column titled “Regenerative Braking Energy Recovered (kWh/mile)”. The values displayed in the proposal were the fractional value of the column titled “Regenerative Braking Energy Recovered (%)” and we have updated the values to reflect the actual regenerative braking used in the final rule, which are the same value as used in the proposal.

Table 2-16 Percent Energy Recovery and Energy Recovered per Mile from Regenerative Braking

GEM Energy ID	Regenerative Braking Energy Recovered (%)	Regenerative Braking Energy Recovered (kWh/mile)
C7_DC_HR	6.0	0.11
C8_DC_HR	7.0	0.15
C8_DC_HR_CdA036	8.9	0.17
C8_HH	8.5	0..26
C8_SC_HR	4.3	0.09
C8_SC_HR_CdA036	5.9	0.10
HHD_R	4.5	0.09
HHD_M	11.1	0.23
HHD_U	17.9	0.38
MHD_R	3.9	0.06
MHD_M	10.1	0.14
MHD_U	16.8	0.23
LHD_R	3.8	0.04
LHD_M	9.8	0.09
LHD_U	16.5	0.14
RV	3.9	0.05
School Bus	16.8	0.22
Coach Bus	4.5	0.09
Emergency	17.9	0.18
Concrete Mixer	17.9	0.38
Transit Bus	17.9	0.37
Refuse Truck	17.9	0.37

Note that GEM outputs are by vehicle type. Energy recovered from regenerative braking per mile for each regulatory subcategory was then applied to the applicable 101 vehicle types in HD TRUCS. RIA Chapters 2.3, 2.4, and 2.5 discuss how electrical energy and fuel consumption per mile are attributed to the 101 HD TRUCS vehicle types for ICE vehicles, BEVs, and FCEVs, respectively.

2.2.2.1.4 Power Take Off (PTO)

Some vocational vehicles selected as representative of the heavy-duty industry have attachments that perform work, typically by powering a hydraulic pump, which are powered by PTOs. In HD TRUCS, the vehicle applications with PTO energy consumption estimates include boom (utility) truck, cement mixer/cement pumper[940], dump truck, fire truck, garbage truck (refuse handler), snowplow, (street) sweeper, tanker truck, and wrecker (tow truck). Information on in-use PTO energy demand cycles is limited. NREL published two papers describing investigative work into PTO usage and energy consumption.[941,942] These studies, however, were limited to electric utility vehicles, such as bucket trucks and material handlers. To account for

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[940] Cement mixer is used to represent both cement mixers and cement pumpers.

[941] Konan, Arnaud, et al.“Characterization of PTO and Idle Behavior for Utility Vehicles.” Sept 2017. NREL. Available online: https://www.nrel.gov/docs/fy17osti/66747.pdf.

[942] Konan, Arnaud, et al. “Fuel and Emissions Reduction in Electric Power Take-Off Equipped Utility Vehicles” June 2016. NREL. Available online: https://www.nrel.gov/docs/fy17osti/66737.pdf

PTO usage in HD TRUCS, we relied on a table described in California's Diesel Tax Fuel Regulations, specifically in Regulation 1432, "Other Nontaxable Uses of Diesel Fuel in a Motor Vehicle."[943] The table for Regulation 1432 covers a wider range of vehicles beyond the electric utility vehicles in the previously mentioned NREL studies. This table contains "safe-harbor" percentages that are presumed amounts of diesel fuel used for "auxiliary equipment" operated from the same fuel tank as the motor vehicle. In California, a person may apply for a fuel tax refund for diesel fuel that is not used to operate a motor vehicle upon a highway in California.[944] In the NPRM, we used this table to estimate PTO energy use as a function of total fuel consumed by vehicle type, as shown in Table 2-17. We received comment suggesting that a cement mixer may have PTO fuel burn in the range of 35%-49%. After consideration of this comment, for the final rule we have updated the cement mixer/pumper PTO rate to 42%, the midpoint of the range suggested by the commenter to more accurately reflect the industry average PTO energy consumption for concrete mixers.

The percent PTO energy use for specific vehicle types in HD TRUCS are shown in Table 2-18.

Table 2-17 PTO Energy Use as a Function of Total Energy Consumed from CA Regulation 1432[945]

Type	PTO Percent (%) from CA Regulation 1432	PTO Percent (%) as Used in HD TRUCS
None	0	0
Boom truck/block boom	15	15
Cement mixer	25	42
Cement pumper	40	42
Dump truck	15	15
Fire truck	25	25
Garbage truck	35	35
Snow plow	15	15
Sweeper truck	20	20
Tank truck	15	15
Wrecker	15	15

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[943] *See* Cal. Code Regs. tit. 18, § 1432, "Other Nontaxable Uses of Diesel Fuel in a Motor Vehicle," *available at* https://www.cdtfa.ca.gov/lawguides/vol3/dftr/dftr-reg1432.html.

[944] *Ibid.*

[945] California Department of Tax and Fee Administration. Regulation 1432. Other Nontaxable Uses of Diesel Fuel in a Motor Vehicle. Accessed October 2022. Available online: https://www.cdtfa.ca.gov/lawguides/vol3/dftr/dftr-reg1432.html#:~:text=in%20these%20percentages%3A-,Boom%20truck/block%20boom,10%25,-(3)%20For%20transactions.

Table 2-18 PTO Assignment in HD TRUCS

Vehicle ID	PTO Percent Energy Consumption (%)
19C_Mix_Cl8_MP	42%
20T_Dump_Cl8_U	15%
21T_Dump_Cl8_MP	15%
22T_Dump_Cl6-7_MP	15%
23T_Dump_Cl8_U	15%
24T_Dump_Cl6-7_U	15%
25T_Fire_Cl8_MP	25%
26T_Fire_Cl8_U	25%
34T_Ref_Cl8_MP	35%
35T_Ref_Cl6-7_MP	35%
36T_Ref_Cl8_U	35%
37T_Ref_Cl6-7_U	35%
60S_Plow_Cl6-7_MP	15%
61S_Plow_Cl8_MP	15%
62S_Plow_Cl6-7_U	15%
63S_Plow_Cl8_U	15%
70S_Sweep_Cl6-7_U	20%
71T_Tanker_Cl8_R	15%
72T_Tanker_Cl8_MP	15%
73T_Tanker_Cl8_U	15%
74T_Tow_Cl8_R	15%
75T_Tow_Cl6-7_R	15%
76T_Tow_Cl8_U	15%
77T_Tow_Cl6-7_U	15%
89T_Utility_Cl8_MP	15%
90T_Utility_Cl8_R	15%
91T_Utility_Cl6-7_MP	15%
92T_Utility_Cl6-7_R	15%
93T_Utility_Cl4-5_MP	15%
94T_Utility_Cl2b-3_MP	15%
95T_Utility_Cl4-5_R	15%
96T_Utility_Cl2b-3_R	15%
97T_Utility_Cl8_U	15%
98T_Utility_Cl6-7_U	15%
99T_Utility_Cl4-5_U	15%
100T_Utility_Cl2b-3_U	15%

Table 2-17 shows the PTO energy as a percent of total energy consumed. We assumed the fuel is consumed while operating a diesel-powered vehicle on an annual basis. To incorporate the value into the ZEV baseline energy consumption on a kWh/mi basis, we converted the fuel consumption of vehicles listed in Table 2-18 from the fuel economy (MPG) of the comparable ICE vehicle into annual diesel fuel consumption using 250 operating days in a year. Since GEM does not include PTO of these vehicles, the PTO fuel consumption is the PTO percent multiplied by the annual fuel consumption projected for the vehicles due to driving operation only. This is then converted back to a daily value by dividing by 250 operating days per year, and then to an axle and per-mile value by applying the diesel energy content and losses from the ICE powertrain system. A detailed description of PTO calculations can be found in RIA Chapter 2.3.3.

2.2.2.2 Heating, Ventilation, and Air Conditioning (HVAC) Energy Consumption

Heating, ventilation, and air conditioning (HVAC) energy requirements vary by vehicle type, vocation, and duty cycle. The HVAC energy required to heat and cool interior cabins is considered separately from the baseline energy, since these energy loads are not required year-round or in all regions of the country and most vehicles are equipped with air conditioning (A/C). Nearly all commercial vehicles are equipped with heat and basic ventilation. In ICE vehicles, traditional cabin heating makes use of excess thermal energy produced by the main ICE. This is the only source of cabin heating for many vehicle types. Additionally, on ICE vehicles, cabin A/C uses a mechanical refrigerant compressor that is engine belt driven. A/C utilizes a thermodynamic cycle to move thermal energy from the cabin to the ambient air outside the vehicle, cooling and dehumidifying the cabin. Compressors can also be driven by an electric motor.

Energy consumption associated with vehicle heating and cooling is dependent on passenger comfort requirements, cabin size and materials, ambient air temperature, relative humidity, number of occupants, number of door openings and closings, and the HVAC system technology type and efficiency.

Cabin heating utilizing engine waste heat requires electrical power to run the controls and blower motors. A/C operation adds mechanical load on the engine to run the compressor and requires electric power to operate the HVAC blower motor.

As described in RIA Chapter 2.2.2.1.2, although GEM already includes HVAC load in its power consumption, because of the unique and different nature of BEVs and FCEVs, this incorporated load is removed from the calculated GEM energy consumption at the axle for ZEV baseline energy. Then, a separate HVAC calculation is performed to calculate the "axle" level HVAC consumption of BEVs and FCEVs irrespective of the energy source (i.e., the battery or hydrogen). We describe how HVAC is considered for BEVs and FCEVs in RIA Chapters 2.4.1.1.1 and 2.5.1.2.2. For ICE vehicles, the GEM results (including the HVAC energy demand) are used.

2.2.3 HD Vehicle Sales

At proposal, EPA calculated sales percentages for each vehicle application using certification data from MY 2019 and MOVES 3.R1 new vehicle sales data. DRIA at p. 134. For the final rule we have updated our approach for calculating the sales percentages for each vehicle application to use the most recent available data: MY 2021 sales of new vehicles in the latest version of MOVES that is being used in conjunction with the final rule.

We started by updating all HD TRUCS vehicles that were previously categorized as regClassID 41 with regClassID 42. MOVES defines regClassID 41 as chassis certified Class 2b-3 vehicles with a gross vehicle weight rating (GVWR) between 8,500 pounds and 14,000 pounds. Chassis certified vehicles are not included in this rulemaking. However, the vehicles modeled in the NPRM version of HD TRUCS as regClassID 41 do exist in the marketplace as engine certified vehicles with lower sales volumes. We therefore changed the regClassID of those vehicles to regClassID 42 which MOVES defines as Class 4-5 vehicles and engine-certified Class 3 vehicles between 14,000 lbs and 19,500 pounds GVWR. Engine certified LHD vehicles are included in this rulemaking and have lower sales in MOVES which reflects a more appropriate approach to approximating vehicle sales in HD TRUCS.

We then checked that HD TRUCS contained the same MOVES sourceTypeIDs and regClassIDs present in the latest version of MOVES. Table 2-19 contains that analysis as well as the total number of new vehicle sales for each sourceTypeID and regClassID. However, based on consideration of comments received on the proposal, we modified the total number of sales for sourceTypeID 41 and regClassID 47 to a maximum value of 2,500 sales. We were using the sales in this source type and reg class to represent coach buses exclusively and comments pointed out that sales of Class 8 coach buses do not exceed 2,500 sales. In response, we moved the remainder of sales of sourceTypeID 41 and regClassID 47 to sourceTypeID 42 and regClassID 47 to represent sales of Class 8 transit buses which had no sales in MOVES before this change. These changes are reflected in Table 2-19.

Table 2-19 MY 2021 MOVES New Vehicle Sales by sourceTypeID and regClassID

sourceTypeID	sourceTypeName	regClassID	regClassName	newSales	In HD TRUCS?
41	Other Buses	42	LHD45	6386	Yes
41	Other Buses	46	MHD67	394	Yes
41	Other Buses	47	HHD8	2500	Yes
42	Transit Bus	42	LHD45	1897	Yes
42	Transit Bus	46	MHD67	117	Yes
42	Transit Bus	47	HHD8	13738	Yes
42	Transit Bus	48	Urban Bus	4823	Yes
43	School Bus	42	LHD45	1746	Yes
43	School Bus	46	MHD67	23977	Yes
43	School Bus	47	HHD8	1787	Yes
51	Refuse Truck	42	LHD45	0	No
51	Refuse Truck	46	MHD67	468	Yes
51	Refuse Truck	47	HHD8	2544	Yes
52	Single Unit Short-haul Truck	42	LHD45	163889	Yes
52	Single Unit Short-haul Truck	46	MHD67	78860	Yes
52	Single Unit Short-haul Truck	47	HHD8	39435	Yes
53	Single Unit Long-haul Truck	42	LHD45	7228	Yes
53	Single Unit Long-haul Truck	46	MHD67	3478	Yes
53	Single Unit Long-haul Truck	47	HHD8	1739	Yes
54	Motor Home	42	LHD45	16877	Yes
54	Motor Home	46	MHD67	7969	Yes
54	Motor Home	47	HHD8	4618	Yes
61	Combination Short-haul Truck	46	MHD67	28746	Yes
61	Combination Short-haul Truck	47	HHD8	72193	Yes
61	Combination Short-haul Truck	49	Gliders	0	No
62	Combination Long-haul Truck	46	MHD67	4416	No
62	Combination Long-haul Truck	47	HHD8	114523	Yes
62	Combination Long-haul Truck	49	Gliders	0	No

We found that there were four MOVES sourceTypeID and regClassID combinations that did not exist in HD TRUCS. Three of those four combinations contained zero sales and they are summarized in Table 2-20.

Table 2-20 MY 2021 MOVES New Vehicle Sales with Zero Sales Not in HD TRUCS

sourceTypeID	sourceTypeName	regClassID	regClassName	newSales	In HD TRUCS?
51	Refuse Truck	42	LHD45	0	No
61	Combination Short-haul Truck	49	Gliders	0	No
62	Combination Long-haul Truck	49	Gliders	0	No

The fourth combination of MOVES sourceTypeID and regClassID that did contain sales is summarized in Table 2-21 as well as the number of sales.

Table 2-21 MY 2021 MOVES New Vehicle Sales Not in HD TRUCS With Sales

sourceTypeID	sourceTypeName	regClassID	regClassName	newSales	In HD TRUCS?
62	Combination Long-haul Truck	46	MHD67	4416	No

Since the CO_2 emission standards for Class 7 tractors apply for all cab types (see 40 CFR 1037.106(b)), we determined it was appropriate to move the sales from sourceTypeID 62 and regClassID 46 to sourceTypeID 61 regClassID 46 which are the Class 6 and 7 combination short haul trucks (day cab tractors). This allowed us to retain the same number of sales in HD TRUCS as in MOVES. We determined that keeping the sales in a GHG regulatory subcategory that was in the same weight class so that the additional sales in the combination short haul would still describe a physically similar vehicle by payload and energy consumption, albeit with fewer miles travelled per day.

We then calculated the number of vehicle types in HD TRUCS for each MOVES sourceTypeID and regClassID combination. The results are in Table 2-22.

Table 2-22 Number of HD TRUCS Vehicle Types for each Combination of MOVES sourceTypeID and regClass ID

MOVES source TypeID	MOVES regClassID	# of HD TRUCS Vehicle Types
41	42	2
41	46	1
41	47	2
42	42	1
42	46	3
42	47	1
42	48	1
43	42	4
43	46	2
43	47	2
51	46	2
51	47	2
52	42	16
52	46	17
52	47	19
53	42	4
53	46	1
53	47	1
54	42	2
54	46	2
54	47	2
61	46	4
61	47	6
62	47	4
51	42	0
61	49	0
62	46	0
62	49	0

We then calculated the number of new vehicle sales for each HD TRUCS vehicle types by dividing the sales of each MOVES sourceTypeID and regClassID by the number of HD TRUCS vehicle types. The results are in Table 2-23. However, we did not distribute sales evenly for certain vehicle applications. For tractors, we have left the last column of Table 2-23 blank for combinations of MOVES sourceTypeID/regClassID combinations 61/46, 61/47, and 62/47 to reflect that the sales in these combinations were not evenly divided into the HD TRUCS vehicles; the sales fractions for tractors are described below Table 2-23. For MOVES sourceTypeID/ regClassID combinations 52/64, 52/47, 61/46, 61/47, and 62/47 most vehicle applications are assigned an evenly divided share of sales; however, dump trucks and snow plows have been assigned distinct sales shares, as described below. Final sales for each vehicle in HD TRUCS can be found in Table 2-24.

Table 2-23 Number of Sales of MY2021 MOVES New Vehicle Sales for each HD TRUCS Vehicle Type

MOVES source TypeID	MOVES regClassID	# of HD TRUCS Vehicle Types	# of MOVES MY 2021 Sales	Sales for Each HD TRUCS Vehicle Type
41	42	2	6386	3193
41	46	1	394	394
41	47	2	2500	1250
42	42	1	1897	1897
42	46	3	117	39
42	47	1	13738	13738
42	48	1	4823	4823
43	42	4	1746	437
43	46	2	23977	11988
43	47	2	1787	894
51	46	2	468	234
51	47	2	2544	1272
52	42	16	163889	10243
52	46	17	78860	4639
52	47	19	39435	2076
53	42	4	7228	1807
53	46	1	3478	3478
53	47	1	1739	1739
54	42	2	16877	8439
54	46	2	7969	3985
54	47	2	4618	2309
61	46	4	33162	
61	47	6	72193	
62	47	4	114523	
51	42	0	0	0
61	49	0	0	0
62	46	0	0	0
62	49	0	0	0

Next, we applied the values from the last column of Table 2-23 to each vehicle in HD TRUCS, using the appropriate MOVES sourceTypeID and regClassID. We updated the sales shares for tractors, snow plows, and dump trucks, as described below, to ensure that the sales shares were representative of technology types that are being assessed for tractors and after consideration of a comment that snow plows and dump trucks are often the same vehicles that have different implements applied in different seasons.

For the final rule, the sales allocation for sleeper cabs (MOVES SourceTypeID = 62) were split along different technology pathways. The four sleeper cab tractors included in HD TRUCS are the following: 32Tractor_SC_Cl8 which is a BEV with a range of 420 miles that represents an aerodynamically optimized tractor; 54Tractor_SC_Cl8 which is a BEV with a range of 420 miles and represents a BEV that is designed with the same aerodynamic drag as the ICE sleeper cab tractor; 78Tractor_SC_Cl9 which is a BEV with a range of 300 miles; and 79Tractor_SC_Cl8 which is a FCEV with 420 miles of range. 78Tractor_SC_Cl8 was assigned a sales percentage of 28 percent as explained in Chapter 2.2.1.2 of this RIA, leaving 72 percent of the sales fraction to split among the remaining three vehicles. We assigned 20 percent of the remaining sales to 32Tractor_SC_Cl8, as a conservative estimate of vehicles that may be designed with a BEV-specific aerodynamic improvements in the MY 2027-2032 timeframe. The remaining sales are attributed to the FCEV tractor, 79Tractor_SC_Cl8. The BEV long-range sleeper cab, 54Tractor_SC_Cl8, has a sales allocation of 0 percent because our assessment is that fuel cells are likely to be the dominant long-range sleeper cab technology until (1) a greater percentage of BEV sleeper cabs are redesigned with the type of aerodynamic improvements that are feasible without an internal combustion engine, and (2) the energy density of batteries has further improved beyond the projections in this final rule, such that the potential impacts on payload mass are reduced.[946]

For the final rule, we allocated the day cab sales allocations using the sales shares from Table 18 of CARB's "Large Entity Fleet Reporting."[947] We assigned the Class 7 short-range day cab, 31Tractor_DC_Cl6-7, with a daily operational VMT of 97 miles, 31 percent of the Class 7 day cab sales, consistent with the percent of day cabs that operate up to 100 miles per day in the Large Entity Fleet Reporting table. We assigned the Class 7 mid-range day cab, 83Tractor_DC_Cl7, with a daily operational VMT of 120 miles, 31 percent of the Class 7 day cab sales, consistent with the sum of the percent of day cabs that operate in the 101-150 miles and 151-200 miles per day categories in the Large Entity Fleet Reporting table. We assigned the Class 7 long-range day cabs, 41Tractor_DC_Cl7 and 81Tractor_DC_Cl7, with a daily operational VMT of 216 miles, half of 38 percent of the Class 7 day cab sales, consistent with splitting the sales evenly after summing the percent of day cabs that operate in the 201-300 miles and over 300 miles per day categories in the Large Entity Fleet Reporting table.

We assigned the Class 8 day cabs sales shares using a process that is similar to the Class 7 day cabs; with the exception of the vehicle 101Tractor_DC_Cl8 which represents a yard tractor that is road legal. We assigned the Class 8 short range day cab, 30Tractor_DC_Cl8, with a daily operational VMT of 97 miles, 90 percent of 31 percent (= 27.9%) of the Class 8 day cab sales. As described for Class 7 day cabs above, 31 percent is consistent with the percent of day cabs that operate up to 100 miles per day in the Large Entity Fleet Reporting table. The reason that only 90 percent of the fraction of short-range day cabs were assigned to vehicle 30Tractor_DC_Cl8 is that 10 percent of the short-range day cab sales were assigned to the road-legal yard tractor, 101Tractor_DC_Cl8. Only a small fraction of tractors that are used as yard tractors are certified as on-road vehicles; therefore, the number of sales is a small fraction (about 3%) of the total Class 8 day cab sales. We assigned the Class 8 mid-range day cab similarly to the Class 7 mid-range day cabs, where vehicle 84Tractor_DC_Cl8 is assigned 31 percent of the Class 8 day cab sales. We also assigned the Class 8 long-range day cabs, similar to the Class 7 long-range day cabs; we split 38 percent of the Class 8 day cab sales evenly among 33Tractor_DC_Cl8, 45Tractor_DC_Cl8, and 82Tractor_DC_Cl8.

For the final rule, we have determined that snow plows should represent a much smaller portion of the snow plow and dump truck sales. To represent this in HD TRUCS we combined the sales of snow plows and dump trucks respective to their weight classes and ratioed the sales by the temperature weighted VMT value for cold temperatures which is 5.3%. For further discussion on this topic, see RTC Section 4.

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[946] See Chapter 2.9.1 for an assessment of potential impacts on payload.

[947] CARB. Large Entity Fleet Reporting. Available online https://ww2.arb.ca.gov/sites/default/files/2022-02/Large_Entity_Reporting_Aggregated_Data_ADA.pdf

The final HD TRUCS sales shares are summarized in Table 2-24.

Table 2-24 Final HD TRUCS Sales Shares

Vehicle ID	MOVES source TypeID	MOVES regClassID	Sales %
01V_Amb_Cl4-5_MP	52	42	1.7%
02V_Amb_Cl2b-3_MP	52	42	1.7%
03V_Amb_Cl4-5_U	52	42	1.7%
04V_Amb_Cl2b-3_U	52	42	1.7%
05T_Box_Cl8_MP	52	47	0.3%
06T_Box_Cl8_R	53	47	0.3%
07T_Box_Cl6-7_MP	52	46	0.8%
08T_Box_Cl6-7_R	53	46	0.6%
09T_Box_Cl8_U	52	47	0.3%
10T_Box_Cl6-7_U	52	46	0.8%
11T_Box_Cl2b-3_U	52	42	1.7%
12T_Box_Cl2b-3_R	52	42	1.7%
13T_Box_Cl2b-3_MP	52	42	1.7%
14T_Box_Cl4-5_U	52	42	1.7%
15T_Box_Cl4-5_R	52	42	1.7%
16T_Box_Cl4-5_MP	52	42	1.7%
17B_Coach_Cl8_R	41	47	0.2%
18B_Coach_Cl8_MP	41	47	0.2%
19C_Mix_Cl8_MP	52	47	0.3%
20T_Dump_Cl8_U	52	47	0.5%
21T_Dump_Cl8_MP	52	47	0.5%
22T_Dump_Cl6-7_MP	52	46	1.5%
23T_Dump_Cl8_U	52	47	0.5%
24T_Dump_Cl6-7_U	52	46	1.5%
25T_Fire_Cl8_MP	52	47	0.3%
26T_Fire_Cl8_U	52	47	0.3%
27T_Flat_Cl6-7_MP	52	46	0.8%
28T_Flat_Cl6-7_R	52	46	0.8%
29T_Flat_Cl6-7_U	52	46	0.8%
30Tractor_DC_Cl8_MP	61	47	3.3%
31Tractor_DC_Cl6-7_MP	61	46	1.7%
32Tractor_SC_Cl8_U	62	47	2.7%
33Tractor_DC_Cl8_U	61	47	1.5%
34T_Ref_Cl8_MP	51	47	0.2%
35T_Ref_Cl6-7_MP	51	46	0.0%
36T_Ref_Cl8_U	51	47	0.2%
37T_Ref_Cl6-7_U	51	46	0.0%
38RV_Cl8_R	54	47	0.4%
39RV_Cl6-7_R	54	46	0.7%
40RV_Cl4-5_R	54	42	1.4%
41Tractor_DC_Cl7_R	61	46	1.0%
42RV_Cl8_MP	54	47	0.4%
43RV_Cl6-7_MP	54	46	0.7%
44RV_Cl4-5_MP	54	42	1.4%
45Tractor_DC_Cl8_R	61	47	1.5%
46B_School_Cl8_MP	43	47	0.1%
47B_School_Cl6-7_MP	43	46	2.0%
48B_School_Cl4-5_MP	43	42	0.1%

49B_School_Cl2b-3_MP	43	42	0.1%
50B_School_Cl8_U	43	47	0.1%
51B_School_Cl6-7_U	43	46	2.0%
52B_School_Cl4-5_U	43	42	0.1%
53B_School_Cl2b-3_U	43	42	0.1%
54Tractor_SC_Cl8_R	62	47	0.0%
55B_Shuttle_Cl2b-3_MP	42	42	0.3%
56B_Shuttle_Cl4-5_U	41	42	0.5%
57B_Shuttle_Cl2b-3_U	41	42	0.5%
58B_Shuttle_Cl6-7_MP	42	46	0.0%
59B_Shuttle_Cl6-7_U	41	46	0.1%
60S_Plow_Cl6-7_MP	52	46	0.1%
61S_Plow_Cl8_MP	52	47	0.0%
62S_Plow_Cl6-7_U	52	46	0.1%
63S_Plow_Cl8_U	52	47	0.0%
64V_Step_Cl6-7_MP	52	46	0.8%
65V_Step_Cl4-5_MP	52	42	1.7%
66V_Step_Cl2b-3_MP	53	42	0.3%
67V_Step_Cl6-7_U	52	46	0.8%
68V_Step_Cl4-5_U	52	42	1.7%
69V_Step_Cl2b-3_U	53	42	0.3%
70S_Sweep_Cl6-7_U	52	46	0.8%
71T_Tanker_Cl8_R	52	47	0.3%
72T_Tanker_Cl8_MP	52	47	0.3%
73T_Tanker_Cl8_U	52	47	0.3%
74T_Tow_Cl8_R	52	47	0.3%
75T_Tow_Cl6-7_R	52	46	0.8%
76T_Tow_Cl8_U	52	47	0.3%
77T_Tow_Cl6-7_U	52	46	0.8%
78Tractor_SC_Cl8_MP	62	47	5.3%
79Tractor_SC_Cl8_R	62	47	10.9%
80Tractor_DC_Cl8_HH	52	47	0.3%
81Tractor_DC_Cl7_R	61	46	1.0%
82Tractor_DC_Cl8_R	61	47	1.5%
83Tractor_DC_Cl7_U	61	46	1.7%
84Tractor_DC_Cl8_U	61	47	3.7%
85B_Transit_Cl8_MP	42	47	2.3%
86B_Transit_Cl6-7_MP	42	46	0.0%
87B_Transit_Cl8_U	42	48	0.8%
88B_Transit_Cl6-7_U	42	46	0.0%
89T_Utility_Cl8_MP	52	47	0.3%
90T_Utility_Cl8_R	52	47	0.3%
91T_Utility_Cl6-7_MP	52	46	0.8%
92T_Utility_Cl6-7_R	52	46	0.8%
93T_Utility_Cl4-5_MP	52	42	1.7%
94T_Utility_Cl2b-3_MP	52	42	1.7%
95T_Utility_Cl4-5_R	53	42	0.3%
96T_Utility_Cl2b-3_R	53	42	0.3%
97T_Utility_Cl8_U	52	47	0.3%
98T_Utility_Cl6-7_U	52	46	0.8%
99T_Utility_Cl4-5_U	52	42	1.7%
100T_Utility_Cl2b-3_U	52	42	1.7%
101Tractor_DC_Cl8_U	61	47	0.4%

2.3 ICE Vehicle Technology

As previously discussed, a goal of EPA's HD TRUCS analysis is to ensure that we evaluate ZEVs that can perform the same work as comparable ICE vehicles. HD TRUCS only considers powertrain or propulsion technologies and operational costs that are the incremental differences between a ZEV and a comparable ICE vehicle; this RIA chapter thus does not include total manufacturing or total operating costs.

RIA Chapter 2.2 introduced how we estimated the baseline amount of energy required to move each benchmark HD vehicle type, considering regenerative braking and additional work required for PTO operations, independent of the powertrain. RIA Chapter 2.3 explains how we applied the values in RIA Chapter 2.2 to ICE vehicles and then considered HVAC and other powertrain-specific energy consumption. First, we defined the vehicle size and powertrain for each of the 101 vehicles in HD TRUCS, and then estimated upfront DMC and RPE of the ICE vehicle powertrain components that are different from ZEV components.[948] We also then assessed the sales tax and FET costs. Lastly, we projected ICE vehicle fuel use, diesel engine fluid (DEF) consumption, maintenance and repair costs, and insurance costs for each vehicle type for the first ten years of vehicle operation.

2.3.1 ICE Vehicle Attributes

To understand the physical size and powertrain mass of current heavy-duty trucks, we looked at basic powertrain properties and performance criteria of 76 existing diesel vehicles (see RIA Chapter 1) to find averages of the wheelbase and powertrain mass based on weight class and vehicle type. The mass of the powertrain includes the weight of the engine including the aftertreatment system, transmission, fuel, and DEF. Note that the 76 existing vehicles cover all 101 vehicle types used in HD TRUCS because some of the 76 vehicles are further differentiated by duty cycles. We then applied the results of this analysis to the 101 vehicles in HD TRUCS based on the same division of weight class and vehicle type used for averaging the benchmark vehicles. The results of this analysis are in Table 2-25.

Table 2-25 Benchmark ICE Vehicle Dimensions and Weight

Vehicle ID	Vehicle Wheelbase [in]	ICE Powertrain Weight [kg]
01V_Amb_Cl4-5_MP	141	788
02V_Amb_Cl2b-3_MP	148	462
03V_Amb_Cl4-5_U	141	788
04V_Amb_Cl2b-3_U	148	462
05T_Box_Cl8_MP	125	1370
06T_Box_Cl8_R	125	1370
07T_Box_Cl6-7_MP	146	879
08T_Box_Cl6-7_R	146	879
09T_Box_Cl8_U	125	1370

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[948] In our analysis, the ICE vehicles include a suite of technologies that represent a vehicle that meets the MY 2027 Phase 2 CO_2 emission standards and an engine that meets the MY 2027 Low NOx emission standards. The direct manufacturing costs for the vehicle components beyond the powertrain are considered to be $0 because our projected technology package did not add additional CO_2-reducing technologies to the ICE vehicles beyond those in the baseline vehicle.

Vehicle ID	Vehicle Wheelbase [in]	ICE Powertrain Weight [kg]
10T_Box_Cl6-7_U	146	879
11T_Box_Cl2b-3_U	141	462
12T_Box_Cl2b-3_R	141	462
13T_Box_Cl2b-3_MP	141	462
14T_Box_Cl4-5_U	148	788
15T_Box_Cl4-5_R	148	788
16T_Box_Cl4-5_MP	148	788
17B_Coach_Cl8_R	315	2302
18B_Coach_Cl8_MP	315	2302
19C_Mix_Cl8_MP	143	1805
20T_Dump_Cl8_U	125	1370
21T_Dump_Cl8_MP	125	1370
22T_Dump_Cl6-7_MP	146	879
23T_Dump_Cl8_U	125	1370
24T_Dump_Cl6-7_U	146	879
25T_Fire_Cl8_MP	125	1370
26T_Fire_Cl8_U	125	1370
27T_Flat_Cl6-7_MP	146	879
28T_Flat_Cl6-7_R	146	879
29T_Flat_Cl6-7_U	146	879
30Tractor_DC_Cl8	143	1805
31Tractor_DC_Cl7	143	1805
32Tractor_SC_Cl8	143	1805
33Tractor_DC_Cl8	143	1805
34T_Ref_Cl8_MP	173	1762
35T_Ref_Cl6-7_MP	146	879
36T_Ref_Cl8_U	173	1762
37T_Ref_Cl6-7_U	146	879
38RV_Cl8_R	148	879
39RV_Cl6-7_R	169	593
40RV_Cl4-5_R	141	528
41Tractor_DC_Cl7	143	1805
42RV_Cl8_MP	148	879
43RV_Cl6-7_MP	169	593
44RV_Cl4-5_MP	141	528
45Tractor_DC_Cl8	143	1805
46B_School_Cl8_MP	145	1209
47B_School_Cl6-7_MP	169	1209
48B_School_Cl4-5_MP	139	536
49B_School_Cl2b-3_MP	138	536
50B_School_Cl8_U	145	1209
51B_School_Cl6-7_U	169	1209
52B_School_Cl4-5_U	139	536
53B_School_Cl2b-3_U	139	536
54Tractor_SC_Cl8	143	1805
55B_Shuttle_Cl2b-3_MP	133	572
56B_Shuttle_Cl4-5_U	139	788
57B_Shuttle_Cl2b-3_U	133	572
58B_Shuttle_Cl6-7_MP	169	1209
59B_Shuttle_Cl6-7_U	169	1209
60S_Plow_Cl6-7_MP	146	879
61S_Plow_Cl8_MP	125	1370

Vehicle ID	Vehicle Wheelbase [in]	ICE Powertrain Weight [kg]
62S_Plow_Cl6-7_U	146	879
63S_Plow_Cl8_U	125	1370
64V_Step_Cl6-7_MP	158	593
65V_Step_Cl4-5_MP	134	788
66V_Step_Cl2b-3_MP	133	462
67V_Step_Cl6-7_U	158	593
68V_Step_Cl4-5_U	134	593
69V_Step_Cl2b-3_U	133	462
70S_Sweep_Cl6-7_U	169	1209
71T_Tanker_Cl8_R	125	1370
72T_Tanker_Cl8_MP	125	1370
73T_Tanker_Cl8_U	125	1370
74T_Tow_Cl8_R	125	1370
75T_Tow_Cl6-7_R	146	879
76T_Tow_Cl8_U	125	1370
77T_Tow_Cl6-7_U	146	879
78Tractor_SC_Cl8	143	1805
79Tractor_SC_Cl8	143	1805
80Tractor_DC_Cl8	143	1805
81Tractor_DC_Cl7	143	1805
82Tractor_DC_Cl8	143	1805
83Tractor_DC_Cl7	143	1805
84Tractor_DC_Cl8	143	1805
85B_Transit_Cl8_MP	202	1217
86B_Transit_Cl6-7_MP	169	790
87B_Transit_Cl8_U	202	1217
88B_Transit_Cl6-7_U	169	790
89T_Utility_Cl8_MP	125.1	1370
90T_Utility_Cl8_R	125.1	1370
91T_Utility_Cl6-7_MP	146	879
92T_Utility_Cl6-7_R	146	879
93T_Utility_Cl4-5_MP	148	788
94T_Utility_Cl2b-3_MP	149	775
95T_Utility_Cl4-5_R	148	788
96T_Utility_Cl2b-3_R	149	775
97T_Utility_Cl8_U	125.1	1370
98T_Utility_Cl6-7_U	146	879
99T_Utility_Cl4-5_U	148	788
100T_Utility_Cl2b-3_U	149	775
101Tractor_DC_Cl8	116	1036

2.3.2 ICE Vehicle Components and Other Upfront Costs

The purpose of this analysis is to determine the incremental cost differences between ZEV technologies and a comparable ICE vehicle; therefore, in this RIA Chapter 2.3.2, we are focusing on the ICE powertrain components and costs that would differ between a ZEV and a comparable ICE vehicle. These upfront costs are described in the following sections and include powertrain component costs and costs that are assessed when a vehicle is purchased, such as state sales tax and the federal excise tax (FET). Table 2-26 is a summary of these results for MY 2032. The sum of the ICE powertrain RPE, FET, and state sales taxes for MYs 2027, 2030, and 2032 are shown in Chapter 2.9.2.

Table 2-26 ICE Powertrain (PT) RPE, Sales Tax and FET for MY 2032 (2022$)

Vehicle ID	PT DMC	PT RPE	FET	State Sales Tax
01V_Amb_Cl4-5_MP	30011	42616	0	2139
02V_Amb_Cl2b-3_MP	28653	40688	0	2043
03V_Amb_Cl4-5_U	30011	42616	0	2139
04V_Amb_Cl2b-3_U	28653	40688	0	2043
05T_Box_Cl8_MP	57170	81181	9742	4075
06T_Box_Cl8_R	57170	81181	9742	4075
07T_Box_Cl6-7_MP	32183	45699	0	2294
08T_Box_Cl6-7_R	32183	45699	0	2294
09T_Box_Cl8_U	50533	71758	8611	3602
10T_Box_Cl6-7_U	32183	45699	0	2294
11T_Box_Cl2b-3_U	28188	40026	0	2009
12T_Box_Cl2b-3_R	28188	40026	0	2009
13T_Box_Cl2b-3_MP	28188	40026	0	2009
14T_Box_Cl4-5_U	28284	40163	0	2016
15T_Box_Cl4-5_R	28284	40163	0	2016
16T_Box_Cl4-5_MP	28284	40163	0	2016
17B_Coach_Cl8_R	44988	63882	7666	3207
18B_Coach_Cl8_MP	44988	63882	7666	3207
19C_Mix_Cl8_MP	50533	71758	8611	3602
20T_Dump_Cl8_U	57170	81181	9742	4075
21T_Dump_Cl8_MP	57170	81181	9742	4075
22T_Dump_Cl6-7_MP	32002	45443	0	2281
23T_Dump_Cl8_U	50533	71758	8611	3602
24T_Dump_Cl6-7_U	32002	45443	0	2281
25T_Fire_Cl8_MP	57170	81181	9742	4075
26T_Fire_Cl8_U	50533	71758	8611	3602
27T_Flat_Cl6-7_MP	32002	45443	0	2281
28T_Flat_Cl6-7_R	32002	45443	0	2281
29T_Flat_Cl6-7_U	32002	45443	0	2281
30Tractor_DC_Cl8	60231	85528	10263	4294
31Tractor_DC_Cl7	47365	67258	8071	3376
32Tractor_SC_Cl8	62481	88723	10647	4454
33Tractor_DC_Cl8	47942	68078	8169	3418
34T_Ref_Cl8_MP	47568	67547	8106	3391
35T_Ref_Cl6-7_MP	32002	45443	0	2281
36T_Ref_Cl8_U	47568	67547	8106	3391
37T_Ref_Cl6-7_U	32002	45443	0	2281
38RV_Cl8_R	33440	47485	5698	2384
39RV_Cl6-7_R	32083	45558	0	2287
40RV_Cl4-5_R	27686	39314	0	1974
41Tractor_DC_Cl7	47365	67258	8071	3376
42RV_Cl8_MP	33440	47485	5698	2384

Vehicle ID	PT DMC	PT RPE	FET	State Sales Tax
43RV_Cl6-7_MP	32083	45558	0	2287
44RV_Cl4-5_MP	27686	39314	0	1974
45Tractor_DC_Cl8	62481	88723	10647	4454
46B_School_Cl8_MP	33440	47485	5698	2384
47B_School_Cl6-7_MP	32083	45558	0	2287
48B_School_Cl4-5_MP	27686	39314	0	1974
49B_School_Cl2b-3_MP	29015	41201	0	2068
50B_School_Cl8_U	33440	47485	5698	2384
51B_School_Cl6-7_U	32083	45558	0	2287
52B_School_Cl4-5_U	27686	39314	0	1974
53B_School_Cl2b-3_U	29015	41201	0	2068
54Tractor_SC_Cl8	62481	88723	10647	4454
55B_Shuttle_Cl2b-3_MP	29015	41201	0	2068
56B_Shuttle_Cl4-5_U	27686	39314	0	1974
57B_Shuttle_Cl2b-3_U	29015	41201	0	2068
58B_Shuttle_Cl6-7_MP	32083	45558	0	2287
59B_Shuttle_Cl6-7_U	32083	45558	0	2287
60S_Plow_Cl6-7_MP	32002	45443	0	2281
61S_Plow_Cl8_MP	57170	81181	9742	4075
62S_Plow_Cl6-7_U	32002	45443	0	2281
63S_Plow_Cl8_U	50533	71758	8611	3602
64V_Step_Cl6-7_MP	31933	45345	0	2276
65V_Step_Cl4-5_MP	27686	39314	0	1974
66V_Step_Cl2b-3_MP	28653	40688	0	2043
67V_Step_Cl6-7_U	31933	45345	0	2276
68V_Step_Cl4-5_U	27686	39314	0	1974
69V_Step_Cl2b-3_U	28653	40688	0	2043
70S_Sweep_Cl6-7_U	32002	45443	0	2281
71T_Tanker_Cl8_R	57170	81181	9742	4075
72T_Tanker_Cl8_MP	50533	71758	8611	3602
73T_Tanker_Cl8_U	50533	71758	8611	3602
74T_Tow_Cl8_R	58957	83719	10046	4203
75T_Tow_Cl6-7_R	32002	45443	0	2281
76T_Tow_Cl8_U	50533	71758	8611	3602
77T_Tow_Cl6-7_U	32002	45443	0	2281
78Tractor_SC_Cl8	62481	88723	10647	4454
79Tractor_SC_Cl8	62481	88723	10647	4454
80Tractor_DC_Cl8	63190	89730	10768	4504
81Tractor_DC_Cl7	47365	67258	8071	3376
82Tractor_DC_Cl8	62481	88723	10647	4454
83Tractor_DC_Cl7	47365	67258	8071	3376
84Tractor_DC_Cl8	58640	83269	9992	4180
85B_Transit_Cl8_MP	44988	63882	7666	3207
86B_Transit_Cl6-7_MP	32083	45558	0	2287
87B_Transit_Cl8_U	44448	63117	7574	3168
88B_Transit_Cl6-7_U	32083	45558	0	2287

Vehicle ID	PT DMC	PT RPE	FET	State Sales Tax
89T_Utility_Cl8_MP	57170	81181	9742	4075
90T_Utility_Cl8_R	57170	81181	9742	4075
91T_Utility_Cl6-7_MP	32002	45443	0	2281
92T_Utility_Cl6-7_R	32002	45443	0	2281
93T_Utility_Cl4-5_MP	30011	42616	0	2139
94T_Utility_Cl2b-3_MP	28653	40688	0	2043
95T_Utility_Cl4-5_R	30011	42616	0	2139
96T_Utility_Cl2b-3_R	28653	40688	0	2043
97T_Utility_Cl8_U	50533	71758	8611	3602
98T_Utility_Cl6-7_U	32002	45443	0	2281
99T_Utility_Cl4-5_U	30011	42616	0	2139
100T_Utility_Cl2b-3_U	28653	40688	0	2043
101Tractor_DC_Cl8	58640	83269	9992	4180

2.3.2.1 Powertrain Component Costs

The following ICE vehicle components were included in the cost analysis as primary components of the ICE powertrain: engine including exhaust aftertreatment, transmission/gearbox, starter, mechanical accessories, torque converter/clutch, final drive, and generator/alternator. The cost of each component was added to the incremental component cost used in EPA's technology package to meet the new NOx emissions standards in the Control of Air Pollution from New Motor Vehicles: Heavy-Duty Engine and Vehicle Standard Rule (called the "2027 Rule Costs" in Table 2-29).[949] This method was used to estimate a total ICE powertrain cost per vehicle type.

The cost of the engine and transmission/gearbox are two of the most expensive powertrain components in an ICE HD vehicle. The cost of the diesel engine is calculated as a function of engine power. To calculate engine costs, we used data from an ANL report where cost of the engine increases with the power output of the engine, as shown in Figure 2-2.[950,951] It should be noted the aftertreatment cost is incorporated as a part of the engine cost. The power requirements for each vehicle are based on the power requirements that were used to determine GEM energy consumption, as shown in Table 2-27.[952] We used the gearbox costs from the Autonomie Out

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[949] U.S. Environmental Protection Agency. Control of Air Pollution from New Motor Vehicles: Heavy-Duty Engine and Vehicle Standards Regulatory Impact Analysis. See Table 7-5. Available at https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P1016A9N.pdf.

[950] Islam, Ehsan Sabri, Ram Vijayagopal, Aymeric Rousseau. "A Comprehensive Simulation Study to Evaluate Future Vehicle Energy and Cost Reduction Potential", *Report to the U.S. Department of Energy, Contract ANL/ESD-22/6*. October 2022. Available online: https://anl.app.box.com/s/an4nx0v2xpudxtpsnkhd5peimzu4j1hk/folder/242640145714.

[951] Islam, Ehsan Sabri, Daniela Nieto Prada, Ram Vijayagopal, Charbel Mansour, Paul Phillips, Namdoo Kim, Michel Alhajjar, Aymeric Rousseau. "Detailed Simulation Study to Evaluate Future Transportation Decarbonization Potential", *Report to the US Department of Energy, Contract ANL/TAPS-23/3*, October 2023. Available online:https://anl.app.box.com/s/an4nx0v2xpudxtpsnkhd5peimzu4j1hk/file/1429036831008.

[952] For the final rule, we have calculated engine costs for all Class 8 vocational vehicles using a maximum of 350 hp (261 kW). This is done in order to ensure that we do not overestimate the upfront costs of Class 8 vocational vehicle powertrain systems.

Import tab in the 2022 version of ANL's BEAN tool, as shown in Table 2-28.[953] Since the tool presents values for 2025 and 2030, the 2027 values were determined by interpolating between the 2025 and 2030 high costs and then interpolating between the 2025 and 2030 low costs. Then, the low and high MY 2027 values were averaged and converted to 2022$, and MY 2028-MY 2032 costs were calculated using ICE learning scalars as shown in RIA Chapter 3.2.1. ANL vehicle IDs were then mapped to similar vehicles in HD TRUCS as shown in Table 2-2. The remainder of the powertrain cost, including starter, mechanical accessories[954], torque converter/clutch, final drive, and generator/alternator, are binned to vehicle classes according to Table 2-29. They are based on costs from the same Autonomie Out Import tab in the 2022 version of ANL's BEAN tool.[955] These costs are not a major portion of the costs of the ICE powertrain. Costs of all components used for ICE vehicles are shown in Table 2-30 for MY 2032.

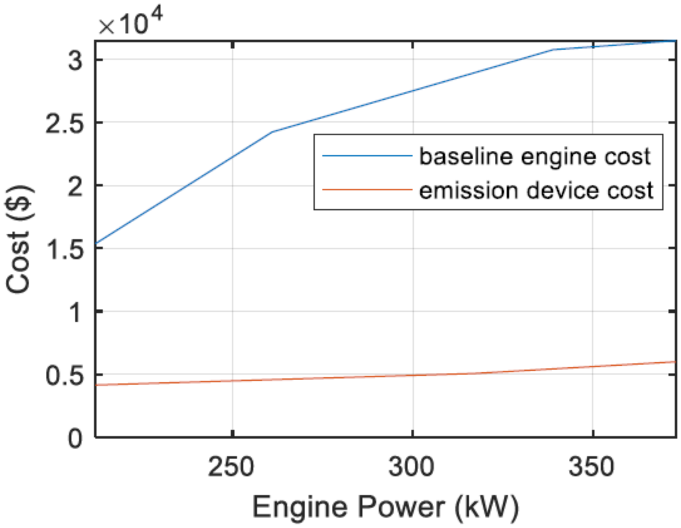

Figure 2-2 Direct Manufacturing Cost of a Diesel Engine as a Function of Engine Power in 2020$ (these costs are adjusted to 2022$ in HD TRUCS)[956]

Table 2-27 Engine Power used as GEM Inputs and to Determine Engine Cost

Vehicle ID	GEM Engine Power (kW)
01V_Amb_Cl4-5_MP	149

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[953] Argonne National Laboratory. VTO HFTO Analysis Reports – 2022. "ANL – ESD-2206 Report – BEAN Tool – MD HD Vehicle Techno-Economic Analysis.xlsm". Available online: https://anl.app.box.com/s/an4nx0v2xpudxtpsnkhd5peimzu4j1hk/folder/242640145714.

[954] Mechanical accessory costs in HD TRUCS include BEAN costs for mechanical accessories, 12 volt batteries, and vehicle propulsion architecture (VPA).

[955] Argonne National Laboratory. VTO HFTO Analysis Reports – 2022. "ANL – ESD-2206 Report – BEAN Tool – MD HD Vehicle Techno-Economic Analysis.xlsm". Available online: https://anl.app.box.com/s/an4nx0v2xpudxtpsnkhd5peimzu4j1hk/folder/242640145714.

[956] Islam, Ehsan Sabri, Ram Vijayagopal, Aymeric Rousseau. "A Comprehensive Simulation Study to Evaluate Future Vehicle Energy and Cost Reduction Potential", *Report to the U.S. Department of Energy, Contract ANL/ESD-22/6*, October 2022. Available online: https://anl.app.box.com/s/an4nx0v2xpudxtpsnkhd5peimzu4j1hk/file/1406494585829.

Vehicle ID	GEM Engine Power (kW)
02V_Amb_Cl2b-3_MP	149
03V_Amb_Cl4-5_U	149
04V_Amb_Cl2b-3_U	149
05T_Box_Cl8_MP	265
06T_Box_Cl8_R	265
07T_Box_Cl6-7_MP	201
08T_Box_Cl6-7_R	201
09T_Box_Cl8_U	261
10T_Box_Cl6-7_U	201
11T_Box_Cl2b-3_U	149
12T_Box_Cl2b-3_R	149
13T_Box_Cl2b-3_MP	149
14T_Box_Cl4-5_U	149
15T_Box_Cl4-5_R	149
16T_Box_Cl4-5_MP	149
17B_Coach_Cl8_R	261
18B_Coach_Cl8_MP	261
19C_Mix_Cl8_MP	261
20T_Dump_Cl8_U	265
21T_Dump_Cl8_MP	265
22T_Dump_Cl6-7_MP	201
23T_Dump_Cl8_U	261
24T_Dump_Cl6-7_U	201
25T_Fire_Cl8_MP	265
26T_Fire_Cl8_U	261
27T_Flat_Cl6-7_MP	201
28T_Flat_Cl6-7_R	201
29T_Flat_Cl6-7_U	201
30Tractor_DC_Cl8	339
31Tractor_DC_Cl7	261
32Tractor_SC_Cl8	339
33Tractor_DC_Cl8	261
34T_Ref_Cl8_MP	261
35T_Ref_Cl6-7_MP	201
36T_Ref_Cl8_U	261
37T_Ref_Cl6-7_U	201
38RV_Cl8_R	201
39RV_Cl6-7_R	201
40RV_Cl4-5_R	149
41Tractor_DC_Cl7	261
42RV_Cl8_MP	201
43RV_Cl6-7_MP	201
44RV_Cl4-5_MP	149
45Tractor_DC_Cl8	339
46B_School_Cl8_MP	201
47B_School_Cl6-7_MP	201
48B_School_Cl4-5_MP	149
49B_School_Cl2b-3_MP	149
50B_School_Cl8_U	201
51B_School_Cl6-7_U	201
52B_School_Cl4-5_U	149
53B_School_Cl2b-3_U	149

Vehicle ID	GEM Engine Power (kW)
54Tractor_SC_Cl8	339
55B_Shuttle_Cl2b-3_MP	149
56B_Shuttle_Cl4-5_U	149
57B_Shuttle_Cl2b-3_U	149
58B_Shuttle_Cl6-7_MP	201
59B_Shuttle_Cl6-7_U	201
60S_Plow_Cl6-7_MP	201
61S_Plow_Cl8_MP	265
62S_Plow_Cl6-7_U	201
63S_Plow_Cl8_U	261
64V_Step_Cl6-7_MP	201
65V_Step_Cl4-5_MP	149
66V_Step_Cl2b-3_MP	149
67V_Step_Cl6-7_U	201
68V_Step_Cl4-5_U	149
69V_Step_Cl2b-3_U	149
70S_Sweep_Cl6-7_U	201
71T_Tanker_Cl8_R	265
72T_Tanker_Cl8_MP	261
73T_Tanker_Cl8_U	261
74T_Tow_Cl8_R	339
75T_Tow_Cl6-7_R	201
76T_Tow_Cl8_U	261
77T_Tow_Cl6-7_U	201
78Tractor_SC_Cl8	339
79Tractor_SC_Cl8	339
80Tractor_DC_Cl8	447
81Tractor_DC_Cl7	261
82Tractor_DC_Cl8	339
83Tractor_DC_Cl7	261
84Tractor_DC_Cl8	339
85B_Transit_Cl8_MP	261
86B_Transit_Cl6-7_MP	201
87B_Transit_Cl8_U	261
88B_Transit_Cl6-7_U	201
89T_Utility_Cl8_MP	265
90T_Utility_Cl8_R	265
91T_Utility_Cl6-7_MP	201
92T_Utility_Cl6-7_R	201
93T_Utility_Cl4-5_MP	149
94T_Utility_Cl2b-3_MP	149
95T_Utility_Cl4-5_R	149
96T_Utility_Cl2b-3_R	149
97T_Utility_Cl8_U	261
98T_Utility_Cl6-7_U	201
99T_Utility_Cl4-5_U	149
100T_Utility_Cl2b-3_U	149
101Tractor_DC_Cl8	339

Table 2-28 MY 2027, MY 2030, and MY 2032 ICE Gearbox Costs in HD TRUCS (2022$)

ANL ID	MY 2027	MY 2030	MY 2032
Box Medium 3	4698	4651	4604
Van Medium 3	5173	5121	5069
School Medium 3	5542	5487	5431
Box Medium 4	4796	4748	4700
StepVan Medium 4	4186	4144	4102
Service Medium 4	6559	6493	6427
StepVan Medium 6	5331	5277	5224
Box Medium 6	5585	5529	5473
Tractor DayCab 7	7452	7377	7303
Vocational Medium 7	5401	5347	5293
School Medium 7	5483	5428	5374
Longhaul Sleeper 8	13692	13555	13418
Beverage DayCab 8	9772	9675	9577
Drayage DayCab 8	11396	11282	11168
Vocational Heavy 8	11771	11653	11535
Transit Heavy 8	6112	6051	5989
Refuse Heavy 8	8745	8657	8570
Regional DayCab 8	13692	13555	13418

Table 2-29 Binned Direct Manufacturing Costs for ICE Powertrain Components for MY 2032 (2022$)

Vehicle Class	Starter Cost ($/unit)[a]	Torque Converter/ Clutch Cost ($/unit)[b]	Mech Acc Cost ($/unit)	Generator Cost ($/unit)[c]	2027 Rule Cost ($/unit)[d]	Final Drive Cost ($/unit)[e]
2b-5	164	554	2439	82	2265	1644
6-7	164	554	2439	82	2103	1644
8	329	554	2439	82	2680	1644

[a] The starter cost in MY 2032 is $329 for all Class 8 vehicles and all tractors, including Class 7 day cabs.

[b] The torque converter/clutch cost in MY 2032 is $430 for all tractors.

[c] The generator cost in MY 2032 is $204 for all tractors.

[d] 2027 Rule Cost for Class 8 transit bus is $2,141 for MY 2032

[e] Note that for tractors, the final drive cost is doubled to account for tandem axles (e.g., one per axle) so is $3,287 for MY 2032.

Table 2-30 ICE Powertrain (PT) Direct Manufacturing Cost (DMC) for MY 2032 (2022$)

Vehicle ID	Engine Cost ($/unit)	Gearbox ($/unit)	2027 Rule Cost ($/unit)	Starter Cost ($/unit)	Mech Acc. Cost ($/unit)	Torque Converter Clutch Cost ($/unit)	Final Drive Cost ($/unit)	Generator Cost ($/unit)	ICE PT DMC ($/unit)
01V_Amb_Cl4-5_MP	16436	6427	2265	164	2439	554	1644	82	30011
02V_Amb_Cl2b-3_MP	16436	5069	2265	164	2439	554	1644	82	28653
03V_Amb_Cl4-5_U	16436	6427	2265	164	2439	554	1644	82	30011
04V_Amb_Cl2b-3_U	16436	5069	2265	164	2439	554	1644	82	28653
05T_Box_Cl8_MP	37907	11535	2680	329	2439	554	1644	82	57170
06T_Box_Cl8_R	37907	11535	2680	329	2439	554	1644	82	57170
07T_Box_Cl6-7_MP	19724	5473	2103	164	2439	554	1644	82	32183
08T_Box_Cl6-7_R	19724	5473	2103	164	2439	554	1644	82	32183
09T_Box_Cl8_U	31271	11535	2680	329	2439	554	1644	82	50533

Vehicle ID	Engine Cost ($/unit)	Gearbox ($/unit)	2027 Rule Cost ($/unit)	Starter Cost ($/unit)	Mech Acc. Cost ($/unit)	Torque Converter Clutch Cost ($/unit)	Final Drive Cost ($/unit)	Generator Cost ($/unit)	ICE PT DMC ($/unit)
10T_Box_Cl6-7_U	19724	5473	2103	164	2439	554	1644	82	32183
11T_Box_Cl2b-3_U	16436	4604	2265	164	2439	554	1644	82	28188
12T_Box_Cl2b-3_R	16436	4604	2265	164	2439	554	1644	82	28188
13T_Box_Cl2b-3_MP	16436	4604	2265	164	2439	554	1644	82	28188
14T_Box_Cl4-5_U	16436	4700	2265	164	2439	554	1644	82	28284
15T_Box_Cl4-5_R	16436	4700	2265	164	2439	554	1644	82	28284
16T_Box_Cl4-5_MP	16436	4700	2265	164	2439	554	1644	82	28284
17B_Coach_Cl8_R	31271	5989	2680	329	2439	554	1644	82	44988
18B_Coach_Cl8_MP	31271	5989	2680	329	2439	554	1644	82	44988
19C_Mix_Cl8_MP	31271	11535	2680	329	2439	554	1644	82	50533
20T_Dump_Cl8_U	37907	11535	2680	329	2439	554	1644	82	57170
21T_Dump_Cl8_MP	37907	11535	2680	329	2439	554	1644	82	57170
22T_Dump_Cl6-7_MP	19724	5293	2103	164	2439	554	1644	82	32002
23T_Dump_Cl8_U	31271	11535	2680	329	2439	554	1644	82	50533
24T_Dump_Cl6-7_U	19724	5293	2103	164	2439	554	1644	82	32002
25T_Fire_Cl8_MP	37907	11535	2680	329	2439	554	1644	82	57170
26T_Fire_Cl8_U	31271	11535	2680	329	2439	554	1644	82	50533
27T_Flat_Cl6-7_MP	19724	5293	2103	164	2439	554	1644	82	32002
28T_Flat_Cl6-7_R	19724	5293	2103	164	2439	554	1644	82	32002
29T_Flat_Cl6-7_U	19724	5293	2103	164	2439	554	1644	82	32002
30Tractor_DC_Cl8	39695	11168	2680	329	2439	430	3287	204	60231
31Tractor_DC_Cl7	31271	7303	2103	329	2439	430	3287	204	47365
32Tractor_SC_Cl8	39695	13418	2680	329	2439	430	3287	204	62481
33Tractor_DC_Cl8	31271	7303	2680	329	2439	430	3287	204	47942
34T_Ref_Cl8_MP	31271	8570	2680	329	2439	554	1644	82	47568
35T_Ref_Cl6-7_MP	19724	5293	2103	164	2439	554	1644	82	32002
36T_Ref_Cl8_U	31271	8570	2680	329	2439	554	1644	82	47568
37T_Ref_Cl6-7_U	19724	5293	2103	164	2439	554	1644	82	32002
38RV_Cl8_R	19724	5989	2680	329	2439	554	1644	82	33440
39RV_Cl6-7_R	19724	5374	2103	164	2439	554	1644	82	32083
40RV_Cl4-5_R	16436	4102	2265	164	2439	554	1644	82	27686
41Tractor_DC_Cl7	31271	7303	2103	329	2439	430	3287	204	47365
42RV_Cl8_MP	19724	5989	2680	329	2439	554	1644	82	33440
43RV_Cl6-7_MP	19724	5374	2103	164	2439	554	1644	82	32083
44RV_Cl4-5_MP	16436	4102	2265	164	2439	554	1644	82	27686
45Tractor_DC_Cl8	39695	13418	2680	329	2439	430	3287	204	62481
46B_School_Cl8_MP	19724	5989	2680	329	2439	554	1644	82	33440
47B_School_Cl6-7_MP	19724	5374	2103	164	2439	554	1644	82	32083
48B_School_Cl4-5_MP	16436	4102	2265	164	2439	554	1644	82	27686
49B_School_Cl2b-3_MP	16436	5431	2265	164	2439	554	1644	82	29015
50B_School_Cl8_U	19724	5989	2680	329	2439	554	1644	82	33440
51B_School_Cl6-7_U	19724	5374	2103	164	2439	554	1644	82	32083
52B_School_Cl4-5_U	16436	4102	2265	164	2439	554	1644	82	27686
53B_School_Cl2b-3_U	16436	5431	2265	164	2439	554	1644	82	29015
54Tractor_SC_Cl8	39695	13418	2680	329	2439	430	3287	204	62481
55B_Shuttle_Cl2b-3_MP	16436	5431	2265	164	2439	554	1644	82	29015
56B_Shuttle_Cl4-5_U	16436	4102	2265	164	2439	554	1644	82	27686
57B_Shuttle_Cl2b-3_U	16436	5431	2265	164	2439	554	1644	82	29015
58B_Shuttle_Cl6-7_MP	19724	5374	2103	164	2439	554	1644	82	32083

Vehicle ID	Engine Cost ($/unit)	Gearbox ($/unit)	2027 Rule Cost ($/unit)	Starter Cost ($/unit)	Mech Acc. Cost ($/unit)	Torque Converter Clutch Cost ($/unit)	Final Drive Cost ($/unit)	Generator Cost ($/unit)	ICE PT DMC ($/unit)
59B_Shuttle_Cl6-7_U	19724	5374	2103	164	2439	554	1644	82	32083
60S_Plow_Cl6-7_MP	19724	5293	2103	164	2439	554	1644	82	32002
61S_Plow_Cl8_MP	37907	11535	2680	329	2439	554	1644	82	57170
62S_Plow_Cl6-7_U	19724	5293	2103	164	2439	554	1644	82	32002
63S_Plow_Cl8_U	31271	11535	2680	329	2439	554	1644	82	50533
64V_Step_Cl6-7_MP	19724	5224	2103	164	2439	554	1644	82	31933
65V_Step_Cl4-5_MP	16436	4102	2265	164	2439	554	1644	82	27686
66V_Step_Cl2b-3_MP	16436	5069	2265	164	2439	554	1644	82	28653
67V_Step_Cl6-7_U	19724	5224	2103	164	2439	554	1644	82	31933
68V_Step_Cl4-5_U	16436	4102	2265	164	2439	554	1644	82	27686
69V_Step_Cl2b-3_U	16436	5069	2265	164	2439	554	1644	82	28653
70S_Sweep_Cl6-7_U	19724	5293	2103	164	2439	554	1644	82	32002
71T_Tanker_Cl8_R	37907	11535	2680	329	2439	554	1644	82	57170
72T_Tanker_Cl8_MP	31271	11535	2680	329	2439	554	1644	82	50533
73T_Tanker_Cl8_U	31271	11535	2680	329	2439	554	1644	82	50533
74T_Tow_Cl8_R	39695	11535	2680	329	2439	554	1644	82	58957
75T_Tow_Cl6-7_R	19724	5293	2103	164	2439	554	1644	82	32002
76T_Tow_Cl8_U	31271	11535	2680	329	2439	554	1644	82	50533
77T_Tow_Cl6-7_U	19724	5293	2103	164	2439	554	1644	82	32002
78Tractor_SC_Cl8	39695	13418	2680	329	2439	430	3287	204	62481
79Tractor_SC_Cl8	39695	13418	2680	329	2439	430	3287	204	62481
80Tractor_DC_Cl8	42286	11535	2680	329	2439	430	3287	204	63190
81Tractor_DC_Cl7	31271	7303	2103	329	2439	430	3287	204	47365
82Tractor_DC_Cl8	39695	13418	2680	329	2439	430	3287	204	62481
83Tractor_DC_Cl7	31271	7303	2103	329	2439	430	3287	204	47365
84Tractor_DC_Cl8	39695	9577	2680	329	2439	430	3287	204	58640
85B_Transit_Cl8_MP	31271	5989	2680	329	2439	554	1644	82	44988
86B_Transit_Cl6-7_MP	19724	5374	2103	164	2439	554	1644	82	32083
87B_Transit_Cl8_U	31271	5989	2141	329	2439	554	1644	82	44448
88B_Transit_Cl6-7_U	19724	5374	2103	164	2439	554	1644	82	32083
89T_Utility_Cl8_MP	37907	11535	2680	329	2439	554	1644	82	57170
90T_Utility_Cl8_R	37907	11535	2680	329	2439	554	1644	82	57170
91T_Utility_Cl6-7_MP	19724	5293	2103	164	2439	554	1644	82	32002
92T_Utility_Cl6-7_R	19724	5293	2103	164	2439	554	1644	82	32002
93T_Utility_Cl4-5_MP	16436	6427	2265	164	2439	554	1644	82	30011
94T_Utility_Cl2b-3_MP	16436	5069	2265	164	2439	554	1644	82	28653
95T_Utility_Cl4-5_R	16436	6427	2265	164	2439	554	1644	82	30011
96T_Utility_Cl2b-3_R	16436	5069	2265	164	2439	554	1644	82	28653
97T_Utility_Cl8_U	31271	11535	2680	329	2439	554	1644	82	50533
98T_Utility_Cl6-7_U	19724	5293	2103	164	2439	554	1644	82	32002
99T_Utility_Cl4-5_U	16436	6427	2265	164	2439	554	1644	82	30011
100T_Utility_Cl2b-3_U	16436	5069	2265	164	2439	554	1644	82	28653
101Tractor_DC_Cl8	39695	9577	2680	329	2439	430	3287	204	58640

2.3.2.2 State Sales Tax and Federal Excise Tax

The NPRM version of HD TRUCS did not include estimates for state sales taxes on the purchase of a vehicle or Federal Excise Tax (FET) where applicable. After consideration of comments, we have added these values to the final version of HD TRUCS to better assess incremental upfront purchaser costs. Sales tax and FET are calculated by first applying a retail price equivalent (RPE) factor[957] to the upfront powertrain DMC costs. One industry commenter recommended using a state sales tax rate of 5.02%, an average of the 50 state sales tax values, which we assessed and confirmed was appropriate.[958] This rate was applied to the upfront costs (RPE) for all HD TRUCS vehicles for the final rule. A Federal Excise tax of 12% was applied to the upfront costs (RPE) for all Class 8 (heavy heavy-duty) vehicles and all tractors.[959]

2.3.3 ICE Vehicle Fuel Consumption

To estimate fuel consumption for a diesel version of each vehicle type in HD TRUCS, we assigned the GEM Energy ID fuel consumption value to the appropriate vehicle segment in HD TRUCS to get the GEM-weighted fuel consumption by vehicle type. As previously noted, HVAC is already incorporated into the GEM runs and thus we did not need to determine HVAC separately for ICE vehicles.

For each regulatory subcategory, grams of CO_2 emissions from our GEM simulations were converted to gallons of diesel fuel consumed using a CO_2 conversion of 10,180 grams of CO_2 per gallon of diesel.[960,961] The gallons of diesel were then divided by the distance of each driving cycle and weighted appropriately for their respective regulatory subcategories. The results of these calculations are shown in Table 2-31.

There are two tractors, 33Tractor_DC_Cl8 and 32Tractor_SC_Cl8, which when assessed as BEVs were simulated in GEM with lower aerodynamic drag than their diesel counterparts. This is because typical engine packaging precludes the type of aerodynamic reductions that are available to BEVs; therefore, when these two tractors are assessed as diesel vehicles, the fuel consumption (MPGD) values used are C8_DC_HR. and C8_SC_HR, from Table 2-31.

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[957] See Chapter 3.2 for a discussion of RPE.

[958] See page 38 of docket number EPA-HQ-OAR-2022-0985-2668-A1.

[959] U.S. Internal Revenue Service. 26 USC 4051. Available at http://uscode.house.gov/view.xhtml?req=granuleid:USC-prelim-title26-section4051&num=0&edition=prelim

[960] A value of 10,180 grams of CO_2 per gallon of diesel was used as our conversion factor as it was agreed upon as a common conversion factor between the EPA and Department of Transportation (DOT) in a rulemaking that established the initial National Program fuel economy standards for model years 2012-2016 (75 FR 25324, May 7, 2010). Available at https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references

[961] U.S. Environmental Protection Agency. “Greenhouse Gas Equivalencies Calculator—Calculations and References. Accessed December 2022. Available online: https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references#:~:text=of%20diesel%20consumed,In%20the%20preamble%20to%20the%20joint%20EPA%2FDepartment%20of%20Transportation,emissions%20per%20gallon%20of%20diesel.

Table 2-31 GEM Fuel Consumption in Miles per Gallon Diesel (MPGD)

GEM Energy ID	Fuel Consumption (MPGD)
C8_SC_HR	8.5
C8_DC_HR	7.5
C7_DC_HR	8.6
C8_HH	5.3
HHD_R	7.2
HHD_M	6.4
HHD_U	5.2
MHD_R	8.2
MHD_M	8.0
MHD_U	7.3
LHD_R	12.2
LHD_M	11.4
LHD_U	10.2
RV	8.4
School Bus	7.2
Coach Bus	6.9
Emergency	5.0
Mixer	5.0
Transit Bus	5.2
Refuse Truck	5.0

We then assigned the GEM fuel consumption value to the appropriate vehicle segment in HD TRUCS to obtain the GEM-weighted fuel consumption by vehicle type. We also took fuel consumption due to PTO loads into account, as some of the vehicles in HD TRUCS have auxiliary loads supplied by a PTO. If a vehicle was equipped with a PTO, we calculated the additional fuel used when operating the PTO. These percent PTO values are a function of the propulsion ICE values as determined from GEM, where the MPG value for each Vehicle ID can be found in Table 2-32 (see discussion of PTO loads as a percentage of diesel fuel consumption in Chapter 2.2.2.1.4). For vehicles without a PTO unit, the percent PTO is zero. The PTO fuel consumption in terms of MPG was then converted into annual PTO fuel requirement for each vehicle using the annual operational VMT. Table 2-32 shows the GEM-weighted fuel consumption, gallons of diesel consumed per year by driving, and gallons of diesel consumed per year by PTO operation. As discussed in Chapter 2.2.1.1.3, for the final version for HD TRUCS, we have assessed each year of operation using the appropriate changes that occur with the age of the vehicle for inputs such as VMT and maintenance and repair costs or vary by calendar year such as fuel costs; however, we are continuing to show 10-year average values in tables such as the one below, as a single value point of comparison. Appendix A to this RIA includes each year of a 10-year schedule for VMT, which can be used to calculate the diesel and DEF gallons consumed for each year of the 10-year schedule.

Table 2-32 Annual Diesel Fuel Consumption from Driving and PTO Use (MY 2032), 10 Year Average

Vehicle ID	GEM Weighted Fuel Consumption (MPGD)	Annual Average Gallons of Diesel Consumed – Driving	Annual Average Gallons of Diesel Consumed - PTO	Annual Average Gallons of DEF Consumed
01V_Amb_Cl4-5_MP	11.36	662	0	34
02V_Amb_Cl2b-3_MP	11.36	965	0	50

Vehicle ID	GEM Weighted Fuel Consumption (MPGD)	Annual Average Gallons of Diesel Consumed – Driving	Annual Average Gallons of Diesel Consumed - PTO	Annual Average Gallons of DEF Consumed
03V_Amb_Cl4-5_U	10.24	846	0	44
04V_Amb_Cl2b-3_U	10.24	861	0	45
05T_Box_Cl8_MP	6.39	2292	0	119
06T_Box_Cl8_R	7.24	1982	0	103
07T_Box_Cl6-7_MP	8.01	1104	0	57
08T_Box_Cl6-7_R	8.23	1053	0	55
09T_Box_Cl8_U	5.15	2844	0	147
10T_Box_Cl6-7_U	7.27	1186	0	61
11T_Box_Cl2b-3_U	10.24	1285	0	67
12T_Box_Cl2b-3_R	12.15	1084	0	56
13T_Box_Cl2b-3_MP	11.36	1159	0	60
14T_Box_Cl4-5_U	10.24	825	0	43
15T_Box_Cl4-5_R	12.15	696	0	36
16T_Box_Cl4-5_MP	11.36	744	0	39
17B_Coach_Cl8_R	6.92	4955	0	257
18B_Coach_Cl8_MP	6.92	4955	0	257
19C_Mix_Cl8_MP	5.02	3952	2861	353
20T_Dump_Cl8_U	5.15	1724	304	105
21T_Dump_Cl8_MP	6.39	1389	245	85
22T_Dump_Cl6-7_MP	8.01	1557	275	95
23T_Dump_Cl8_U	5.15	1724	304	105
24T_Dump_Cl6-7_U	7.27	1715	303	104
25T_Fire_Cl8_MP	6.39	1389	463	96
26T_Fire_Cl8_U	5.15	1724	575	119
27T_Flat_Cl6-7_MP	8.01	1104	0	57
28T_Flat_Cl6-7_R	8.23	1074	0	56
29T_Flat_Cl6-7_U	7.27	1216	0	63
30Tractor_DC_Cl8	7.53	2767	0	143
31Tractor_DC_Cl7	8.60	2426	0	126
32Tractor_SC_Cl8	8.51	10969	0	568
33Tractor_DC_Cl8	7.53	6153	0	319
34T_Ref_Cl8_MP	5.05	2332	1256	186
35T_Ref_Cl6-7_MP	8.01	2648	1426	211
36T_Ref_Cl8_U	5.05	2332	1256	186
37T_Ref_Cl6-7_U	7.27	2917	1571	232
38RV_Cl8_R	8.39	313	0	16
39RV_Cl6-7_R	8.23	319	0	17
40RV_Cl4-5_R	12.15	216	0	11
41Tractor_DC_Cl7	8.60	5392	0	279
42RV_Cl8_MP	8.39	313	0	16
43RV_Cl6-7_MP	8.01	328	0	17
44RV_Cl4-5_MP	11.36	231	0	12
45Tractor_DC_Cl8	7.53	6152	0	319
46B_School_Cl8_MP	6.39	1630	0	84
47B_School_Cl6-7_MP	7.19	1541	0	80
48B_School_Cl4-5_MP	11.36	917	0	47
49B_School_Cl2b-3_MP	11.36	917	0	47
50B_School_Cl8_U	5.15	2023	0	105
51B_School_Cl6-7_U	7.19	1541	0	80
52B_School_Cl4-5_U	10.24	1017	0	53

Vehicle ID	GEM Weighted Fuel Consumption (MPGD)	Annual Average Gallons of Diesel Consumed – Driving	Annual Average Gallons of Diesel Consumed - PTO	Annual Average Gallons of DEF Consumed
53B_School_Cl2b-3_U	10.24	1017	0	53
54Tractor_SC_Cl8	8.51	10969	0	568
55B_Shuttle_Cl2b-3_MP	11.36	2248	0	116
56B_Shuttle_Cl4-5_U	10.24	2493	0	129
57B_Shuttle_Cl2b-3_U	10.24	2493	0	129
58B_Shuttle_Cl6-7_MP	8.01	3190	0	165
59B_Shuttle_Cl6-7_U	7.27	3514	0	182
60S_Plow_Cl6-7_MP	8.01	1104	195	67
61S_Plow_Cl8_MP	6.39	1536	271	94
62S_Plow_Cl6-7_U	7.27	1216	215	74
63S_Plow_Cl8_U	5.15	1907	336	116
64V_Step_Cl6-7_MP	8.01	1687	0	87
65V_Step_Cl4-5_MP	11.36	744	0	39
66V_Step_Cl2b-3_MP	11.36	1136	0	59
67V_Step_Cl6-7_U	7.27	1859	0	96
68V_Step_Cl4-5_U	10.24	825	0	43
69V_Step_Cl2b-3_U	10.24	1260	0	65
70S_Sweep_Cl6-7_U	7.27	1538	385	100
71T_Tanker_Cl8_R	7.24	1581	279	96
72T_Tanker_Cl8_MP	6.39	1792	316	109
73T_Tanker_Cl8_U	5.15	2224	392	136
74T_Tow_Cl8_R	7.24	1973	348	120
75T_Tow_Cl6-7_R	8.23	1511	267	92
76T_Tow_Cl8_U	5.15	2775	490	169
77T_Tow_Cl6-7_U	7.27	1712	302	104
78Tractor_SC_Cl8	8.51	7835	0	406
79Tractor_SC_Cl8	8.51	10969	0	568
80Tractor_DC_Cl8	5.34	4403	0	228
81Tractor_DC_Cl7	8.60	5392	0	279
82Tractor_DC_Cl8	7.53	6152	0	319
83Tractor_DC_Cl7	8.60	3008	0	156
84Tractor_DC_Cl8	7.53	3423	0	177
85B_Transit_Cl8_MP	5.15	5715	0	296
86B_Transit_Cl6-7_MP	8.01	2170	0	112
87B_Transit_Cl8_U	5.15	5715	0	296
88B_Transit_Cl6-7_U	7.27	2391	0	124
89T_Utility_Cl8_MP	6.39	927	164	56
90T_Utility_Cl8_R	7.24	818	144	50
91T_Utility_Cl6-7_MP	8.01	1363	241	83
92T_Utility_Cl6-7_R	8.23	1326	234	81
93T_Utility_Cl4-5_MP	11.36	961	170	59
94T_Utility_Cl2b-3_MP	11.36	440	78	27
95T_Utility_Cl4-5_R	12.15	881	155	54
96T_Utility_Cl2b-3_R	12.15	881	155	54
97T_Utility_Cl8_U	5.15	1150	203	70
98T_Utility_Cl6-7_U	7.27	1502	265	92
99T_Utility_Cl4-5_U	10.24	1066	188	65
100T_Utility_Cl2b-3_U	10.24	488	86	30
101Tractor_DC_Cl8	7.53	1723	0	89

2.3.4 ICE Vehicle Operating Costs

Operating costs for HD vehicles encompass a variety of costs, such as labor, insurance, registration fees, fueling, maintenance and repair (M&R), and other costs. For this analysis, we are primarily interested in costs that differ for a comparable ICE vehicle and a ZEV because these costs will be used to calculate the year that a ZEV is estimated to pay back relative to a comparable ICE vehicle (see RIA Chapter 2.8.8 and 2.9.2). We focus on fueling costs, M&R costs, and insurance costs[962] because we expect these costs to be different for ZEVs than for comparable diesel vehicles, but we do not anticipate other operating costs, such as labor,[963] to differ meaningfully. For ICE vehicles, we also estimated the cost of the diesel exhaust fluid (DEF) required for the selective catalytic reduction aftertreatment system.

For each vehicle in HD TRUCS, the 10-year average annual operating costs are as shown in Table 2-33 and described in the sections below. As discussed in RIA Chapter 2.2.1.1.3, for the final rule version of HD TRUCS, we have assessed each year of operation using the appropriate changes that occur over time for inputs such as VMT, maintenance and repair, and fuel costs; however, we are continuing to show a 10-year average value in tables such as the one below, as a single value point of comparison. Appendix A to this RIA includes each year of a 10-year schedule for VMT, which, with the M&R cost per mile (by vehicle age), the cost of diesel and DEF per gallon (by calendar year), and the cost of insurance can be used to calculate the operating costs for each year of a 10-year schedule.

Table 2-33 ICE Operating Costs for a MY 2032 Vehicle (2022$, 10-Year Average)

Vehicle ID	Average Annual Cost ($/year)			
	DEF	ICE Vehicle M&R	Diesel	Powertrain Insurance
01V_Amb_Cl4-5_MP	148	1997	2481	1278
02V_Amb_Cl2b-3_MP	216	2909	3781	1221
03V_Amb_Cl4-5_U	189	2301	3317	1278
04V_Amb_Cl2b-3_U	193	2341	3375	1221
05T_Box_Cl8_MP	512	3886	8981	2435
06T_Box_Cl8_R	443	3779	7766	2435
07T_Box_Cl6-7_MP	247	2346	4326	1371
08T_Box_Cl6-7_R	235	2281	4125	1371
09T_Box_Cl8_U	636	3886	11147	2153
10T_Box_Cl6-7_U	265	2289	4650	1371
11T_Box_Cl2b-3_U	287	3494	5037	1201
12T_Box_Cl2b-3_R	242	3494	4246	1201
13T_Box_Cl2b-3_MP	259	3494	4541	1201
14T_Box_Cl4-5_U	184	2243	3234	1205
15T_Box_Cl4-5_R	156	2243	2726	1205
16T_Box_Cl4-5_MP	166	2243	2915	1205

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[962] Insurance costs were not included in the proposal; however, EPA added these incremental costs to the final version of HD TRUCS after consideration of comments. See RIA Chapter 2.3.4.4

[963] We do not expect the labor costs for drivers to differ between ICE and ZEV vehicles. After consideration of comments stating that ZEV technicians may initially require additional training, EPA has phased in the ZEV maintenance and repair scaling factors to address this potential transition period. See RIA Chapters 2.4.4.1 and 2.5.3.2 and RTC Section 3.6 for more information.

Vehicle ID	Average Annual Cost ($/year)			
	DEF	ICE Vehicle M&R	Diesel	Powertrain Insurance
17B_Coach_Cl8_R	1109	9203	19420	1916
18B_Coach_Cl8_MP	1109	9203	19420	1916
19C_Mix_Cl8_MP	1523	5261	26700	2153
20T_Dump_Cl8_U	453	2355	7948	2435
21T_Dump_Cl8_MP	365	2355	6404	2435
22T_Dump_Cl6-7_MP	409	3307	7176	1363
23T_Dump_Cl8_U	453	2355	7948	2153
24T_Dump_Cl6-7_U	451	3307	7905	1363
25T_Fire_Cl8_MP	414	2355	7257	2435
26T_Fire_Cl8_U	514	2355	9007	2153
27T_Flat_Cl6-7_MP	247	2346	4326	1363
28T_Flat_Cl6-7_R	240	2346	4208	1363
29T_Flat_Cl6-7_U	272	2346	4766	1363
30Tractor_DC_Cl8	618	5458	10839	2566
31Tractor_DC_Cl7	542	5459	9501	2018
32Tractor_SC_Cl8	2452	24793	42985	2662
33Tractor_DC_Cl8	1374	12137	24102	2042
34T_Ref_Cl8_MP	803	3150	14067	2026
35T_Ref_Cl6-7_MP	911	5673	15972	1363
36T_Ref_Cl8_U	803	3150	14067	2026
37T_Ref_Cl6-7_U	1004	5673	17594	1363
38RV_Cl8_R	70	722	1227	1425
39RV_Cl6-7_R	72	722	1251	1367
40RV_Cl4-5_R	48	722	848	1179
41Tractor_DC_Cl7	1204	12134	21119	2018
42RV_Cl8_MP	70	722	1227	1425
43RV_Cl6-7_MP	74	722	1286	1367
44RV_Cl4-5_MP	52	722	906	1179
45Tractor_DC_Cl8	1373	12134	24097	2662
46B_School_Cl8_MP	365	2795	6389	1425
47B_School_Cl6-7_MP	345	2976	6042	1367
48B_School_Cl4-5_MP	205	2795	3592	1179
49B_School_Cl2b-3_MP	205	2795	3592	1236
50B_School_Cl8_U	453	2795	7929	1425
51B_School_Cl6-7_U	345	2976	6042	1367
52B_School_Cl4-5_U	228	2795	3985	1179
53B_School_Cl2b-3_U	228	2795	3985	1236
54Tractor_SC_Cl8	2452	24793	42985	2662
55B_Shuttle_Cl2b-3_MP	503	6856	8810	1236
56B_Shuttle_Cl4-5_U	558	6856	9773	1179
57B_Shuttle_Cl2b-3_U	558	6856	9773	1236
58B_Shuttle_Cl6-7_MP	714	6856	12503	1367
59B_Shuttle_Cl6-7_U	786	6856	13773	1367
60S_Plow_Cl6-7_MP	290	2346	5091	1363
61S_Plow_Cl8_MP	404	2605	7083	2435
62S_Plow_Cl6-7_U	320	2346	5608	1363
63S_Plow_Cl8_U	501	2605	8790	2153
64V_Step_Cl6-7_MP	377	3585	6612	1360
65V_Step_Cl4-5_MP	166	2243	2915	1179
66V_Step_Cl2b-3_MP	254	3398	4451	1221
67V_Step_Cl6-7_U	415	3585	7284	1360

Vehicle ID	Average Annual Cost ($/year)			
	DEF	ICE Vehicle M&R	Diesel	Powertrain Insurance
68V_Step_Cl4-5_U	184	2243	3234	1179
69V_Step_Cl2b-3_U	281	3398	4937	1221
70S_Sweep_Cl6-7_U	430	2967	7536	1363
71T_Tanker_Cl8_R	416	3038	7287	2435
72T_Tanker_Cl8_MP	471	3038	8261	2153
73T_Tanker_Cl8_U	585	3038	10252	2153
74T_Tow_Cl8_R	519	3792	9095	2512
75T_Tow_Cl6-7_R	397	3302	6968	1363
76T_Tow_Cl8_U	730	3792	12796	2153
77T_Tow_Cl6-7_U	450	3302	7892	1363
78Tractor_SC_Cl8	1751	17709	30704	2662
79Tractor_SC_Cl8	2452	24793	42985	2662
80Tractor_DC_Cl8	984	6241	17256	2692
81Tractor_DC_Cl7	1204	12134	21119	2018
82Tractor_DC_Cl8	1373	12134	24097	2662
83Tractor_DC_Cl7	672	6770	11783	2018
84Tractor_DC_Cl8	764	6752	13408	2498
85B_Transit_Cl8_MP	1279	7904	22400	1916
86B_Transit_Cl6-7_MP	486	4664	8507	1367
87B_Transit_Cl8_U	1279	7904	22400	1893
88B_Transit_Cl6-7_U	535	4664	9371	1367
89T_Utility_Cl8_MP	244	1571	4273	2435
90T_Utility_Cl8_R	215	1571	3769	2435
91T_Utility_Cl6-7_MP	359	2897	6285	1363
92T_Utility_Cl6-7_R	349	2897	6113	1363
93T_Utility_Cl4-5_MP	253	2897	4429	1278
94T_Utility_Cl2b-3_MP	116	1326	2027	1221
95T_Utility_Cl4-5_R	231	2817	4060	1278
96T_Utility_Cl2b-3_R	231	2817	4060	1221
97T_Utility_Cl8_U	302	1571	5303	2153
98T_Utility_Cl6-7_U	395	2897	6924	1363
99T_Utility_Cl4-5_U	280	2897	4913	1278
100T_Utility_Cl2b-3_U	128	1326	2248	1221
101Tractor_DC_Cl8	385	3397	6747	2498

2.3.4.1 Diesel Exhaust Fluid Costs

To estimate DEF consumption for a diesel version of each vehicle type in HD TRUCS, we referenced the work in the final rulemaking, Control of Air Pollution From New Motor Vehicles: Heavy-Duty Engine and Vehicle Standards[964] (HD2027 Low NOx Rule). The HD 2027 Final Rule defined the consumption of DEF as a function of NOx reduction over the Selective Catalyst Reduction (SCR) system considering Federal Test Procedure (FTP) emissions.[965] The engine out

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[964] 88 FR 4412 (January 24, 2023).

[965] The relationship between DEF dose rate and NOx reduction across the SCR catalyst is based on methodology presented in the Technical Support Document to the 2012 Non-conformance Penalties for On-highway Heavy-duty Diesel Engines rule (the NCP Technical Support Document, or NCP TSD).

and tailpipe NOx emissions as well as the DEF dosing rate from the HD 2027 Final Rule are summarized below in Table 2-34.

Table 2-34 DEF Consumption Rates for Diesel Vehicles in HD TRUCS

	Value
Engine-out NOx (FTP g/hp-hr)	4.0
Tailpipe NOx (FTP g/hp-hr)	0.2
DEF Dose Rate (% of fuel consumed)	5.18%

The percentage of DEF dosing as a function of diesel fuel consumed was then multiplied by the sum of Annual Gallons of Diesel Consumed – Driving and Annual Gallons of Diesel Consumed – PTO (see Table 2-32), and the results are shown in Table 2-35. As discussed in RIA Chapter 2.2.1.1.3, for the final version for HD TRUCS, we have assessed each year of operation using the appropriate changes that occur over time for inputs such as VMT, maintenance and repair, and fuel costs; however, we are continuing to show a 10-year average value in tables such as the one below, as a single value point of comparison. Appendix A to this RIA includes each year of a 10-year schedule for VMT.

Table 2-35 Annual DEF Consumption, 10 Year Average

Vehicle ID	**Average Annual Gallons of DEF Consumed**
01V_Amb_Cl4-5_MP	34
02V_Amb_Cl2b-3_MP	50
03V_Amb_Cl4-5_U	44
04V_Amb_Cl2b-3_U	45
05T_Box_Cl8_MP	119
06T_Box_Cl8_R	103
07T_Box_Cl6-7_MP	57
08T_Box_Cl6-7_R	55
09T_Box_Cl8_U	147
10T_Box_Cl6-7_U	61
11T_Box_Cl2b-3_U	67
12T_Box_Cl2b-3_R	56
13T_Box_Cl2b-3_MP	60
14T_Box_Cl4-5_U	43
15T_Box_Cl4-5_R	36
16T_Box_Cl4-5_MP	39
17B_Coach_Cl8_R	257
18B_Coach_Cl8_MP	257
19C_Mix_Cl8_MP	353
20T_Dump_Cl8_U	105
21T_Dump_Cl8_MP	85
22T_Dump_Cl6-7_MP	95
23T_Dump_Cl8_U	105
24T_Dump_Cl6-7_U	104
25T_Fire_Cl8_MP	96

Vehicle ID	Average Annual Gallons of DEF Consumed
26T_Fire_Cl8_U	119
27T_Flat_Cl6-7_MP	57
28T_Flat_Cl6-7_R	56
29T_Flat_Cl6-7_U	63
30Tractor_DC_Cl8	143
31Tractor_DC_Cl7	126
32Tractor_SC_Cl8	568
33Tractor_DC_Cl8	319
34T_Ref_Cl8_MP	186
35T_Ref_Cl6-7_MP	211
36T_Ref_Cl8_U	186
37T_Ref_Cl6-7_U	232
38RV_Cl8_R	16
39RV_Cl6-7_R	17
40RV_Cl4-5_R	11
41Tractor_DC_Cl7	279
42RV_Cl8_MP	16
43RV_Cl6-7_MP	17
44RV_Cl4-5_MP	12
45Tractor_DC_Cl8	319
46B_School_Cl8_MP	84
47B_School_Cl6-7_MP	80
48B_School_Cl4-5_MP	47
49B_School_Cl2b-3_MP	47
50B_School_Cl8_U	105
51B_School_Cl6-7_U	80
52B_School_Cl4-5_U	53
53B_School_Cl2b-3_U	53
54Tractor_SC_Cl8	568
55B_Shuttle_Cl2b-3_MP	116
56B_Shuttle_Cl4-5_U	129
57B_Shuttle_Cl2b-3_U	129
58B_Shuttle_Cl6-7_MP	165
59B_Shuttle_Cl6-7_U	182
60S_Plow_Cl6-7_MP	67
61S_Plow_Cl8_MP	94
62S_Plow_Cl6-7_U	74
63S_Plow_Cl8_U	116
64V_Step_Cl6-7_MP	87
65V_Step_Cl4-5_MP	39
66V_Step_Cl2b-3_MP	59
67V_Step_Cl6-7_U	96
68V_Step_Cl4-5_U	43
69V_Step_Cl2b-3_U	65
70S_Sweep_Cl6-7_U	100
71T_Tanker_Cl8_R	96
72T_Tanker_Cl8_MP	109
73T_Tanker_Cl8_U	136
74T_Tow_Cl8_R	120
75T_Tow_Cl6-7_R	92
76T_Tow_Cl8_U	169

Vehicle ID	**Average Annual Gallons of DEF Consumed**
77T_Tow_Cl6-7_U	104
78Tractor_SC_Cl8	406
79Tractor_SC_Cl8	568
80Tractor_DC_Cl8	228
81Tractor_DC_Cl7	279
82Tractor_DC_Cl8	319
83Tractor_DC_Cl7	156
84Tractor_DC_Cl8	177
85B_Transit_Cl8_MP	296
86B_Transit_Cl6-7_MP	112
87B_Transit_Cl8_U	296
88B_Transit_Cl6-7_U	124
89T_Utility_Cl8_MP	56
90T_Utility_Cl8_R	50
91T_Utility_Cl6-7_MP	83
92T_Utility_Cl6-7_R	81
93T_Utility_Cl4-5_MP	59
94T_Utility_Cl2b-3_MP	27
95T_Utility_Cl4-5_R	54
96T_Utility_Cl2b-3_R	54
97T_Utility_Cl8_U	70
98T_Utility_Cl6-7_U	92
99T_Utility_Cl4-5_U	65
100T_Utility_Cl2b-3_U	30
101Tractor_DC_Cl8	89

DEF costs were based on Table 7-31 in the RIA for the Control of Air Pollution from New Motor Vehicles: Heavy-Duty Engine and Vehicle Standards,[966] then adjusted from 2017$ to 2022$.

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[966] U.S. Environmental Protection Agency. Control of Air Pollution from New Motor Vehicles: Heavy-Duty Engine and Vehicle Standards Regulatory Impact Analysis. See Table 7-31. Available at https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P1016A9N.pdf

Table 2-36 DEF Price per Gallon (2022$)

Calendar Year	DEF $/Gallon
2027	3.84
2028	3.89
2029	3.93
2030	3.98
2031	4.03
2032	4.08
2033	4.15
2034	4.20
2035	4.25
2036	4.30
2037	4.35
2038	4.42
2039	4.47
2040	4.54
2041	4.59

2.3.4.2 Maintenance and Repair Cost

Maintenance and repair costs contribute to the overall operating costs for HD vehicles. To establish a baseline cost for maintenance and repair of diesel-fueled ICE vehicles, we relied on the research compiled by Burnham et al. in Chapter 3.5.5 of "Comprehensive Total Cost of Ownership Quantification for Vehicles with Different Size Classes and Powertrains"[967,968] and used equations found in the 2022 BEAN tool (see the "TCO" tab).[969] Burnham et al. used data from Utilimarc and American Transportation Research Institute (ATRI) to estimate maintenance and repair costs per mile for multiple heavy-duty vehicle categories over time. In the proposal we selected the box truck curve to represent vocational vehicles and short-haul tractors[970], and the semi-tractor curve to represent long-haul tractors. The box truck equation has a higher slope and intercept than the semi-tractor equation which means that in the NPRM version of HD TRUCS, vocational vehicle and short haul tractor diesel maintenance costs per mile (and therefore also the ZEV M&R savings per mile) were much higher than the long-haul tractors' M&R costs (and savings) per mile. Even though EPA did not receive any comments that specifically challenged the underlying diesel M&R estimates, after consideration of comments more generally asserting that M&R savings in our analysis were high, EPA is updating our approach for the final rule HD TRUCS M&R analysis to be more conservative by using the semi-tractor equation for calculating ICE vehicle maintenance and repair costs per mile for all vehicles. This change reduces the overall maintenance cost estimates for ICE vehicles, which in turn reduces the

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[967] Burnham, Andrew, David Gohlke, Luke Rush, Thomas Stephens, Yan Zhou, Mark A. Delucchi, Alicia Birky, Chad Hunter, Zhenhong Lin, Shiqi Ou, Fei Xie, Camron Proctor, Steven Wiryadinata, Nawei Liu, and Madhur Boloor. "Comprehensive Total Cost of Ownership Quantification for Vehicles with Different Size Classes and Powertrains". April 2021. Accessible online: https://publications.anl.gov/anlpubs/2021/05/167399.pdf.

[968] Burnham, et al uses 2019$ in this report. See page 22 of https://publications.anl.gov/anlpubs/2021/05/167399.pdf.

[969] Argonne National Laboratory. VTO HFTO Analysis Reports – 2022. "ANL – ESD-2206 Report – BEAN Tool – MD HD Vehicle Techno-Economic Analysis.xlsm". Available online: https://anl.app.box.com/s/an4nx0v2xpudxtpsnkhd5peimzu4j1hk/folder/242640145714.

[970] Short haul tractors and vocational vehicles were represented by the same M&R equation because they have duty cycles and annual VMT that are similar.

overall savings from ZEV M&R, since the savings values are estimated as a cost reduction from the ICE vehicle maintenance and repair values. M&R cost per mile (2022$/mi) are shown in Figure 2-3.

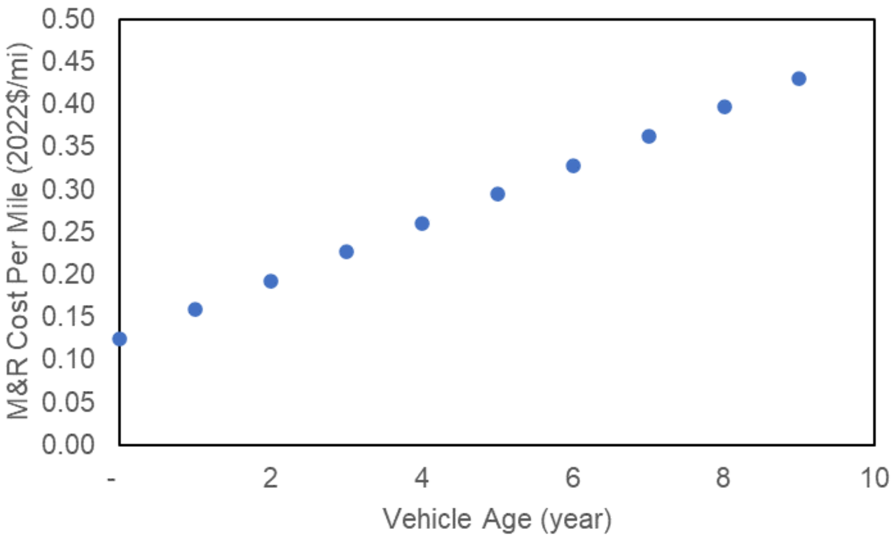

Figure 2-3 M&R Cost Per Mile (2022$/mi)

Annual M&R costs are a function of yearly VMT and the M&R costs per mile by vehicle age, using the VMT shown in Appendix A to this RIA and M&R cost per mile (2022$/mi) as shown in Figure 2-3. Averaging years 0–9 yields about 28 cents per mile, after adjusting to 2022$.

2.3.4.3 Diesel Fuel Costs

The yearly fuel cost for the HD vehicle is a function of yearly fuel consumption, as described in Chapter 2.3.3, and the cost of diesel fuel. We used the DOE Energy Information Administration's (EIA's) Annual Energy Outlook (AEO) 2023 for diesel price. For the transportation sector, the reference case projection for diesel fuel for on-road use is in Table 2-37 in 2022$.[971] This value includes Federal and State taxes but excludes county and local taxes. For each vehicle and each model year, the annual gallons consumed for each year is multiplied by the diesel fuel cost for each year. For example, for MY 2027 vehicles, the annual gallons of diesel consumed for years CY 2027-CY 2036 is computed using the operational energy per mile, the annual operational VMT (which changes over the life of the vehicle) and the diesel fuel price for CY 2027-CY 2036. Similarly, MY 2032 vehicles will have similar annual gallons of diesel consumed as MY 2027 vehicles for years 2032 to 2041, however, the diesel fuel price used will be for CY 2032 - CY 2041.

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[971] U.S. Energy Information Administration. Annual Energy Outlook 2023. Table 57: Components of Selected Petroleum Product Prices. Diesel Fuel End User Price. Last accessed on 12/2/2023 at *https://www.eia.gov/outlooks/aeo/data/browser/#/?id=70-AEO2023&cases=ref2023&sourcekey=0.*

Table 2-37 AEO 2023 Reference Case Diesel Price (2022$)

Calendar Year	Diesel Price ($/gal)
2027	3.74
2028	3.63
2029	3.65
2030	3.65
2031	3.67
2032	3.69
2033	3.71
2034	3.71
2035	3.74
2036	3.74
2037	3.76
2038	3.78
2039	3.78
2040	3.79
2041	3.81

2.3.4.4 Insurance cost

One commenter recommended using an insurance rate of 3%, based originally on an ICCT April 2023 paper on ZEV TCO.[972] We have considered these sources and found them reasonable. Similar to State sales tax and the FET, insurance costs are calculated as a percentage, after applying the RPE to the upfront technology costs shown in Table 2-26; however, unlike the state sales tax and FET, the insurance costs are added to operating costs each year in HD TRUCS, as part of the payback calculation. See Table 2-33 for MY 2032 ICE powertrain insurance costs.

2.4 Battery Electric Vehicle Technology

For the purposes of comparing ICE and BEV technology costs and performance, this section explains how we assessed heavy-duty BEVs based on the performance and use criteria in Chapter 2.2. First, we determined BEV battery pack size,[973] range, and peak motor power requirements to meet energy and daily operational needs of each vehicle, and we projected energy and fuel use for each vehicle type (kWh/mi) on an annual basis. Then, we projected the DMC and RPE of BEV components and considered the impacts of the IRA battery and vehicle tax credits for heavy-duty electric vehicles. We also then assessed the sales tax and FET cost of the BEVs. Next, we determined the weight and physical volume of the battery pack for each of the vehicles to evaluate the impact on payload capability. Lastly, we projected charging costs, maintenance and repair costs, insurance costs, and an annual ZEV registration fee for each

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[972] Basma, Hussein, et.al. “Total Cost of Ownership of Alternative Powertrain Technologies for Class 8 Long-Haul Trucks in the United States.” April 2023. Page 17. Available online: https://theicct.org/wp-content/uploads/2023/04/tco-alt-powertrain-long-haul-trucks-us-apr23.pdf

[973] Please note that HD TRUCS focuses on the traction battery, which is the rechargeable battery that supplies power to the electric motor.

vehicle type for the first ten years of vehicle operation. Finally, we projected relevant operational costs, for each year, for the first ten years of operation.

2.4.1 BEV Component Sizing

Two of the major components in a BEV are the battery and the motor. The size of these components is determined by the needs of the specific vehicle. In HD TRUCS, we determined the battery storage capacity, projected range of the vehicle, and peak motor power requirement for each of the 101 vehicles represented in HD TRUCS, as described in the following two subsections. The resulting values are shown in Table 2-38.

Table 2-38 Battery and Motor Sizes (MY 2032)

Vehicle ID	Battery Size (kWh))	Projected Electric Range (mi)	Motor Peak Power (kW)
01V_Amb_Cl4-5_MP	120	100	245
02V_Amb_Cl2b-3_MP	113	100	245
03V_Amb_Cl4-5_U	111	100	245
04V_Amb_Cl2b-3_U	104	100	245
05T_Box_Cl8_MP	244	100	322
06T_Box_Cl8_R	252	100	322
07T_Box_Cl6-7_MP	168	100	203
08T_Box_Cl6-7_R	183	100	203
09T_Box_Cl8_U	236	100	322
10T_Box_Cl6-7_U	162	105	203
11T_Box_Cl2b-3_U	100	100	245
12T_Box_Cl2b-3_R	118	100	245
13T_Box_Cl2b-3_MP	109	100	245
14T_Box_Cl4-5_U	100	100	245
15T_Box_Cl4-5_R	118	100	245
16T_Box_Cl4-5_MP	109	100	245
17B_Coach_Cl8_R	710	300	322
18B_Coach_Cl8_MP	1052	450	322
19C_Mix_Cl8_MP	428	100	322
20T_Dump_Cl8_U	283	111	322
21T_Dump_Cl8_MP	286	111	322
22T_Dump_Cl6-7_MP	277	156	203
23T_Dump_Cl8_U	283	111	322
24T_Dump_Cl6-7_U	259	156	203
25T_Fire_Cl8_MP	300	111	322
26T_Fire_Cl8_U	301	111	322
27T_Flat_Cl6-7_MP	168	100	203
28T_Flat_Cl6-7_R	183	100	203
29T_Flat_Cl6-7_U	155	100	203
30Tractor_DC_Cl8	351	136	528
31Tractor_DC_Cl7	317	147	367
32Tractor_SC_Cl8	973	420	400
33Tractor_DC_Cl8	531	216	551
34T_Ref_Cl8_MP	355	118	322
35T_Ref_Cl6-7_MP	290	118	203
36T_Ref_Cl8_U	355	118	322
37T_Ref_Cl6-7_U	286	118	203
38RV_Cl8_R	564	335	322
39RV_Cl6-7_R	599	335	203

Vehicle ID	Battery Size (kWh))	Projected Electric Range (mi)	Motor Peak Power (kW)
40RV_Cl4-5_R	381	335	245
41Tractor_DC_Cl7	744	349	367
42RV_Cl8_MP	564	335	322
43RV_Cl6-7_MP	550	335	203
44RV_Cl4-5_MP	350	335	245
45Tractor_DC_Cl8	891	349	528
46B_School_Cl8_MP	266	100	322
47B_School_Cl6-7_MP	160	100	203
48B_School_Cl4-5_MP	120	100	245
49B_School_Cl2b-3_MP	113	100	245
50B_School_Cl8_U	252	100	322
51B_School_Cl6-7_U	160	100	203
52B_School_Cl4-5_U	111	100	245
53B_School_Cl2b-3_U	104	100	245
54Tractor_SC_Cl8	1164	420	400
55B_Shuttle_Cl2b-3_MP	164	150	245
56B_Shuttle_Cl4-5_U	158	150	245
57B_Shuttle_Cl2b-3_U	151	150	245
58B_Shuttle_Cl6-7_MP	264	150	203
59B_Shuttle_Cl6-7_U	245	150	203
60S_Plow_Cl6-7_MP	199	111	203
61S_Plow_Cl8_MP	394	156	322
62S_Plow_Cl6-7_U	187	111	203
63S_Plow_Cl8_U	388	156	322
64V_Step_Cl6-7_MP	169	101	203
65V_Step_Cl4-5_MP	109	100	245
66V_Step_Cl2b-3_MP	109	100	245
67V_Step_Cl6-7_U	156	101	203
68V_Step_Cl4-5_U	100	100	245
69V_Step_Cl2b-3_U	100	100	245
70S_Sweep_Cl6-7_U	182	100	203
71T_Tanker_Cl8_R	269	100	322
72T_Tanker_Cl8_MP	264	100	322
73T_Tanker_Cl8_U	263	100	322
74T_Tow_Cl8_R	413	157	322
75T_Tow_Cl6-7_R	300	157	203
76T_Tow_Cl8_U	400	157	322
77T_Tow_Cl6-7_U	261	157	203
78Tractor_SC_Cl8	834	300	400
79Tractor_SC_Cl8	1164	420	400
80Tractor_DC_Cl8	647	180	450
81Tractor_DC_Cl7	531	216	367
82Tractor_DC_Cl8	635	216	528
83Tractor_DC_Cl7	459	214	367
84Tractor_DC_Cl8	356	120	528
85B_Transit_Cl8_MP	472	203	322
86B_Transit_Cl6-7_MP	373	219	203
87B_Transit_Cl8_U	472	203	322
88B_Transit_Cl6-7_U	341	219	203
89T_Utility_Cl8_MP	254	100	322
90T_Utility_Cl8_R	261	100	322
91T_Utility_Cl6-7_MP	184	100	203

Vehicle ID	Battery Size (kWh))	Projected Electric Range (mi)	Motor Peak Power (kW)
92T_Utility_Cl6-7_R	198	100	203
93T_Utility_Cl4-5_MP	120	100	245
94T_Utility_Cl2b-3_MP	114	100	245
95T_Utility_Cl4-5_R	128	100	245
96T_Utility_Cl2b-3_R	128	100	245
97T_Utility_Cl8_U	250	100	322
98T_Utility_Cl6-7_U	174	100	203
99T_Utility_Cl4-5_U	113	100	245
100T_Utility_Cl2b-3_U	106	100	245
101Tractor_DC_Cl8	279	108	528

2.4.1.1 Battery Pack Energy

In HD TRUCS, we sized the battery based on the expected energy required for the vehicle to complete operations (i.e., based on the daily sizing VMT). This daily energy consumption is a function of miles the vehicle is driven and the energy it consumes because of: (1) energy at the axle used to move the vehicle per unit mile, including the impact of regenerative braking, and operational PTO[974] energy requirements (together this energy required to perform required work is the "ZEV baseline energy"), (2) battery conditioning and HVAC energy requirements, and (3) BEV efficiency, depth of discharge, and deterioration.

The ZEV baseline energy loads are described in RIA Chapter 2.2.2 and are reported in terms of kWh/mi, which are then converted into kWh/day using the daily sizing VMT as previously described in RIA Chapter 2.2.1.2.2.

The energy required to maintain the battery at a constant temperature (battery conditioning) and to heat and cool interior cabins (HVAC) are considered separately from the baseline energy, since these energy loads are not required year-round or in all regions of the country. The HVAC energy is calculated as a power requirement, which is converted into an energy requirement by multiplying the HVAC power by the 8-hour operational day. The battery conditioning energy requirements are determined as a percent of total battery size; a detailed explanation of battery conditioning may be found in RIA Chapters 2.4.1.1.1 and 2.5.1.2.2.

The total daily battery demand is assumed to be the sum of the daily ZEV baseline energy (including regenerative braking and PTO) as well as battery conditioning and HVAC. The appropriate losses from the BEV powertrain system are applied to the battery size. Also, the battery is oversized based on the level of depth of discharge for an EV battery and to compensate for deterioration of the battery over time if the battery is expected to exceed 2000 cycles before the tenth year of operation. A detailed explanation of the oversizing parameters may be found in RIA Chapter 2.4.1.1.3 and RIA Chapter 2.4.1.1.4. The battery pack size for MY 2032 is shown in Table 2-38 for each of the 101 vehicle types.

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[974] PTO energy consumption is calculated from the benchmark diesel operational fuel consumption (operational VMT), rather than the sizing energy consumption (sizing VMT). While batteries are sized using the sizing VMT to calculate the daily propulsion energy, we think that PTO usage per day is unlikely to vary proportionally with the high mileage activity of the sizing VMT.

2.4.1.1.1 HVAC Considerations in a BEV

In this subsection, we describe the HVAC energy requirements, which vary by the cabin size of the vehicle, and our approach to considering different HVAC requirements across the U.S.

For BEVs, the energy required for cabin thermal management is different than for ICE vehicles because the vehicle is not able to utilize excess (waste) heat from an engine. BEVs could be equipped with either a positive temperature coefficient (PTC) heater with a traditional A/C, or a full heat pump system. (See RIA Chapter 1 for a description of both). Because heat pumps are many times more efficient than a PTC heater, a smaller battery is required for the same duty cycle. This will likely make heat pumps a cost-effective solution in the heavy-duty sector, considering the avoided upfront costs of a sufficiently larger battery and reduced electricity costs during operation. Given the success and increasing adoption of heat pumps in light-duty EVs, we project the use of heat pumps for heavy-duty vehicles in our HD TRUCS analysis.

To estimate HVAC energy consumption of ZEVs in HD TRUCS, we performed a literature and market review. Even though there are limited real-world studies, we agreed with the HVAC modeling approach described in Basma et. al.[975] This physics-based cabin thermal model considers four vehicle characteristics: the cabin interior, walls, and materials, as well as the number of passengers. The authors modelled a Class 8 electric transit bus with an HVAC system consisting of two 20 kW-rated reversible heat pumps, an air circulation system, and a battery thermal management system. The HVAC control strategy is a traditional on-off controller. The modeled power demand as a function of ambient temperature for the Class 8 transit bus is shown in Figure 2-4. In response to our request for data in the NPRM on HVAC loads for BEVs, we received additional modeling data from one commenter that included HVAC loads for European long-haul tractors. We found the new data to be corroborative with our HVAC loads and the sleeper cab scaling factor; therefore, we continued to use the same HVAC power demand model in the final rule version of HD TRUCS.

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[975] Basma, Hussein, Charbel Mansour, Marc Haddad, Maroun Nemer, Pascal Stabat. “Comprehensive energy modeling methodology for battery electric buses”. Energy: Volume 207, 15 September 2020, 118241. Available online: https://www.sciencedirect.com/science/article/pii/S0360544220313487.

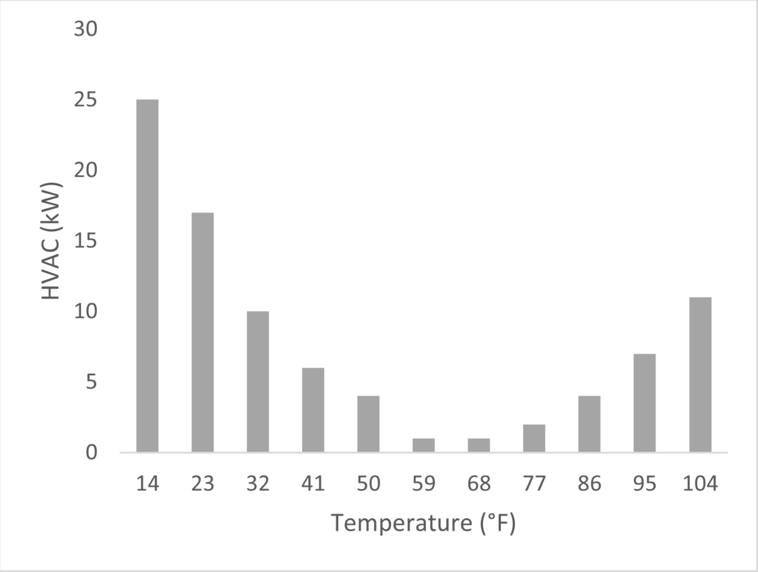

Figure 2-4 Modeled HVAC Power Demand of a Class 8 Transit Bus as a Function of Ambient Temperature

We recognize that HVAC is not evenly used across the nation. For example, some regions will be more reliant on heater use while others may depend more on air conditioning. The energy used for HVAC consumption in HD TRUCS is HVAC energy consumption using Basma for power demand at a specific temperature and weighted by the percent HD VMT traveled at a specific temperature range.[976] To properly account for the temperature variation throughout the nation and throughout the year, we calculated the percent of HD VMT for several temperature bins as available from MOVES; this national distribution of VMT as a function of temperature is shown in Figure 2-5. For example, if power demand from HVAC at 75 °F is 1 kW and 9.3 percent of HD VMT percent occurs at 75 °F, then the VMT-weighted energy demand is equal to 0.093 kW. Once multiplied, we summed the values that are less than 55 °F and divided by the percent VMT for temperatures below 55 °F. However, for the final rule analysis, considering Figure 2-4 and Figure 2-5, HVAC loads are the highest for temperatures less than 55 °F and for greater than 75 °F, so we made an adjustment to HD TRUCS to reflect a wider range of cooling temperatures (as compared to the proposed greater than 80 °F). This creates three separate bins - one for heating (<55 °F), one for cooling (>75 °F), and one for a temperature range that requires only ventilation (55-75 °F), so we simplified the temperature bins further in HD TRUCS to only include three bins (<55 °F, 55–75 °F, >75 °F). The results of the VMT-weighted HVAC power demand for a Class 8 Transit Bus for each of the HVAC temperature bins are shown in Table 2-39. In HD TRUCS, we already accounted for the energy loads due to ventilation in the axle loads, so no additional energy consumption is applied here for the ventilation-only operation. We then weighted the power demands by the percent HD VMT traveled at each specific temperature range, as shown in Table 2-40.

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[976] It should be noted that Basma model has discrete values in Celsius and MOVES data has discrete values in Fahrenheit. The Basma discrete values in the Basma model is fitted to a parabolic curve and converted into Fahrenheit to best fit the VMT distribution that is available in MOVES.

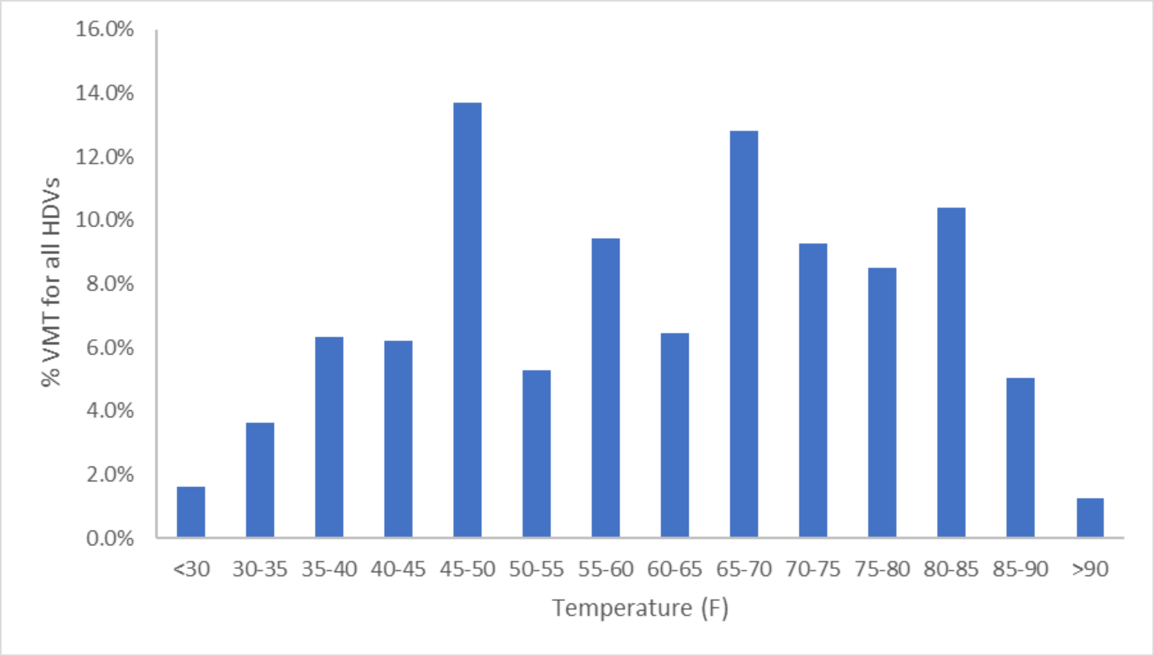

Figure 2-5 MOVES National VMT Distribution as a Function of Temperature for 2b-8 HD Vehicles

Table 2-39 HD TRUCS HVAC Power Consumption of a Class 8 Transit Bus

	Temperature (°F)	**Consumption (kW)**
Heating	<55	5.06
Ventilation	55-75	0.00
Cooling	>75	2.01

Table 2-40 Distribution of VMT for HD TRUCS Temperature Bins

Temperature Bins	**Heating <55 °F**	**55-75 °F**	**Cooling >75 °F**
% VMT	37%	16%	47%

HVAC load is dependent on cabin size—the larger the size of the cabin, the greater the HVAC demand. The values for HVAC power demand shown in Table 2-39 represent the power demand to heat or cool the interior of a Class 8 transit bus. However, HD vehicles have a range of cabin sizes; therefore, we developed scaling ratios relative to the cabin size of a Class 8 bus as derived from Equation 2-20 discussed in Chapter 2.8.5.1 with the results shown in Table 2-41. Each vehicle's scaling factor is based on the surface area of the vehicle compared to the surface area of the Class 8 bus. Cabin sizes for most HD vehicle types have a similar cabin to a mid-size light duty vehicle and therefore, an average scaling factor of 0.2 was applied to all of those vehicle types.[977] The buses and sleeper cab tractors have cabin sizes similar to the transit bus or

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[977] The interior cabin where the driver and passengers sit are heated while where the cargo is stored is not heated.

scaled down to reflect its cabin size. For example, a Class 4-5 shuttle bus has a cabin size ratio of 0.6; in this case, the heating demand for the vehicle will be 3.04 kW (equal to 5.06 kW multiplied by 0.6) and the cooling demand would be 1.21 kW (2.01 kW multiplied by 0.6).

Table 2-41 Vehicle Surface Area as a Function of a Class 8 Transit Bus Surface Area

Vehicle ID	Cabin Size ratio
01V_Amb_Cl4-5_MP	0.6
02V_Amb_Cl2b-3_MP	0.4
03V_Amb_Cl4-5_U	0.6
04V_Amb_Cl2b-3_U	0.4
05T_Box_Cl8_MP	0.2
06T_Box_Cl8_R	0.2
07T_Box_Cl6-7_MP	0.2
08T_Box_Cl6-7_R	0.2
09T_Box_Cl8_U	0.2
10T_Box_Cl6-7_U	0.2
11T_Box_Cl2b-3_U	0.2
12T_Box_Cl2b-3_R	0.2
13T_Box_Cl2b-3_MP	0.2
14T_Box_Cl4-5_U	0.2
15T_Box_Cl4-5_R	0.2
16T_Box_Cl4-5_MP	0.2
17B_Coach_Cl8_R	1.0
18B_Coach_Cl8_MP	1.0
19C_Mix_Cl8_MP	0.2
20T_Dump_Cl8_U	0.2
21T_Dump_Cl8_MP	0.2
22T_Dump_Cl6-7_MP	0.2
23T_Dump_Cl8_U	0.2
24T_Dump_Cl6-7_U	0.2
25T_Fire_Cl8_MP	0.2
26T_Fire_Cl8_U	0.2
27T_Flat_Cl6-7_MP	0.2
28T_Flat_Cl6-7_R	0.2
29T_Flat_Cl6-7_U	0.2
30Tractor_DC_Cl8_MP	0.2
31Tractor_DC_Cl6-7_MP	0.2
32Tractor_SC_Cl8_U	0.3
33Tractor_DC_Cl8_U	0.2
34T_Ref_Cl8_MP	0.2
35T_Ref_Cl6-7_MP	0.2
36T_Ref_Cl8_U	0.2
37T_Ref_Cl6-7_U	0.2
38RV_Cl8_R	0.2
39RV_Cl6-7_R	0.2
40RV_Cl4-5_R	0.2
41Tractor_DC_Cl7_R	0.2
42RV_Cl8_MP	0.2
43RV_Cl6-7_MP	0.2
44RV_Cl4-5_MP	0.2
45Tractor_DC_Cl8_R	0.2
46B_School_Cl8_MP	1.0
47B_School_Cl6-7_MP	0.7

Vehicle ID	Cabin Size ratio
48B_School_Cl4-5_MP	0.6
49B_School_Cl2b-3_MP	0.4
50B_School_Cl8_U	0.7
51B_School_Cl6-7_U	0.7
52B_School_Cl4-5_U	0.6
53B_School_Cl2b-3_U	0.4
54Tractor_SC_Cl8_R	0.3
55B_Shuttle_Cl2b-3_MP	0.4
56B_Shuttle_Cl4-5_U	0.6
57B_Shuttle_Cl2b-3_U	0.4
58B_Shuttle_Cl6-7_MP	0.7
59B_Shuttle_Cl6-7_U	0.7
60S_Plow_Cl6-7_MP	0.2
61S_Plow_Cl8_MP	0.2
62S_Plow_Cl6-7_U	0.2
63S_Plow_Cl8_U	0.2
64V_Step_Cl6-7_MP	0.2
65V_Step_Cl4-5_MP	0.2
66V_Step_Cl2b-3_MP	0.2
67V_Step_Cl6-7_U	0.2
68V_Step_Cl4-5_U	0.2
69V_Step_Cl2b-3_U	0.2
70S_Sweep_Cl6-7_U	0.2
71T_Tanker_Cl8_R	0.2
72T_Tanker_Cl8_MP	0.2
73T_Tanker_Cl8_U	0.2
74T_Tow_Cl8_R	0.2
75T_Tow_Cl6-7_R	0.2
76T_Tow_Cl8_U	0.2
77T_Tow_Cl6-7_U	0.2
78Tractor_SC_Cl8_MP	0.3
79Tractor_SC_Cl8_R	0.3
80Tractor_DC_Cl8_HH	0.2
81Tractor_DC_Cl7_R	0.2
82Tractor_DC_Cl8_R	0.2
83Tractor_DC_Cl7_U	0.2
84Tractor_DC_Cl8_U	0.2
85B_Transit_Cl8_MP	0.7
86B_Transit_Cl6-7_MP	0.7
87B_Transit_Cl8_U	0.7
88B_Transit_Cl6-7_U	0.7
89T_Utility_Cl8_MP	0.2
90T_Utility_Cl8_R	0.2
91T_Utility_Cl6-7_MP	0.2
92T_Utility_Cl6-7_R	0.2
93T_Utility_Cl4-5_MP	0.2
94T_Utility_Cl2b-3_MP	0.2
95T_Utility_Cl4-5_R	0.2
96T_Utility_Cl2b-3_R	0.2
97T_Utility_Cl8_U	0.2
98T_Utility_Cl6-7_U	0.2
99T_Utility_Cl4-5_U	0.2

Vehicle ID	Cabin Size ratio
100T_Utility_Cl2b-3_U	0.2
101Tractor_DC_Cl8_U	0.2

2.4.1.1.2 Effects of Temperature on the Battery

Battery range and life can be impacted by ambient temperatures, as described in Chapter 1. Therefore, BEVs have thermal management systems to maintain battery core temperatures within an optimal range of approximately 68 to 95 degrees Fahrenheit (F) (20 to 35 degrees Celsius).[978] Since BEVs may not have an additional energy source beyond what is stored inside the battery, some stored energy in the battery is used to maintain a constant battery temperature. The Basma et al. report discusses the battery conditioning power requirements at various temperatures. Figure 2-6, based on Basma et. al, shows the power demand for battery conditioning as a function of ambient temperature.[979]

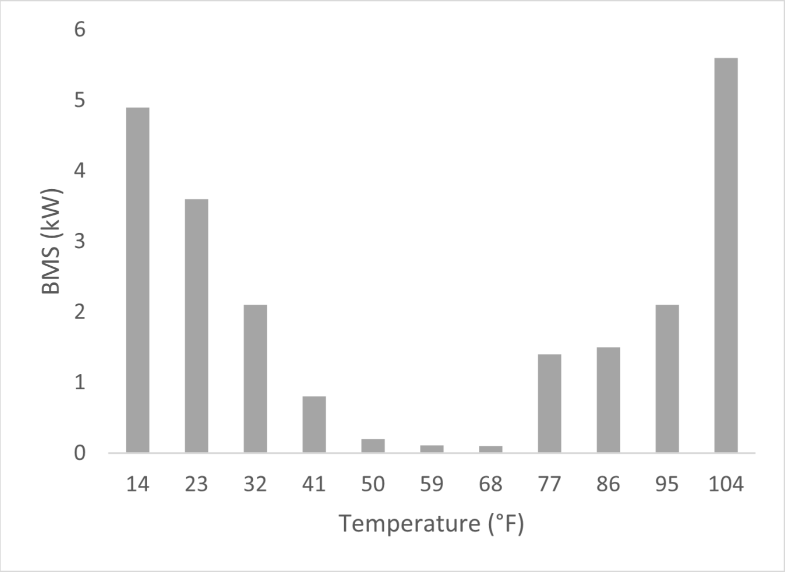

Figure 2-6 Modeled Power Demand for Battery Conditioning for Class 8 Transit Bus with a 300 kWh Battery

For this we determined the energy consumed to maintain a constant battery temperature for ambient temperature ranges presented in the Basma et. al paper as well as the HD VMT distribution by temperature in MOVES Similar to the methods used for HVAC in RIA Chapter 2.4.1.1.1, we determined the VMT-weighted battery conditioning loads associated with requirements to heat the battery in cold operating temperatures (below 55 °F) and cool the battery during operations in warm temperatures (over 75 °F for the final version of HD TRUCS). For the ambient temperatures between these two regimes, we agreed with Basma, et. al that only ambient air cooling is required for the batteries, which requires no additional load. We

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[978] Ibid.

[979] Basma, Hussein, Charbel Mansour, Marc Haddad, Maroun Nemer, Pascal Stabat. “Comprehensive energy modeling methodology for battery electric buses”. Energy: Volume 207, 15 September 2020, 118241. Available online: https://www.sciencedirect.com/science/article/pii/S0360544220313487.

determined a VMT-weighted power consumption value for battery heating and cooling based on the MOVES HD VMT distribution. Then, we determined the energy required for battery conditioning required for eight hours of daily operation and expressed it in terms of percent of total battery size. Table 2-42 shows the energy consumption for battery conditioning for both hot and cold ambient temperatures, expressed as a percentage of battery capacity, used in HD TRUCS. Some commenters noted heavy-duty vehicles operate in temperatures less than 30 °F, and we recognize heavy-duty vehicles are used in extreme temperatures. The battery heating energy needs shown in Table 2-42 are weighted using the MOVES HD VMT distribution as a function of temperature shown in Figure 2-5, which accounts for operation at temperature less than 30°F.Our assessment is that the battery heating requirements for operations under 30 °F would require approximately 10% of the battery energy consumption and therefore the daily operating VMT could still be met for the BEVs. Furthermore, during the timeframe of this final rule ICE vehicles will be available and could also be used in those circumstances.

Table 2-42 VMT Weighted Battery Conditioning Energy Consumption

	Ambient Temperature (°F)	Energy Consumption (%)
Battery Heating	<55	1.9%
Battery Cooling	>75	3.0%

2.4.1.1.3 Determining BEV Battery Size

In HD TRUCS, the ZEV baseline energy, HVAC, and battery conditioning demands are summed for one operational day. The HVAC and battery conditioning demands are added using a weighted average of these demands by the temperature bins in Table 2-40. These values are used to determine BEV battery size.

We determined the axle energy required to move the vehicle over its drive cycle at the specified payload, as described in RIA Chapter 2.2.2.1. Then, to determine the energy required at the battery, we account for losses in the inverter, gearbox, and electric motor (e-motor). These losses for the inverter, gearbox, and e-motor are calculated using loss maps of each component.[980,981] Table 2-43 includes a summary of the data used for the analysis. As outlined in Table 2-43, we evaluated different components for Light and Medium HDVs (iDM HVH250-115 and iDM 190) than for Heavy HDVs (HVH320-216 and the 3 Speed BorgWarner gear box). This was because the iDM HVH250-115 and iDM 190 are representative of an e-motor and gearbox that would be installed in a Class 5 vehicle, and HVH320-216 and the 3 Speed BorgWarner gear box are representative of components that would be installed in a Class 8 tractor. Since we did not have data for each of the 101 vehicle IDs in HD TRUCS, vehicle data from representative Vehicle IDs was used to determine system efficiency for each GEM duty cycle and then we weighted the efficiency for each duty cycle based on the specific weighting factors for each regulatory subcategory.

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[980] The loss maps for the inverter, gearbox, and e-motor were provided to the agency as claimed confidential business information from BorgWarner. We examined the loss maps carefully and find the information reliable.

[981] Sanchez, James. Memorandum to Docket EPA-HQ-OAR-2022-0985. “Estimating Electric Powertrain Efficiency with CBI Data Provided by BorgWarner” February 28, 2024.

Table 2-43 Summary of Inverter, Gearbox, and E-motor Data Used for Each Vehicle ID

Vehicle ID Data was used for	Light Heavy and Medium Heavy Vocational Vehicles	Heavy Heavy Vocational Vehicles and Tractors
E-motor	iDM HVH250-115	HVH320-216
Gearbox	iDM 190	3 speed BorgWarner
Inverter technology	Silicon Carbide	Silicon Carbide
GEM Energy ID	16T_Box_CI4-5_MP	78Tractor_SC_Cl8_MP

To determine the efficiency for each component, the loss maps were interpolated for each duty cycle based on the axle speed and torque. The axle speed and torque were determined using the vehicle parameters for GEM vehicle ID 16 and 78 as show in Table 2-43. For the inverter, we used a silicon carbide (SiC) based inverter for both sets of vehicles. For the heavy heavy-duty vocational and tractors this was done by using a loss map from a SiC inverter. For the light and medium heavy-duty vocational vehicles, the provided data was from a silicon (Si) based inverter, so we modified the efficiency of the inverter to be representative of a SiC based inverter. This was done using data from a mid-size SUV where we had loss maps for both Si and SiC based inverters. The absolute efficiency improvement for the SiC versus the Si inverter was 4 percent, 0.5 percent, and 0.5 percent for the transient, 55mph cruise, and 65mph cruise cycles. The absolute efficiencies were then added to the efficiencies of the Class 5 Si based inverter. The combined efficiency values of the components are shown in Table 2-44.

Table 2-44 Combined Inverter, Gearbox, and E-motor Efficiency for each GEM Energy ID

GEM Energy ID	Combined inverter, gearbox, and e-motor efficiency
C7_DC_HR	91%
C8_DC_HR	91%
C8_HH	91%
C8_SC_HR	93%
C8_SC_HR_CdA036	93%
C8_DC_HR_CdA036	91%
HHD_R	91%
HHD_M	88%
HHD_U	84%
MHD_R	89%
MHD_M	86%
MHD_U	83%
LHD_R	89%
LHD_M	86%
LHD_U	83%
RV	89%
School Bus	83%
Coach Bus	91%
Emergency	84%
Concrete Mixer	84%
Transit Bus	84%
Refuse Truck	84%

When sizing the battery, we also accounted for the battery depth of discharge, or the amount of charge or discharge level during a charge or discharging cycle, and battery deterioration over time. We received numerous comments about limiting depth of discharge to 80 percent as well as 20 percent extra battery capacity to account for battery deterioration over time, as described in RTC Section 3.3.3. Some of these commenters said we should reduce or remove the additional 20 percent of extra battery capacity for degradation and the 80 percent depth of discharge. Others pointed out that batteries degrade over time and will reduce in capacity, up to 3 percent annual capacity loss.

One commenter cited a February 2022 Roush report on the electrification of tractors where Roush had set the depth of discharge to 90 percent and a 10 percent battery degradation value and suggested using those values. They also pointed out that the decrease in VMT over time used in the proposal’s version of HD TRUCS for calculating operating costs meets or exceeds the 20 percent reduction in battery capacity over that same time. They argued that the decrease in VMT already accounts for 20 percent battery deterioration and that it should not be included, or that EPA should adopt the 10 percent value that Roush used in their report. Another commenter questioned the source for a 20 percent battery capacity fade. They agreed that batteries will degrade over time but stated that data is scarce for HD applications and that recent developments in battery technology have resulted in prolonged battery life with long-distance BEVs reaching over 900,000 miles. Another commenter stated that the additional 20 percent battery sizing for deterioration was an overly conservative estimate and that fleets would adjust the mileage and routes used for a vehicle over time as they currently do with ICE vehicles from the secondary market. They stated that fleets would not pay for the additional unused battery capacity. This commenter also raised concerns about using an 80 percent depth of discharge value saying that it would be more appropriate to model battery usage and mileage based on capacity fade and citing a demonstration by Yang et al. and Dunn et al. Another commenter stated that oversizing the battery harms the projected rate of BEV adoption due to increased costs attributable to the extra battery capacity. Relatedly, a few commenters raised concerns about the cost of replacing a vehicle battery. They stated that is a very large cost that should be accounted for.

After considering these comments, and further supported by the depth of discharge window value used in the 2022 Autonomie tool from ANL, we revised the battery depth of discharge window to 90 percent in HD TRUCS.[982,983] We separately address the battery deterioration as discussed in the following subsection.

2.4.1.1.4 Battery Cycling and Deterioration Addition

As at proposal, we continue to account for battery deterioration in our analysis. However, after consideration of comments, including comments that the proposal was overly conservative and other comments that EPA had failed to account for battery replacement, we updated our methodology to do so. Rather than oversize the battery (analytically) by a constant factor of 20% as at proposal (see DRIA at p. 165), in the final rule, we determined the battery deterioration factor for each of the 101 vehicle applications based on the number of charging cycles the battery would require during its first ten years of operation. Ten years represents the longest payback period we consider for the technologies in our HD TRUCS analysis for MYs 2027-2032.

To better assess the number of cycles a battery will go through in a 10-year time frame, we modeled the number of charge and discharge cycles in HD TRUCS, based on the operating VMT. Here, a single full cycle is considered to be when a battery is completely discharged of energy and fully recharged of energy. Since the daily use of energy is less than the total amount of energy stored in the battery, one full cycle can be extended to more than one day. Annual number of cycles is computed using the number of cycles per day and the number of operating days.

For example, a battery with an operating VMT of 50 miles and operating energy consumption of 2 kWh/mi will use 100 kWh per day. If the battery has a usable energy of 200 kWh, this battery will go through half a cycle per day or one full cycle every two days. For this example, the annual number of cycles would be 125 cycles using 250 operating days in year one of operation.

The cumulative number of cycles is then summed over 10 years using this same method. Since the operating VMT changes each year based on the MOVES schedule for each source type ID as described in RIA Chapter 2.2.1.2.3, the annual number of cycles will change each year.

We selected 2,000 cycles as our number of cycles target at 10 years of age while recognizing this value depends on a number of internal and external parameters including battery chemistry, the discharge window while cycling, power output of the battery, and how the battery is

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[982] In the "Battery" tab, we calculated the difference between the "SOC Max" and "SOC Min" columns for BEVs and chose the lowest depth of discharge as a conservative value.

[983] Argonne National Laboratory. VTO HFTO Analysis Reports – 2022. "ANL – ESD-2206 Report – MD HD Truck – Autonomie Assumptions.xlsx". Available online: https://anl.app.box.com/s/an4nx0v2xpudxtpsnkhd5peimzu4j1hk/folder/242640145714.

managed while in and not in use. A study shows LFP batteries can maintain 80 to 95 percent state of charge at 3,000 cycles and NMC batteries can retain 80 percent state of charge at 2,000 cycles under some test conditions.[984,985] c Using this method for the final version of HD TRUCS, there is not a need for battery replacement during the first 10 years of vehicle operation, which would otherwise be an additional cost. We note that only eight vehicles of the 101 in HD TRUCS required a 15 percent increase in battery size to meet the 2,000-cycle limit over a 10-year period. Most of the 101 vehicle types would experience less than 1,500 cycles over the 10-year period.

Outside of HD TRUCS, we accounted for the cost of battery replacements (and parallel engine rebuilding costs for ICE vehicles) in the program cost analysis as a purchaser cost, as discussed in RIA Chapter 3.4.6.5.

2.4.1.2 E-Motor Sizing Based on Power Needs

The electric motor (e-motor) is part of the electric drive system that converts the electric power from the battery or fuel cell into mechanical or motive power to move the wheels of the vehicle. In the case of a BEV, there are losses associated with converting current and voltage output from the electric motor into mechanical power at any given time. The e-motor is sized to meet the peak power requirements of each vehicle in HD TRUCS.

BEVs operate at peak power to accelerate up to a driving speed and to climb steep inclines at a reasonable pace. Peak power requirements are important to ensure that BEVs can match the speed-related performance of comparable ICE vehicles. Peak power is the maximum power required to perform the work of an HD vehicle. To estimate peak power needs to size the e-motor, we used the maximum power among the peak power requirement generated from the following performance targets: the peak required during the ARB transient cycle[986] and performance targets included in ANL's 2021 Autonomie model[987] (see "0-30mph", "0-60mph" in the Performance Sizing tab) and in Islam et al[988] (for 6 percent Grade Speed), as indicated in Table 2-45. We assigned the target maximum time to accelerate a vehicle from stop to 30 mph and 60 mph based on weight class of each vehicle. We also used the criteria that the vehicle must

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[984] Preger, Yuliya, et. al. "Degradation of Commercial Lithium-Ion Cells as a Function of Chemistry and Cycling Conditions". Journal of The Electrochemical Society. September 2, 2020. Available online: https://iopscience.iop.org/article/10.1149/1945-7111/abae37.

[985] Tankou, Alexander, Georg Bieker, and Dale Hall. "White Paper—Scaling Up Reuse and Recycling of Electric Vehicle Batteries: Assessing Challenges and Policy Approaches". International Council on Clean Transportation. February 2023. Available online: https://theicct.org/wp-content/uploads/2023/02/recycling-electric-vehicle-batteries-feb-23.pdf.

[986] EPA uses three representative duty cycles for calculating Carbon Dioxide (CO_2) emissions in GEM: transient cycle and two highway cruise cycles. The ARB transient duty cycle was developed by the California Air Resources Board (CARB) and includes no grade—just stops and starts. The highway cruise duty cycles represent 55-mph and 65-mph vehicle speeds on a representative highway. They use the same drive cycle profile but at different vehicle speeds, along with a percent grade ranging from -5 percent to +5 percent.

[987] Argonne National Laboratory. VTO HFTO Analysis Reports – 2021. "ANL – ESD-2110 Report – BEAN Tool – Heavy Duty Vehicle Techno-Economic Analysis.xlsx". Available online: https://anl.app.box.com/s/an4nx0v2xpudxtpsnkhd5peimzu4j1hk/folder/177858439896.

[988] Islam, Ehsan Sabri, Ram Vijayagopal, Aymeric Rousseau. "A Comprehensive Simulation Study to Evaluate Future Vehicle Energy and Cost Reduction Potential", *Report to the U.S. Department of Energy, Contract ANL/ESD-22/6*, October 2022. Available online: https://anl.app.box.com/s/an4nx0v2xpudxtpsnkhd5peimzu4j1hk/file/1406494585829.

be able to maintain a specified cruise speed while traveling up a road with a 6 percent grade, as shown in Table 2-45. In the case of cruising at 6 percent grade, the road load calculation is set at a constant speed for each weight class bin on a hill with a 6 percent incline. We determined the required power rating of the motor as the greatest power required to drive the vehicle over the ARB transient test cycle, at 55 mph and 65 mph constant cruise speeds, or at constant speed at 6 percent grade, for all vehicles except sleeper cab and heavy haul tractors. For sleeper cabs, the motor size was determined to be 400 kW based on the comparable ICE sleeper cab tractor engine power and the continuous motor power of existing HD BEV tractors.[989] For heavy haul tractors, the BEV motor power is set at 450 kW to reflect the maximum engine power of a heavy heavy-duty engine.[990] The NPRM version of HD TRUCS included a motor efficiency loss; however, we have corrected this for the final rule, as motors are generally sold using their delivered power. Because HD TRUCS motor sizing is largely used to estimate the cost of motors, the application of an efficiency loss is not appropriate for purposes of estimating costs.

Table 2-45 ANL Performance Targets

	Vocational				**Tractors**	
Weight Class Bin	2b-3	4-5	6-7	8	7	8
0-30 mph Time (s)	7	8	16	20	18	20
0-60 mph Time (s)	25	25	50	100	60	100
Cruise Speed (mph) @ 6 % grade	65	55	45	25	35	25

Consistent with the NPRM, for the final version of HD TRUCS, we calculated the motor mass using a kg/kW factor derived from ANL's 2021 BEAN tool.[991] This factor is calculated from the "Autonomie Out Import" tab for MY 2027 by averaging the low and high results of Motor_1_kg divided by Motor_Peak_kW for BEV vehicles. This factor is then used in HD TRUCS by multiplying the factor by the HD TRUCS motor peak power, as shown in Table 2-38.

2.4.2 Battery Weight and Volume

Performance needs of a BEV could result in a battery that is so large or heavy that it negatively impacts payload and, thus, potential work accomplished relative to a comparable ICE vehicle. We determined the battery weight and physical volume for each vehicle application in HD TRUCS using the specific energy and energy density of the battery for each battery capacity. The resulting values for 101 HD TRUCS vehicle types are shown in Table 2-46 and the detailed descriptions for weight and volume determinations, as well as descriptions of specific energy (Wh/kg) and energy density (Wh/L), are described in RIA Chapters 2.4.2.1 and 2.4.2.2. Here, the battery size in kWh is converted into liters (L) and cubic meters (m^3) using the energy density of the battery. For further discussion on battery volume and the packaging assessments, see RIA Chapter 2.9.1.

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[989] Peterbilt. 579EV. Available online: https://www.peterbilt.com/trucks/electric/579EV.

[990] Detroit Diesel Engines. Available online: https://www.demanddetroit.com/engines/dd16/.

[991] Argonne National Laboratory. VTO HFTO Analysis Reports – 2021. "ANL – ESD-2110 Report – BEAN Tool – Heavy Duty Vehicle Techno-Economic Analyisis". Available online: https://anl.app.box.com/s/an4nx0v2xpudxtpsnkhd5peimzu4j1hk/folder/177858439896.

Table 2-46 Battery Size, Weight, and Volume in HD TRUCS

Vehicle ID	Battery Size (kWh)	Battery Weight (kg)	Battery Volume (m^3)
01V_Amb_Cl4-5_MP	120	604	0.30
02V_Amb_Cl2b-3_MP	113	570	0.28
03V_Amb_Cl4-5_U	111	563	0.28
04V_Amb_Cl2b-3_U	104	528	0.26
05T_Box_Cl8_MP	244	1231	0.62
06T_Box_Cl8_R	252	1272	0.64
07T_Box_Cl6-7_MP	168	850	0.42
08T_Box_Cl6-7_R	183	924	0.46
09T_Box_Cl8_U	236	1193	0.60
10T_Box_Cl6-7_U	162	819	0.41
11T_Box_Cl2b-3_U	100	505	0.25
12T_Box_Cl2b-3_R	118	596	0.30
13T_Box_Cl2b-3_MP	109	548	0.27
14T_Box_Cl4-5_U	100	505	0.25
15T_Box_Cl4-5_R	118	596	0.30
16T_Box_Cl4-5_MP	109	548	0.27
17B_Coach_Cl8_R	710	3588	1.79
19C_Mix_Cl8_MP	428	2160	1.08
20T_Dump_Cl8_U	283	1427	0.71
21T_Dump_Cl8_MP	286	1446	0.72
22T_Dump_Cl6-7_MP	277	1400	0.70
23T_Dump_Cl8_U	283	1427	0.71
24T_Dump_Cl6-7_U	259	1310	0.66
25T_Fire_Cl8_MP	300	1518	0.76
26T_Fire_Cl8_U	301	1521	0.76
27T_Flat_Cl6-7_MP	168	850	0.42
28T_Flat_Cl6-7_R	183	924	0.46
29T_Flat_Cl6-7_U	155	784	0.39
30Tractor_DC_Cl8	351	1773	0.89
31Tractor_DC_Cl7	317	1603	0.80
32Tractor_SC_Cl8	973	4914	2.46
33Tractor_DC_Cl8	531	2682	1.34
34T_Ref_Cl8_MP	355	1791	0.90
35T_Ref_Cl6-7_MP	290	1462	0.73
36T_Ref_Cl8_U	355	1791	0.90
37T_Ref_Cl6-7_U	286	1443	0.72
38RV_Cl8_R	564	2847	1.42
39RV_Cl6-7_R	599	3027	1.51
40RV_Cl4-5_R	381	1926	0.96
42RV_Cl8_MP	564	2847	1.42
43RV_Cl6-7_MP	550	2775	1.39
44RV_Cl4-5_MP	350	1765	0.88
46B_School_Cl8_MP	266	1345	0.67
47B_School_Cl6-7_MP	160	810	0.41
48B_School_Cl4-5_MP	120	604	0.30
49B_School_Cl2b-3_MP	113	570	0.28
50B_School_Cl8_U	252	1274	0.64
51B_School_Cl6-7_U	160	810	0.41
52B_School_Cl4-5_U	111	563	0.28
53B_School_Cl2b-3_U	104	528	0.26

Vehicle ID	Battery Size (kWh)	Battery Weight (kg)	Battery Volume (m^3)
54Tractor_SC_Cl8	1164	5877	2.94
55B_Shuttle_Cl2b-3_MP	164	829	0.41
56B_Shuttle_Cl4-5_U	158	799	0.40
57B_Shuttle_Cl2b-3_U	151	764	0.38
58B_Shuttle_Cl6-7_MP	264	1332	0.67
59B_Shuttle_Cl6-7_U	245	1236	0.62
60S_Plow_Cl6-7_MP	199	1007	0.50
61S_Plow_Cl8_MP	394	1991	1.00
62S_Plow_Cl6-7_U	187	943	0.47
63S_Plow_Cl8_U	388	1957	0.98
64V_Step_Cl6-7_MP	169	856	0.43
65V_Step_Cl4-5_MP	109	548	0.27
66V_Step_Cl2b-3_MP	109	548	0.27
67V_Step_Cl6-7_U	156	790	0.39
68V_Step_Cl4-5_U	100	505	0.25
69V_Step_Cl2b-3_U	100	505	0.25
70S_Sweep_Cl6-7_U	182	919	0.46
71T_Tanker_Cl8_R	269	1361	0.68
72T_Tanker_Cl8_MP	264	1336	0.67
73T_Tanker_Cl8_U	263	1329	0.66
74T_Tow_Cl8_R	413	2086	1.04
75T_Tow_Cl6-7_R	300	1518	0.76
76T_Tow_Cl8_U	400	2019	1.01
77T_Tow_Cl6-7_U	261	1316	0.66
78Tractor_SC_Cl8	834	4211	2.11
80Tractor_DC_Cl8	647	3267	1.63
81Tractor_DC_Cl7	531	2682	1.34
82Tractor_DC_Cl8	635	3207	1.60
83Tractor_DC_Cl7	459	2319	1.16
84Tractor_DC_Cl8	356	1799	0.90
85B_Transit_Cl8_MP	472	2383	1.19
86B_Transit_Cl6-7_MP	373	1882	0.94
87B_Transit_Cl8_U	472	2383	1.19
88B_Transit_Cl6-7_U	341	1724	0.86
89T_Utility_Cl8_MP	254	1285	0.64
90T_Utility_Cl8_R	261	1318	0.66
91T_Utility_Cl6-7_MP	184	931	0.47
92T_Utility_Cl6-7_R	198	1001	0.50
93T_Utility_Cl4-5_MP	120	606	0.30
94T_Utility_Cl2b-3_MP	114	575	0.29
95T_Utility_Cl4-5_R	128	647	0.32
96T_Utility_Cl2b-3_R	128	647	0.32
97T_Utility_Cl8_U	250	1263	0.63
98T_Utility_Cl6-7_U	174	877	0.44
99T_Utility_Cl4-5_U	113	571	0.29
100T_Utility_Cl2b-3_U	106	535	0.27
101Tractor_DC_Cl8	279	1411	0.71

2.4.2.1 Battery Weight

Battery specific energy (also referred to as gravimetric energy density) is a measure of battery energy per unit of mass (e.g., watt-hours or Wh per kg). While there have been tremendous advancements in battery chemistries, materials, and pack design in recent years, current ZEV batteries add mass to the vehicle. Battery specific energy is expected to continue to improve as next generation battery technologies are developed.[992]

To determine the weight impact, we used the specific energy of battery packs with lithium-ion cell chemistries. For the final rule, instead of relying on the 2021 version of Autonomie as we did at proposal,[993] we utilized energy density values from DOE as provided by a recent comprehensive ANL study.[994] This ANL study aligns with our analysis requirements as it covers the period of 2023 – 2035. The results are in line with studies previously reviewed and are given merit due to DOE/ANL expertise. The study applies the Argonne National Laboratory's Battery Performance and Cost (BatPaC) model. Prior to establishing this direction, we reviewed the specific energy of the battery based on consideration of the comments received on the proposal and ANL BEAN values. ANL's 2022 BEAN tool includes values of 216 Wh/kg for the "low" technology scenario and 267 Wh/kg for the "high" technology scenario in 2027 (interpolated from 2025 and 2030 values).[995] For a complete discussion of information provided by commenters on battery specific energy, see RTC Section 3.2.3.

We calculated the pack specific energy of 2027 batteries by using the correlation provided by ANL in their January 2024 report.[996] The constants provided by ANL for NiMn and LFP battery packs were applied, using the 2027 values. Since specific energy is a function of the total battery energy required, the specific energy was calculated for battery energy ranging from 50 to 1200 kWh to cover the probable range for HD BEV battery sizes (pack energy). The corresponding pack specific energy is 217 to 236 Wh/kg for NiMn and 164 to 177 Wh/kg for LFP.[997] Since our minimum pack size is 100 kWh (per HD TRUCS analysis), and the specific energy changes little (4%) for both battery types as energy is increased from 100 to 1200 kWh, the value at 100 kWh was chosen, as a conservative estimate. As with battery cost, a 50/50 mix of NiMn and LFP batteries are applied. With 100 kWh NiMn batteries at 226 Wh/kg and LFP at 170 Wh/kg, the resulting value, used in our analysis, is 198 Wh/kg.

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[992] Mitchell, George. Memorandum to docket EPA-HQ-OAR-2022-0985. " ACT Research Co. LLC. "Charging Forward" 2020-2040 BEV & FCEV Forecast & Analysis, updated December 2021.

[993] Argonne National Laboratory. VTO HFTO Analysis Reports – 2021. "ANL – ESD-2110 Report – MD HD Truck – Autonomie Assumptions.xlsm". Available online: https://anl.app.box.com/s/an4nx0v2xpudxtpsnkhd5peimzu4j1hk/folder/177858439896.

[994] Kevin Knehr, Joseph Kubal, Shabbir Ahmed, "Cost Analysis and Projections for U.S.-Manufactured Automotive Lithium-ion Batteries", Argonne National Laboratory report ANL/CSE-24/1 for US Department of Energy. January 2024. Available online: https://www.osti.gov/biblio/2280913.

[995] Argonne National Laboratory. VTO HFTO Analysis Reports – 2022. "ANL – ESD-2206 Report – BEAN Tool – MD HD Vehicle Techno-Economic Analysis.xlsm". Available online: https://anl.app.box.com/s/an4nx0v2xpudxtpsnkhd5peimzu4j1hk/folder/242640145714.

[996] Kner, Kevin et al. "Cost Analysis and Projections for U.S.-Manufactured Automotive Lithium-ion Batteries", Argonne National Laboratory report ANL/CSE-24/1 for US Department of Energy. January 2024. Available online: https://www.osti.gov/biblio/2280913

[997] Ibid.

Table 2-47 Pack Energy Density[998]

	2027 Pack Energy Density (Wh/kg)		
Pack Energy (kWh)	NiMn	LFP	Average
50	217	164	190
100	226	170	198
150	230	173	201
200	231	174	202
1200	236	177	206

Although the ANL study suggests increasing battery specific energy over time, we maintained the 2027 value in our analysis as a conservative technology assumption in case manufacturers choose to focus on cost reductions rather than improved energy density.

We recognize that there likely will be improvements made between 2027 and 2032, as predicted by ANL. It is difficult to determine if the degree of improvements during that time will be as rapid as between 2020 and 2027, especially considering that manufacturers will have to balance the cost of additional weight reduction and overall costs of the BEV. Therefore, for the final rule we reasonably, and arguably conservatively, held the battery specific energy constant for MYs 2027 through 2032.

For additional discussion on the impact of battery weight see RIA Chapter 2.9.1.1.

2.4.2.2 Battery Volume

To evaluate battery volume and determine the packaging space required for each HD vehicle type, we used battery energy density. In the proposal, we also estimated the battery's width using the wheelbase and frame depths.

Battery energy density (also referred to as volumetric energy density) is a measure of battery energy per unit of volume, (e.g., Wh/L). This value was not available as a part of the Autonomie, nor did we find many projections for battery pack-level specific energy or energy density specifically for heavy-duty vehicles in the literature. For the foreseeable future, battery packs likely will consist of numerous battery cells where the pack-level energies are lower than that of the cell-level energies because of added mass or volume from the creation of the module or pack.

In response to our request for data in the NPRM, one commenter provided data from a study that included battery properties of specific energy and energy density. For more details on the comment and our response, see RTC Section 3.2.3. The average energy density calculated from the data provided was 2.2.

For the final rule, we used a ratio of 2.0 as a conservative estimate because the properties cited by the initial commenter discussed here are on a cell level, not a pack level. Based on our update to battery pack specific energy, we used an energy density value of 396 Wh/L for MYs 2027 through 2032 in HD TRUCS.

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[998] Ibid.

Battery volume for each vehicle type in each model year is calculated by dividing the battery size (kWh) by the energy density as shown in Table 2-46. For additional discussion on battery packaging, see RIA Chapter 2.9.1.2.

2.4.3 BEV Component Costs

A BEV powertrain system has different components than an ICE powertrain system. To account for differences in powertrain system costs between BEVs and ICEs, we considered the following HD BEV powertrain systems in HD TRUCS: battery, electric motor, inverter, converter, onboard charger, power converter and electric accessories, transmission or gearbox, and final drive.

Although there are many components in a BEV, two components play an outsized role in the cost of the BEV: the battery and the motor. The cost of these components varies depending on the size of these components which is determined by the requirements of the HD BEV; the sizing aspect of these components are explained in RIA Chapter 2.4.1. The remaining components, including the power converter and electric accessories, gearbox, and final drive impart some cost on the BEV total cost, but to a much lesser degree.

In HD TRUCS, BEV component DMC are generally estimated from literature values, as discussed in following sections, for MY 2027 and then extrapolated through MY 2032 using an EPA learning curve that is described in RIA Chapter 3.2.1.[999]

As described in RIA Chapter 1.3.2, the IRA provides a tax credit to reduce the cost of producing qualified batteries (battery tax credit) and to reduce the cost of purchasing qualified ZEVs (vehicle tax credit).[1000] The battery tax credit is considered in HD TRUCS before determining the total incremental cost, as described in RIA Chapter 2.4.3.1. The vehicle tax credit is considered after determining the total incremental cost (i.e., increase in purchase cost) of a BEV relative to a comparable ICE vehicle, effectively reducing the cost of the BEV for the purchaser. This vehicle tax credit does not affect the cost of BEVs for the manufacturers, as reflected in our accounting described in RIA Chapter 3. Please see RIA Chapter 2.4.3.5 for further discussion of this IRA vehicle tax credit.

2.4.3.1 EV Battery Cost

Battery costs are an important component of BEV costs. Battery costs are widely discussed in the literature because they are a key driver of the cost of a heavy-duty BEV. The per unit cost of the battery, in terms of $/kWh, is the most common metric in determining the cost of the battery as the final size of the battery may vary significantly between different applications. The total battery pack cost is a function of the per-unit-kWh cost and the size (in terms of kWh) of the battery pack.

We received many comments regarding the values we used for the battery costs in the NPRM, as well as comments regarding when and how learning should be applied in assessing those costs. Comments addressing battery cost projections advocated for costs both higher and lower

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[999] For the final rule, we updated the learning curve for BEV (and FCEV) final drive costs to be consistent with the ICE learning curve since we are basing final drive costs on a component that is similar to an ICE vehicle final drive.

[1000] Inflation Reduction Act of 2022, Pub. L. No. 117-169, 136 Stat. 1818 (2022), *available at* https://www.congress.gov/117/bills/hr5376/BILLS-117hr5376enr.pdf.

than the costs EPA used at proposal. Comments supporting higher (more expensive) values cited reasons including volatility in the minerals market, adjustment to rate of learning, inability to capture some or all of BIL and IRA incentives and pass those through to the vehicle purchaser, as well as general uncertainty within the sector. Commenters supporting lower values cited reasons including incentives from BIL and IRA, rapid development in the EV sector including the light-duty market, cheaper chemistries including LFP and sodium-ion batteries, and (more) recent stabilization within the lithium market.

One industry commenter recommended that EPA use a figure roughly 26 percent greater than estimated at proposal: $183/kWh in MY 2027. Two industry commenters echoed these comments. Another industry commenter shared four CBI battery pack costs for 2029 under four scenarios; these scenarios include smaller and larger battery packs, and with low and high lithium raw material costs. Another commenter questioned EPA's reliance on the ICCT Working Paper 2022-09 value for battery pack cost given ICCT's caution about uncertainty within the market for this sector. This commenter further maintained that the ICCT Paper did not adequately explain or cite empirical support for averaging of the values, and that upper and lower bounds should be adopted instead.

Other commenters believe the battery costs used for the NPRM were too high. One of these commenters referenced a Roush report of HDV battery cost of $98/kWh in MY 2030 and $88/kWh in MY 2032 without IRA adjustment. Another of these commenters believes the battery used for HDV will be less conservative than the one modeled by EPA in terms of both specific energy and energy density, and that these inappropriately conservative parameters resulted in an overly high estimated battery pack price. Their estimates align with those of BloombergNEF projecting that battery cost will decline to $100/kWh by 2026 as a result of mineral price stabilization.[1001] Another of these commenters referenced an ICCT report where batteries would reach a cost of $120/kWh at the pack level by 2030 but did not produce a battery pack cost of their own.[1002]

For the final rule, we re-evaluated our values used for battery cost in MY 2027 based on consideration of comments provided by stakeholders, as well as additional studies provided by the FEV and the Department of Energy BatPaC model.

FEV conducted a technology and cost study for a variety of powertrains as applicable to Class 4, 5, 7, and 8 heavy-duty vehicles.[1003,1004] Powertrains included BEVs and FCEVs, in addition to other ICE technologies. Vehicles studied include Class 4-8 box trucks, step vans, buses, vocational vehicles, and tractors. FEV also costed three (15L (Class 8), 10L (Class 7), 6.6L (Class 4/5)) diesel ICE powertrains that would meet the emission standards as required by the HD2027 Low NOx Rule and the Phase 2 CO_2 emission standards in MY 2027. These are used to calculate the incremental cost of the alternative powertrain to the current day powertrain. The

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[1001] BloombergNEF 2022 Lithium-Ion Battery Price Survey (subscription required).

[1002] Xie, Yihao, Hussein Basma, and Felipe Rodriguez, "Purchase Costs of Zero-Emission Trucks In The United States To Meet Future Phase 3 GHG Standards." International Council on Clean Transportation. March 2, 2023. Available online: https://theicct.org/publication/cost-zero-emission-trucks-us-phase-3-mar23/

[1003] FEV Consulting. "Heavy Duty Commercial Vehicles Class 4 to 8: Technology and Cost Evaluation for Electrified Powertrains—Final Report". Prepared for EPA. March 2024.

[1004] Daniels, Jessica and Alex Wang. Memorandum to Docket EPA-HQ-OAR-2022-0985. FEV Component Cost Estimates. March 2024.

direct manufacturing costs for the battery packs ranged between $128 and $143/kWh for MY 2027. We used an average value of $135.50/kWh as the representative cost projected by FEV.

To support the final rulemaking analysis, Argonne National Laboratory (ANL) conducted modeling of light, medium-, and heavy-duty battery costs using their BatPaC model.[1005] ANL conducted a detailed analysis of battery costs in which they utilized the current version of BatPaC to estimate future battery pack costs by taking into account mineral price forecasts from leading analyst firms, and a technology roadmap of production and chemistry improvements likely to occur over the time frame of the rule.

To update our estimate of current and future battery pack costs, we worked with the Department of Energy and Argonne National Laboratory to develop a year-by-year projection of battery costs from 2023 to 2035, using specific inputs that represent ANL's expert view of the current state-of-the-art and of the path of future battery chemistries and the battery manufacturing industry. By default, BatPaC estimates only a current-year battery production cost and does not support the specification of a future year for cost estimation purposes. However, some parameters can be modified within BatPaC to represent anticipated improvements in specific aspects of cell and pack production. For example, cell yield is controlled by an input parameter that can be modified to represent higher cell yields likely to result from learning-by-doing and improved manufacturing processes. ANL identified several parameters that could similarly represent future improvements. This allowed ANL to estimate future pack costs in each of several specific future years from 2023 to 2035, allowing cost trends over time to be characterized by a mathematical regression.

A major element of the approach was to select BatPaC input parameters to reflect current and future technology advances and calculate the cost of batteries for different classes of vehicles at their anticipated production volumes. Material cost inputs to the BatPaC simulations were based on forecasted material prices by Benchmark Mineral Intelligence. That is, pack costs were estimated from current and anticipated future battery materials, cell and pack design parameters, and market prices and vehicle penetration. Pack cost improvements in future years were represented at three levels: manufacturing (increasing cell yield and plant capacity), pack (reducing cell and module numbers and increasing cell capacity), and cell (changing active material compositions and increasing electrode thickness). The simulations yielded battery pack cost estimates that can be represented by correlations for model years 2023 to 2035.

The ANL battery cost explicitly represents the most recent trends and forecasts of future mineral costs and also are an outcome of basing the future costs on a specific set of technology pathways instead of applying a year-over-year cost reduction rate. Most other forecasts of future battery costs, including those that we cited in the proposal, are based largely on application of a historical year-over-year cost reduction rate (i.e., learning rate), without reference to the specific technology pathways that might lead to those cost reductions. ANL’s approach is consistent with that of the Mauler paper,[111] which also identified and modeled a specific set of technology pathways. EPA acknowledges one potential criticism of such an approach is that it may lead to conservative results, because it excludes the potential effect of currently unanticipated or highly uncertain developments that may nonetheless come to fruition. On the other hand, basing the

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[1005] Kevin Knehr, Joseph Kubal, Shabbir Ahmed, “Cost Analysis and Projections for U.S.-Manufactured Automotive Lithium-ion Batteries”, Argonne National Laboratory report ANL/CSE-24/1 for US Department of Energy. January 2024. Available online: https://www.osti.gov/biblio/2280913.

costs on specific high confidence pathways allows the basis of the projections to have greater transparency.

Accordingly, the ANL battery costs are responsive to many of the comments. First, the ANL work accounts more explicitly for the potential effect of critical mineral prices on the cost of batteries over time. We worked with ANL to make available medium- and long-term mineral price forecasts from Benchmark Mineral Intelligence, a leading minerals analysis firm. These were then used to estimate electrode material prices over the years of the ANL analysis. Second, as one outcome of this change, in the early years of the program, our battery cost inputs are now in closer agreement with the 2022 BNEF battery price survey, which commenters mentioned.

Additionally, the 5.1 version of BatPaC used in this analysis includes several significant feature updates that improve its ability to estimate pack manufacturing costs in realistic production scenarios. This version accounts for cell production volume and pack production volume separately, allowing economy of scale for cells and packs to be considered independently. This allows the analysis to use pack production volumes that are more representative of the annual production of a single pack design, while continuing to operate cell production at full plant capacity to provide cells for other product lines.

The ANL analysis provided EPA with several battery pack direct manufacturing costs as a function of model year and battery capacity (kWh), for both nickel-based (NMC) chemistry and iron-phosphate based (LFP) chemistry. We used a weighted average of ANL's costs for LFP and NMC batteries, with a 50/50 weighting. LFP is expected to increase in the future, due to its lower cost and absence of the critical minerals such as cobalt, manganese, and nickel. Our assessment is that on average the battery pack costs from the ANL study most representative of our average HD TRUCS vehicle types is an average of the heavy-duty 190, 220, and 250 kWh battery packs. Based on a linear interpolation of ANL's 2026 and 2030 costs, we used a value of $101.75 as the ANL battery pack direct manufacturing cost for MY 2027.[1006]

We considered a wide range of MY 2027 battery pack costs ranging from the $183/kWh cited by manufacturers in comments to $101.75/kWh projected in ANL's BatPaC model for HD battery packs for the final rule. In our analysis, we primarily relied on ANL's BatPaC model results. However, we also accounted for the data provided in comments and the recent FEV cost study. Based on our engineering judgement, we applied a weighting of 60% for the BatPac results in our assessment. We then attributed a 10% weighting to the FEV value of $135.50/kWh, 10% weighting to the EMA value of $183/kWh, 10% weighting of MFN's value of $148.74/kWh (converted from 2021$ supplied in comments to 2022$), and 10% weighting to a value of $123.42/kWh based on EDF's comment citing a study conducted by Roush (which provided a 2030 value of $106/kWh, which we back-learned using the learning scalars shown in RIA Chapter 3.2). Based on this assessment, we project a battery pack cost value for MY 2027 of $120/kWh (2022$).

We calculated MYs 2028–2032 battery costs using learning scalars as shown in RIA Chapter 3.2.1, resulting in the values shown in Table 2-48. Per-unit battery pack cost for each of the 101 vehicles can be seen in Table 2-57 through Table 2-59 for MYs 2027, 2030, and 2032, respectively.

[1006] Ibid. Appendix A1, Page 35.

Table 2-48 Pack-Level Battery Pack Direct Manufacturing Costs in HD TRUCS (2022$)

$/kWh	MY 2027	MY 2028	MY 2029	MY 2030	MY 2031	MY 2032
Battery Pack Cost	120	113	107	103	100	97

The battery pack cost estimates discussed thus far do not include the effect of tax credits available to battery manufacturers under the Inflation Reduction Act. As discussed in RIA Chapter 1.3.2, Section 13502 of the IRA[1007] (Section 45X of the Internal Revenue Code, or "45X") provides tax credits from CY 2023 through CY 2032 for the production and sale of battery cells and modules. These include the cell and module production tax credit of up to $45 per kWh available to manufacturers under 45X, and the additional tax credit for 10 percent of the production cost of (a) critical minerals and (b) electrode active materials available to manufacturers under 45X. The 45X credit provides a $35 per kWh tax credit for U.S. manufacture of battery cells, and an additional $10 per kWh for U.S. manufacture of battery modules. 45X also provides a credit equal to 10 percent of the manufacturing cost of electrode active materials and another 10 percent for the manufacturing cost of critical minerals if produced in the U.S. The credits phase out from 2030 to 2032 (with the exception of the 10 percent for critical minerals, which continues indefinitely).

In the proposal, EPA estimated potential future uptake of the IRA credits and how they would impact manufacturing costs for batteries over the time frame of the rule. In the proposal, we assumed that manufacturers would be able to take advantage of the full module credit in 2027 through 2032 and that the cell credit would ramp up from 25 percent of total cells in 2027 to 100 percent in 2030 through 2032. We requested comment on all aspects of our accounting for the IRA credits, including not only the values used for the credits but also whether or not we should also account for the additional 10 percent provisions for electrode active materials and critical mineral production, which we did not estimate for the proposal.

Comments received on our modeling of the 45X cell and module credit led us to further investigate our inputs for the phase-in schedule and average amount realized. Specifically, we received comment questioning the ability of U.S. battery manufacturing facilities currently planned or under construction to ramp up quickly enough; the lack of accounting for the 10 percent electrode active material and critical mineral credit; and the assumption that all of the value of the 45X credit would be realized as a cost reduction by OEMs when purchasing cells or packs from suppliers.

To address the comments related to the ramp up of battery manufacturing facilities, we worked with the Department of Energy and Argonne National Lab (ANL) to update our assessment of U.S. battery manufacturing facilities and to account for gradual ramp-up of these facilities over time. As discussed in preamble Section II.D.2.ii.c, the updated analysis projects that the currently planned U.S. battery cell manufacturing capacity is poised to meet projected U.S. demand during the time frame of the rule. For example, a new joint venture between Daimler Trucks, Cummins, and PACCAR recently announced a 21 GWh factory to be built in the U.S. to manufacture cells and packs initially focusing on lithium iron phosphate (LFP)

[1007] Inflation Reduction Act of 2022, Pub. L. No. 117-169, 136 Stat. 1818 (2022). Available online: https://www.congress.gov/117/bills/hr5376/BILLS-117hr5376enr.pdf.

batteries for heavy-duty and industrial applications.[1008] Tesla is expanding its facilities in Nevada to produce its Semi BEV tractor and battery cells,[1009] and Cummins has entered into an agreement with Arizona-based Sion Power to design and supply battery cells for commercial electric vehicle applications.[1010] In addition, DOE is funding through the BIL battery materials processing and manufacturing projects to "support new and expanded commercial-scale domestic facilities to process lithium, graphite and other battery materials, manufacture components, and demonstrate new approaches, including manufacturing components from recycled materials."[1011] See also Preamble Section II.D.2.ii.b and RTC section 17.2 documenting additional current and projected North American battery production, and discussing facility startup times as being within the timeframe of the Phase 3 rule.

We also received comment that the 10 percent credit for electrode active materials and critical minerals (CM) under 45X could be significant, and therefore should be included in the analysis. To investigate this possibility, we consulted with the Department of Energy and ANL to characterize the potential value of the 10 percent provisions of 45X on a dollar per kWh basis. ANL determined that the maximum value of the credits would change over time, as CM become a larger share of battery manufacturing cost due to efficiencies in other material and manufacturing costs.[1012] As shown in Table 2-49, the maximum value for the cathode active materials (CAM) credit, anode active materials (AAM) credit, CM credit, or the CAM, AAM, and CM credits combined would range from $0.60 to $8.40 per kWh in 2026 and decline to $0.40 to $6.20 per kWh in 2030, depending on chemistry. The decline is a result of ANL's projection that the amount (and hence manufacturing cost) of critical mineral content will decline over time due to improved cell chemistries for which minerals comprise a diminishing portion of total cost.

[1008] Daimler Trucks North America. "Accelera by Cummins, Daimler Truck and PACCAR form a joint venture to advance battery cell production in the United States." September 6, 2023. Available online: https://media.daimlertruck.com/marsMediaSite/en/instance/ko/Accelera-by-Cummins-Daimler-Truck-and-PACCAR-form-a-joint-venture-to-advance-battery-cell-production-in-the-United-States.xhtml?oid=52385590 (last accessed October 23, 2023).

[1009] Sriram, Akash, Aditya Soni, and Hyunjoo Jin. "Tesla plans $3.6 bln Nevada expansion to make Semi truck, battery cells." *Reuters*. January 25, 2023. Last accessed on March 31, 2023. Available online: https://www.reuters.com/markets/deals/tesla-invest-over-36-bln-nevada-build-two-new-factories-2023-01-24/

[1010] Sion Power. "Cummins Invests in Sion Power to Develop Licerion® Lithium Metal Battery Technology for Commercial Electric Vehicle Applications". November 30, 2021. Available online: https://sionpower.com/2021/cummins-invests-in-sion-power-to-develop-licerion-lithium-metal-battery-technology-for-commercial-electric-vehicle-applications/.

[1011] U.S. Department of Energy. "Bipartisan Infrastructure Law: Battery Materials Processing and Battery Manufacturing & Recycling Funding Opportunity Announcement—Factsheets". October 19, 2022. Available online: https://www.energy.gov/sites/default/files/2022-10/DOE%20BIL%20Battery%20FOA-2678%20Selectee%20Fact%20Sheets%20-%201_2.pdf.

[1012] Kevin Knehr, Joseph Kubal, Shabbir Ahmed, "Cost Analysis and Projections for U.S.-Manufactured Automotive Lithium-ion Batteries", Argonne National Laboratory report ANL/CSE-24/1 for US Department of Energy. January 2024. Available online: https://www.osti.gov/biblio/2280913.

Table 2-49 Potential value of 45X 10 percent CAM, AAM, and CM credits for a 75-kWh battery

	Ni/Mn			**LFP**		
	2026	2030	2035	2026	2030	2035
CAM only, $/kWh	4.4	2.9	-	2.2	1.5	-
AAM only, $/kWh	0.7	0.4	-	0.6	0.4	-
CM only, $/kWh	3.3	2.9	1.6	1.0	0.7	0.4
CAM + AAM + CM, $/kWh	8.4	6.2	1.6	3.9	2.6	0.4

While these tax credits will be significant to manufacturers that produce CAM and AAM in the U.S., their effect on average battery manufacturing cost across the fleet depends on the degree to which the average battery uses U.S.-produced CAM and AAM. ANL found that there are means for satisfying domestic AAM and CAM demand.[1013] Because of the uncertainty in predicting the degree of utilization across the industry, and the relatively small average value of the resulting credit, we have chosen to not include an estimate of the 10 percent credits in this analysis. Because some manufacturers will likely be in a position to qualify for some portion of the credit, this is a conservative assumption.

Regarding the passing of 45X credit savings realized by cell and module suppliers to manufacturers via the selling price of the cells or modules, we continue to expect that many suppliers and manufacturers will work closely together as they currently do through contractual agreements and partnerships and that these close connections will promote fair pricing arrangements. The large U.S. production capacity that is projected for the time frame of the rule also suggests that the market will be competitive and that suppliers will be motivated to pass credit savings along to customers in order to compete on price. Thus, we have continued to model a full pass through of the 45X credit savings we project in the final rule to the manufacturers. See RTC Section 2.7 for further discussion of the 45X tax credit pass through.

The tax credits under 45X effectively reduce the costs for batteries via tax credits for cells and modules, but the indirect costs associated with the batteries should persist even with the tax credit.[1014] As we did in the proposal, we applied the 45X credits after the RPE markup. Because RPE is meant to be a multiplier against the direct manufacturing cost, and the 45X credit does not reduce the actual direct manufacturing cost at the factory but only compensates the cost after the fact, it was most appropriate to apply the 45X credit to the marked-up cost. As discussed in Chapter 3, our RPE markup factor estimates these indirect costs and is based on the DMC without tax credits. The 45X cell and module credits per kWh were applied by first marking up

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[1013] David Gohlke et al., “Quantification of Commercially Planned Battery Component Supply in North America through 2035”, Argonne National Laboratory report ANL-24/14. March 2024. Available online: https://publications.anl.gov/anlpubs/2024/03/187735.pdf. See pp. 30-35 and 62-63..

[1014] As discussed further in Chapter 3.2, indirect costs are all the costs associated with producing the unit of output that are not direct manufacturing costs – for example, they may be related to research and development (R&D), warranty, corporate operations (such as salaries, pensions, health care costs, dealer support, and marketing) and profits. We expect the tax credits under 45X to offset costs for the manufacturers by reducing tax liability, which reduces the amount of costs that we anticipate manufacturers will recover by selling their products; the tax credits result in a lower RPE, but we do not expect them to reduce DMC or indirect costs.

the direct manufacturing cost by the RPE factor to determine the indirect cost, then deducting the credit amount from the marked-up cost to create a post-credit marked-up cost.

Taking into account each of these considerations, we model this tax credit in HD TRUCS in the final rule such that HD BEV and FCEV manufacturers fully utilize the module tax credit and gradually increase their utilization of the cell tax credit for MY 2027–2029 until MY 2030 and beyond, when they earn 100 percent of the available cell and module tax credits.

To estimate the price of the battery packs to the purchaser, we projected that the full value of the tax credit earned by the manufacturer is passed through to the purchaser because market competition would drive manufacturers to minimize their prices. See RTC Section 2.7 for further discussion of this projection.

The battery pack cost and battery tax credits are summarized in Table 2-50. As discussed above and in RTC Section 2.7, the literature indicates that there will be sufficient manufacturing capacity for the HDV industry to receive more 45X tax credits than our conservative projections in Table 2-50. Should the HDV industry's use of the 45X tax credit exceed these conservative projections, our cost estimates of BEVs and FCEVs would be overestimated.

Table 2-50 Pack-Level Battery Direct Manufacturing Costs and IRA Tax Credits in HD TRUCS (2022$)

$/kWh	**MY 2027**	**MY 2028**	**MY 2029**	**MY 2030**	**MY 2031**	**MY 2032**
Battery Pack Cost (no Credit)	120	113	107	103	100	97
IRA Cell Credit	8.75	17.50	26.25	26.25	17.50	8.75
IRA Module Credit	10.00	10.00	10.00	7.50	5.00	2.50
IRA Total Battery Credit	18.75	27.50	36.25	33.75	22.50	11.25
Battery Pack Cost Less IRA Total Battery Credit	101	85	71	69	77	85

ICCT and Energy Innovation assessed the impact of the IRA on electric vehicle uptake in the United States and analyzed three scenarios differentiated by how much of the tax credit value is passed through to vehicle purchasers: "From 2024 through 2029, the assumed percentage of the tax credit value passed to consumers is 0 percent in the Low scenario, 50 percent in the Moderate scenario, and 100 percent in the High scenario. For 2023, these values are reduced by a factor of two. By 2030, the 45X production tax credit begins to phase out, and the percentage passed through is reduced by 25 percent per year until fully expiring in 2033."[1015] In comparison with this ICCT and Energy Innovation study, our analysis falls between the Low and High scenarios for 2027–2029 and matches the High scenario for 2030–2032, reflecting our expectation that domestic battery manufacturing capacity will increase over time to capture this incentive and that competition in the market will lead manufacturers to reduce prices in accordance with the tax credits earned.

[1015] Slowik, Peter, et al. "Analyzing the Impact of the Inflation Reduction Act on Electric Vehicle Uptake in the United States". The International Council on Clean Transportation and Energy Innovation: Policy and Technology. January 31, 2023. Available online: https://energyinnovation.org/wp-content/uploads/2023/01/Analyzing-the-Impact-of-the-Inflation-Reduction-Act-on-EV-Uptake-in-the-U.S..pdf

These lower battery prices have the potential to accelerate ZEV technology adoption. For example, the Rocky Mountain Institute found that because of the IRA, the TCO of electric trucks will be lower than the TCO of diesel trucks about five years faster than without the law.[1016]

2.4.3.2 E-Drive

The electric drive in a BEV includes the electric motor (e-motor), power electronics and electrical accessories, and a driveshaft that can include a transmission system or gearbox. The electric energy in the form of DC current is provided from the battery; an inverter is used to change the DC current into AC current for use by the motor. The motor[1017] then converts the electric power into mechanical or motive power to move the vehicle. Conversely, the motor also receives AC current from the regenerative braking, whereby the inverter changes it to DC current to be stored in the battery. Lastly, the transmission or gearbox and final drive reduces the speed of the motor through a set of gears to an appropriate speed at the axle. Although there is an emerging trend of replacing the transmission and driveline with an e-axle, which is an electric motor integrated into the axle, e-axles are not explicitly covered in our cost analysis.[1018]

Like the battery cost described above, there are disparate electric drive cost projections. One reason for the differences is what is included in the definition of "electric drive"; some values include only the electric motor and other values present a more integrated e-motor/inverter/gearbox (or transmission) combination. For example, Sharpe and Basma et al. found the average reported e-drive costs—defined as the e-motor, inverter, and transmission system—to be around $60/kW in 2020, expected to drop to roughly $25/kW by 2030.[1019] But this is difficult to compare to values in Nair et. al,[1020] which include total component costs, where the motor and inverter costs vary by duty cycle, as shown in Figure 2-7.

[1016] Kahn, Ari, et. al. "The Inflation Reduction Act Will Help Electrify Heavy-Duty Trucking". Rocky Mountain Institute. August 25, 2022. Available online: https://rmi.org/inflation-reduction-act-will-help-electrify-heavy-duty-trucking/.

[1017] BEVs and FCEVs with e-motors have high torque at low motor speeds (i.e., low-end torque), which can provide performance benefits for HD ZEVs compared to comparable ICE vehicles, especially for heavy vehicles at low speed in terms of gradeability and acceleration. We did not quantify the potential performance improvements associated with the increase in low-end torque due to e-motors in the HD TRUCS analysis as we focused on matching ICE vehicle performance rather than exceeding it.

[1018] E-axles are an emerging technology that have potential to realize efficiency gains because they have fewer moving parts. Though we did not quantify their impact explicitly due to a lack of data and information at the time of our analysis and to remain technology-neutral, the technology can be used to comply with this regulation.

[1019] Sharpe, Ben and Hussein Basma. "A meta-study of purchase costs for zero-emission trucks". The International Council on Clean Transportation, Working Paper 2022-09 (February 2022). Available online: https://theicct.org/publication/purchase-cost-ze-trucks-feb22/. Costs are prior to integration markups.

[1020] Nair et. al "Technical Review of: Medium and Heavy-Duty Electrification Costs for MY 2027-30—Final Report". Environmental Defense Fund and Roush. February 2, 2022. Available online: https://blogs.edf.org/climate411/files/2022/02/EDF-MDHD-Electrification-v1.6_20220209.pdf.

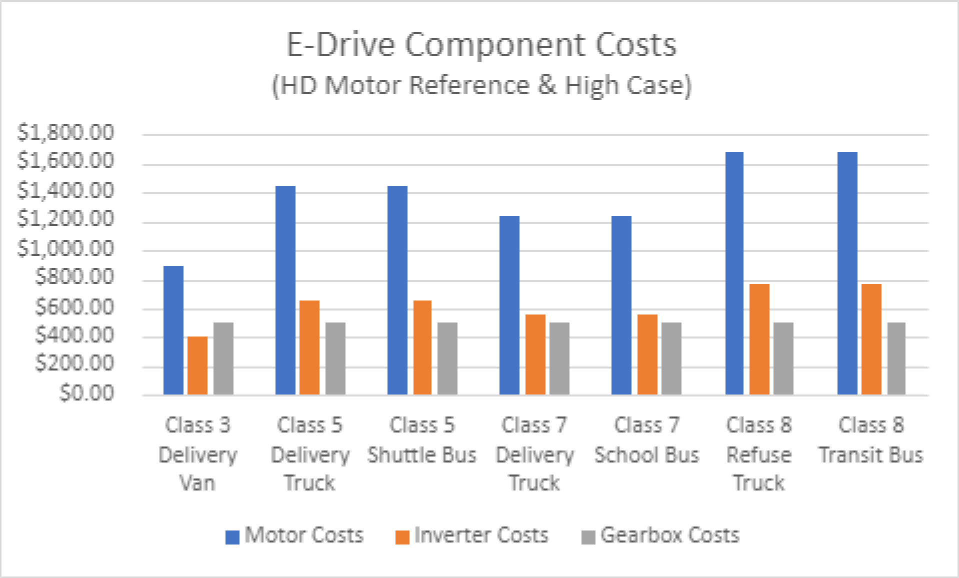

Figure 2-7 Electric Drive Component Costs from (Nair et al. 2022)

Both references cite inverter cost rather than power electronics and electronic accessories costs, which are considered in HD TRUCS. Burke et. al includes electric powertrain costs that represent the motor, power electronics, and DC-DC converters, but not individual component costs.[1021]

To remain consistent with other aspects of HD TRUCS and based on the structure of ANL's 2022 BEAN tool,[1022] our analysis included cost values of individual e-drive components: the e-motor, power electronics and electronic accessories, and gearbox. We primarily used the "Autonomie Out Import" tab, though there are exceptions as described below. Since the tool presents values for 2025 and 2030, the 2027 values were determined by interpolating between the 2025 and 2030 high costs and then interpolating between the 2025 and 2030 low costs. Then, the low and high MY 2027 values were averaged, converted to 2022$, and a learning factor was applied. See RIA Chapter 3.2 for an explanation of BEV learning. ANL vehicle IDs were then mapped to similar vehicles in HD TRUCS as shown in Table 2-2.

2.4.3.2.1 E-Motor

An e-motor—which is another major component of a BEV vehicle[1023]—converts electric energy from the battery into mechanical energy. We did not find sole $ per kW e-motor costs in the literature. A few commenters disagreed with the cost used by EPA at proposal for the electric motor, providing values that were lower and higher than those proposed. One commenter referenced Roush reports of $8/kW for 2030 and 2032, much lower than EPA's value. One industry commenter provided CBI values of the combined costs of e-motor, gearbox, inverter,

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[1021] Burke, Andrew, Marshall Miller, Anish Sinha, et. al. "Evaluation of the Economics of Battery-Electric and Fuel Cell Trucks and Buses: Methods, Issues, and Results". August 1, 2022. Available online: https://escholarship.org/uc/item/1g89p8dn.

[1022] Argonne National Laboratory. VTO HFTO Analysis Reports – 2022. "ANL – ESD-2206 Report – BEAN Tool – MD HD Vehicle Techno-Economic Analysis.xlsm". Available online: https://anl.app.box.com/s/an4nx0v2xpudxtpsnkhd5peimzu4j1hk/folder/242640145714.

[1023] Alternative Fuels Data Center. "How Do All-Electric Cars Work". U.S. Department of Energy. Available online: https://afdc.energy.gov/vehicles/how-do-all-electric-cars-work.

and e-axle. Another industry commenter cited an ICCT report that projected cost reductions of 60 percent by 2030 and that further projected that the price of electric powertrain systems, including the transmission, motor, and inverter, would reach $23/kW. One commenter is concerned that the market will demand different ZEV architectures depending on the application (direct drive, e-axle, and portal axle) and that each of these technologies will have a different $ per kW value due to differences in component costs and their respective manufacturing process.

For the final rule, we maintained the direct manufacturing cost for the e-motor (including the inverter) in HD TRUCS that we used for the proposal but converted it to 2022$. The e-motor costs in HD TRUCS come from ANL's 2022 BEAN tool[1024] as "Integrated Traction Drive Cost" values in the Vehicle Assumptions tab.[1025,1026] The MY 2027 value is a linear interpolation of the average of the high- and low-tech scenarios for 2025 and 2030, adjusted to 2022$. MY 2028–2032 values were then calculated using the BEV learning effects in RIA Chapter 3.2.1. The per-unit cost was calculated from the power of the motor (RIA Chapter 2.4.1.2) and $/kW of the e-motor (shown in Table 2-51). Per-unit e-motor cost for each of the 101 vehicles can be seen in Table 2-57 for MY 2027.

Table 2-51 E-Motor Direct Manufacturing Costs in HD TRUCS (2022$)

MY	2027	2028	2029	2030	2031	2032
E-Motor Cost ($/kW)	21	20	19	18	17	17

2.4.3.2.2 Power Converter and Electric Accessories

Power converter and electric accessories are components that include DC-DC converters, electric accessories, and vehicle propulsion architecture (VPA).

One NREL report includes a cost assumption used in FASTSim Powertrain Modeling for "power electronics with boost and motor" of $41.70/kW (in 2016 dollars) for medium- and heavy-duty trucks by 2025.[1027] EDF/Roush suggest that DC-DC converters, which includes the cost of the motor, in medium- and heavy-duty vehicles could cost $45.31/kW in 2027.[1028] We did not receive additional comments on the power electronics and electric accessories.

The power converter and electric accessories costs in HD TRUCS for both the proposal and final rule came from the "Autonomie Out Import" tab of ANL's 2022 BEAN tool.[1029] For the

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[1024] These values did not come directly from the "Autonomie Out Import" tab but can be calculated from fields on the "Autonomie Out Import" tab.

[1025] Our assumption is that ANL's integrated cost includes the inverter and the motor.

[1026] Argonne National Laboratory. VTO HFTO Analysis Reports – 2022. "ANL – ESD-2206 Report – BEAN Tool – MD HD Vehicle Techno-Economic Analysis.xlsm". Available online: https://anl.app.box.com/s/an4nx0v2xpudxtpsnkhd5peimzu4j1hk/folder/242640145714.

[1027] Hunter et. al. "Spatial and Temporal Analysis of the Total Cost of Ownership for Class 8 Tractors and Class 4 Parcel Delivery Trucks". National Renewable Energy Laboratory. September 2021. Available online: https://www.nrel.gov/docs/fy21osti/71796.pdf.

[1028] Nair et. al "Technical Review of: Medium and Heavy-Duty Electrification Costs for MY 2027-30—Final Report". Environmental Defense Fund and Roush. February 2, 2022. Available online: https://blogs.edf.org/climate411/files/2022/02/EDF-MDHD-Electrification-v1.6_20220209.pdf.

[1029] Argonne National Laboratory. VTO HFTO Analysis Reports – 2022. "ANL – ESD-2206 Report – BEAN Tool – MD HD Vehicle Techno-Economic Analysis.xlsm". Available online: https://anl.app.box.com/s/an4nx0v2xpudxtpsnkhd5peimzu4j1hk/folder/242640145714.

final rulemaking version of HD TRUCS, we updated the term Power Electronics to Power Converter, which represents the cost of a DC-DC converter ($1500 in 2020$).[1030] DC-DC converters transfer energy (i.e., they "step up" or "step down" voltage) between higher- and lower-voltage systems, such as from a high-voltage battery to a common 12V level for auxiliary uses.[1031] We identified an additional cost in BEAN that we added as a second DC-DC converter, which we call an Auxiliary Converter.[1032] This costs is shown by ANL ID in Table 2-53.[1033] We also revised the Electric Accessories costs to include both "ElecAccessory" ($4500 in 2020$) and vehicle propulsion architecture (VPA) costs ($186 in 2020$) from ANL's 2022 BEAN. These values, as shown below in Table 2-52, were converted to 2022$ and include the BEV learning effects included in RIA Chapter 3.2.

Table 2-52 Power Converter and Electric Accessories Direct Manufacturing Costs in HD TRUCS (2022$)

MY	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**
Power Converter ($)	1677	1577	1501	1440	1391	1349
VPA	208	196	186	179	173	167
Electric Accessories ($)	5032	4731	4502	4321	4174	4048

Table 2-53 Auxiliary Converter Direct Manufacturing Costs in HD TRUCS (2022$)

ANL ID	**MY 2027**	**MY 2030**	**MY 2032**
Box Medium 3	134	115	108
Van Medium 3	90	77	72
School Medium 3	224	192	180
Box Medium 4	134	115	108
StepVan Medium 4	134	115	108
Service Medium 4	134	115	108
StepVan Medium 6	224	192	180
Box Medium 6	224	192	180
Tractor DayCab 7	224	192	180
Vocational Medium 7	224	192	180
School Medium 7	448	385	360
Longhaul Sleeper 8	358	308	288
Beverage DayCab 8	313	269	252
Drayage DayCab 8	313	269	252
Vocational Heavy 8	313	269	252
Transit Heavy 8	537	461	432
Refuse Heavy 8	358	308	288
Regional DayCab 8	304	262	245

[1030] In the 2022 version of BEAN, the "BEAN results" tab, this is also represented as "pc2 DC/DC booster".

[1031] Smith, David et. al. "Medium- and Heavy-Duty Vehicle Electrification: An Assessment of Technology and Knowledge Gaps". U.S. Department of Energy: Oak Ridge National Laboratory and National Renewable Energy Laboratory. December 2019. ORNL/SPR-2020/7. Available online: https://info.ornl.gov/sites/publications/Files/Pub136575.pdf..

[1032] In the 2022 version of BEAN, the "Cost & LCOD & CCM" tab, this is called a "pc1 DC/DC ESS". In the "Autonomie Out" tab, this is linked to a DC/DC buck converter cost.

[1033] See Table 2-2 for HD TRUCS Vehicle ID mapping to ANL IDs.

2.4.3.2.3 Gearbox and Final Drive

Gearbox and final drive units are used to reduce the speed of the motor and transmit torque to the axle of the vehicle. In HD TRUCS for the proposal, we set the MY 2027 final drive DMC at $1,500/unit, based on the "Final Drive Costs" column in the "Autonomie Out Import" tab of ANL's 2022 BEAN model for vocational vehicles.[1034] For tractors, the final drive cost is doubled the cost of vocational vehicles. We did not receive any data to support different values, therefore, we adjusted the values used in the proposal to 2022$ and then calculated the MY 2028-2032 costs using the ICE learning curve shown in RIA Chapter 3.2.1.[1035] Final drive costs in HD TRUCS for BEVs are in Table 2-54.

The cost of the gearbox varies depends on the vehicle weight class and duty cycle. In our assessment, all light heavy-duty BEVs will be direct drive and have no transmission and no cost, in keeping with ANL's 2022 BEAN model. We then mapped BEAN gearbox costs for BEVs from the same "Autonomie Out Import" tab to the appropriate medium heavy-duty and heavy heavy-duty vehicles in HD TRUCS by calculating MY 2027 values using linear interpolation of the average of the high- and low-tech scenarios for 2025 and 2030, and then adjusting to 2022$.[1036] We then calculated the MY 2028-2032 costs using the BEV learning curve shown in RIA Chapter 3.2.1. BEV Gearbox costs are shown according to their ANL ID in Table 2-55. Table 2-57, Table 2-58, and Table 2-59 show the final drive and gearbox costs, as assigned to the 101 HD TRUCs vehicle types for model years 2027, 2030, and 2032, respectively. For vehicle Classes 5 and below, the gearbox cost is $0 in BEAN. This is consistent with the NPRM.

Table 2-54 Final Drive Costs in HD TRUCS (2022$)

MY	2027	2028	2029	2030	2031	2032
Vocational Vehicle Final Drive ($)	1677	1660	1660	1660	1644	1644
Tractor Final Drive ($)	3354	3321	3321	3321	3287	3287

Table 2-55 MY 2027, MY 2030, and MY 2032 BEV Gearbox Costs in HD TRUCS (2022$)

ANL ID	MY 2027	MY 2030	MY 2032
Box Medium 3	-	-	-
Van Medium 3	-	-	-
School Medium 3	-	-	-
Box Medium 4	-	-	-
StepVan Medium 4	-	-	-
Service Medium 4	-	-	-
StepVan Medium 6	2421	2079	1948
Box Medium 6	2587	2222	2082
Tractor Day Cab 7	2459	2112	1978
Vocational Medium 7	2489	2138	2003

[1034] Argonne National Laboratory. VTO HFTO Analysis Reports – 2022. "ANL – ESD-2206 Report – BEAN Tool – MD HD Vehicle Techno-Economic Analysis.xlsm". Available online: https://anl.app.box.com/s/an4nx0v2xpudxtpsnkhd5peimzu4j1hk/folder/242640145714.

[1035] For the final rule, we updated the learning curve for BEV (and FCEV) final drive costs to be consistent with the ICE learning curve since we are basing final drive costs on a component that is similar to an ICE vehicle final drive.

[1036] Argonne National Laboratory. VTO HFTO Analysis Reports – 2022. "ANL – ESD-2206 Report – BEAN Tool – MD HD Vehicle Techno-Economic Analysis.xlsm". Available online: https://anl.app.box.com/s/an4nx0v2xpudxtpsnkhd5peimzu4j1hk/folder/242640145714.

School Medium 7	2426	2084	1952
Longhaul Sleeper 8	5450	4681	4385
Beverage Day Cab 8	3858	3313	3104
Drayage Day Cab 8	4525	3887	3641
Vocational Heavy 8	4674	4014	3761
Transit Heavy 8	2666	2290	2145
Refuse Heavy 8	3626	3114	2917
Regional Day Cab 8	5460	4689	4393

2.4.3.3 Onboard Chargers

When using a Level 2 charging plug, an on-board charger converts AC power from the grid to usable DC power via an AC-DC converter. When using a DC fast charger (DCFC), any AC-DC converter is bypassed, and the high-voltage battery is charged directly. We included on-board chargers for all vehicles, even those that we predict will use DC fast chargers at the depot, as a conservative assumption. EPA's on-board charger costs are shown in Table 2-56. These values are significantly higher than the values we used in the NPRM, where we used a value of $38 in MY 2027, based on ANL's BEAN model. In the peer review of HD TRUCS, one reviewer noted that the value used in the NPRM was unrepresentative of the actual costs and suggested a cost of $600. In light of this critique, EPA has increased the on-board charger costs to $600 in MY 2027, We then calculated the MY 2028-2032 costs using the BEV learning curve shown in RIA Chapter 3.2.1.

Table 2-56 Onboard Charger Direct Manufacturing Costs in HD TRUCS (2022$)

Model Year	2027	2028	2029	2030	2031	2032
On-Board Charger Cost ($/unit)	600	564	537	515	498	483

2.4.3.4 Total Upfront BEV Costs

The total upfront BEV DMC is the summation of the per-unit cost of the battery, motor, power converter and electric accessories, on-board charger, gearbox, and final drive. The total BEV technology DMC and associated IRA battery tax credit for each of the 101 vehicle types can be found in Table 2-57 for MY 2027, Table 2-58 for MY 2030, and Table 2-59 for MY 2032.

Table 2-57 Direct Manufacturing BEV Costs Including IRA Tax Credit for MY 2027 (2022$)

Vehicle ID	Battery Cost without IRA Battery Tax Credit ($/unit)	Motor Cost ($/unit)	Power Converter and Electric Accessories ($/unit)	Charger ($/unit)	Gearbox ($/unit)	Final Drive ($/unit)	BEV PT DMC without IRA Battery Tax Credit ($/veh)	Battery Tax Credit ($/veh)
01V_Amb_Cl4-5_MP	14,345	5,093	7,051	600	-	1,677	28,766	2,241
02V_Amb_Cl2b-3_MP	13,542	5,093	7,006	600	-	1,677	27,918	2,116
03V_Amb_Cl4-5_U	13,366	5,093	7,051	600	-	1,677	27,787	2,088
04V_Amb_Cl2b-3_U	12,534	5,093	7,006	600	-	1,677	26,910	1,958
05T_Box_Cl8_MP	29,250	6,700	7,230	600	4,674	1,677	50,132	4,570

Vehicle ID	Battery Cost without IRA Battery Tax Credit ($/unit)	Motor Cost ($/unit)	Power Converter and Electric Accessories ($/unit)	Charger ($/unit)	Gearbox ($/unit)	Final Drive ($/unit)	BEV PT DMC without IRA Battery Tax Credit ($/veh)	Battery Tax Credit ($/veh)
06T_Box_Cl8_R	30,213	6,700	7,230	600	4,674	1,677	51,095	4,721
07T_Box_Cl6-7_MP	20,192	4,236	7,141	600	2,587	1,677	36,433	3,155
08T_Box_Cl6-7_R	21,962	4,236	7,141	600	2,587	1,677	38,202	3,432
09T_Box_Cl8_U	28,339	6,700	7,230	600	4,674	1,677	49,221	4,428
10T_Box_Cl6-7_U	19,458	4,236	7,141	600	2,587	1,677	35,699	3,040
11T_Box_Cl2b-3_U	12,001	5,093	7,051	600	-	1,677	26,422	1,875
12T_Box_Cl2b-3_R	14,150	5,093	7,051	600	-	1,677	28,571	2,211
13T_Box_Cl2b-3_MP	13,028	5,093	7,051	600	-	1,677	27,449	2,036
14T_Box_Cl4-5_U	12,001	5,093	7,051	600	-	1,677	26,422	1,875
15T_Box_Cl4-5_R	14,150	5,093	7,051	600	-	1,677	28,571	2,211
16T_Box_Cl4-5_MP	13,028	5,093	7,051	600	-	1,677	27,449	2,036
17B_Coach_Cl8_R	85,254	6,700	7,454	600	2,666	1,677	104,352	13,321
19C_Mix_Cl8_MP	51,317	6,700	7,230	600	4,674	1,677	72,199	8,018
20T_Dump_Cl8_U	33,909	6,700	7,230	600	4,674	1,677	54,791	5,298
21T_Dump_Cl8_MP	34,347	6,700	7,230	600	4,674	1,677	55,229	5,367
22T_Dump_Cl6-7_MP	33,258	4,236	7,141	600	2,489	1,677	49,400	5,197
23T_Dump_Cl8_U	33,909	6,700	7,230	600	4,674	1,677	54,791	5,298
24T_Dump_Cl6-7_U	31,128	4,236	7,141	600	2,489	1,677	47,271	4,864
25T_Fire_Cl8_MP	36,059	6,700	7,230	600	4,674	1,677	56,941	5,634
26T_Fire_Cl8_U	36,134	6,700	7,230	600	4,674	1,677	57,016	5,646
27T_Flat_Cl6-7_MP	20,192	4,236	7,141	600	2,489	1,677	36,334	3,155
28T_Flat_Cl6-7_R	21,962	4,236	7,141	600	2,489	1,677	38,104	3,432
29T_Flat_Cl6-7_U	18,634	4,236	7,141	600	2,489	1,677	34,776	2,912
30Tractor_DC_Cl8	42,133	10,997	7,230	600	4,525	3,354	68,840	6,583
31Tractor_DC_Cl7	38,077	7,642	7,141	600	2,459	3,354	59,273	5,950
32Tractor_SC_Cl8	116,748	8,328	7,275	600	5,450	3,354	141,755	18,242
33Tractor_DC_Cl8	63,736	11,477	7,141	600	2,459	3,354	88,766	9,959
34T_Ref_Cl8_MP	42,564	6,700	7,275	600	3,626	1,677	62,442	6,651
35T_Ref_Cl6-7_MP	34,744	4,236	7,141	600	2,489	1,677	50,886	5,429
36T_Ref_Cl8_U	42,564	6,700	7,275	600	3,626	1,677	62,442	6,651
37T_Ref_Cl6-7_U	34,284	4,236	7,141	600	2,489	1,677	50,426	5,357
38RV_Cl8_R	67,652	6,700	7,454	600	2,666	1,677	86,750	10,571
39RV_Cl6-7_R	71,928	4,236	7,364	600	2,426	1,677	88,232	11,239
40RV_Cl4-5_R	45,760	5,093	7,051	600	-	1,677	60,181	7,150
42RV_Cl8_MP	67,652	6,700	7,454	600	2,666	1,677	86,750	10,571
43RV_Cl6-7_MP	65,942	4,236	7,364	600	2,426	1,677	82,245	10,303
44RV_Cl4-5_MP	41,941	5,093	7,051	600	-	1,677	56,362	6,553
46B_School_Cl8_MP	31,950	6,700	7,454	600	2,666	1,677	51,048	4,992
47B_School_Cl6-7_MP	19,251	4,236	7,364	600	2,426	1,677	35,555	3,008
48B_School_Cl4-5_MP	14,345	5,093	7,051	600	-	1,677	28,766	2,241
49B_School_Cl2b-3_MP	13,542	5,093	7,141	600	-	1,677	28,053	2,116
50B_School_Cl8_U	30,263	6,700	7,454	600	2,666	1,677	49,361	4,729
51B_School_Cl6-7_U	19,251	4,236	7,364	600	2,426	1,677	35,555	3,008
52B_School_Cl4-5_U	13,366	5,093	7,051	600	-	1,677	27,787	2,088
53B_School_Cl2b-3_U	12,534	5,093	7,141	600	-	1,677	27,044	1,958
54Tractor_SC_Cl8	139,631	8,328	7,275	600	5,450	3,354	164,638	21,817

Vehicle ID	Battery Cost without IRA Battery Tax Credit ($/unit)	Motor Cost ($/unit)	Power Converter and Electric Accessories ($/unit)	Charger ($/unit)	Gearbox ($/unit)	Final Drive ($/unit)	BEV PT DMC without IRA Battery Tax Credit ($/veh)	Battery Tax Credit ($/veh)
55B_Shuttle_Cl2b-3_MP	19,694	5,093	7,141	600	-	1,677	34,205	3,077
56B_Shuttle_Cl4-5_U	18,991	5,093	7,051	600	-	1,677	33,412	2,967
57B_Shuttle_Cl2b-3_U	18,159	5,093	7,141	600	-	1,677	32,670	2,837
58B_Shuttle_Cl6-7_MP	31,645	4,236	7,364	600	2,426	1,677	47,948	4,945
59B_Shuttle_Cl6-7_U	29,357	4,236	7,364	600	2,426	1,677	45,660	4,587
60S_Plow_Cl6-7_MP	23,919	4,236	7,141	600	2,489	1,677	40,062	3,737
61S_Plow_Cl8_MP	47,307	6,700	7,230	600	4,674	1,677	68,189	7,392
62S_Plow_Cl6-7_U	22,407	4,236	7,141	600	2,489	1,677	38,549	3,501
63S_Plow_Cl8_U	46,507	6,700	7,230	600	4,674	1,677	67,389	7,267
64V_Step_Cl6-7_MP	20,339	4,236	7,141	600	2,421	1,677	36,414	3,178
65V_Step_Cl4-5_MP	13,028	5,093	7,051	600	-	1,677	27,449	2,036
66V_Step_Cl2b-3_MP	13,028	5,093	7,006	600	-	1,677	27,404	2,036
67V_Step_Cl6-7_U	18,769	4,236	7,141	600	2,421	1,677	34,844	2,933
68V_Step_Cl4-5_U	12,001	5,093	7,051	600	-	1,677	26,422	1,875
69V_Step_Cl2b-3_U	12,001	5,093	7,006	600	-	1,677	26,377	1,875
70S_Sweep_Cl6-7_U	21,837	4,236	7,141	600	2,489	1,677	37,980	3,412
71T_Tanker_Cl8_R	32,332	6,700	7,230	600	4,674	1,677	53,214	5,052
72T_Tanker_Cl8_MP	31,734	6,700	7,230	600	4,674	1,677	52,616	4,958
73T_Tanker_Cl8_U	31,568	6,700	7,230	600	4,674	1,677	52,450	4,933
74T_Tow_Cl8_R	49,558	6,700	7,230	600	4,674	1,677	70,440	7,743
75T_Tow_Cl6-7_R	36,058	4,236	7,141	600	2,489	1,677	52,201	5,634
76T_Tow_Cl8_U	47,977	6,700	7,230	600	4,674	1,677	68,859	7,496
77T_Tow_Cl6-7_U	31,264	4,236	7,141	600	2,489	1,677	47,407	4,885
78Tractor_SC_Cl8	100,054	8,328	7,275	600	5,450	3,354	125,061	15,633
80Tractor_DC_Cl8	77,624	9,369	7,230	600	4,674	3,354	102,852	12,129
81Tractor_DC_Cl7	63,732	7,642	7,141	600	2,459	3,354	84,928	9,958
82Tractor_DC_Cl8	76,208	10,997	7,221	600	5,460	3,354	103,840	11,907
83Tractor_DC_Cl7	55,097	7,642	7,141	600	2,459	3,354	76,292	8,609
84Tractor_DC_Cl8	42,754	10,997	7,230	600	3,858	3,354	68,794	6,680
85B_Transit_Cl8_MP	56,627	6,700	7,454	600	2,666	1,677	75,725	8,848
86B_Transit_Cl6-7_MP	44,724	4,236	7,364	600	2,426	1,677	61,027	6,988
87B_Transit_Cl8_U	56,627	6,700	7,454	600	2,666	1,677	75,725	8,848
88B_Transit_Cl6-7_U	40,967	4,236	7,364	600	2,426	1,677	57,270	6,401
89T_Utility_Cl8_MP	30,535	6,700	7,230	600	4,674	1,677	51,417	4,771
90T_Utility_Cl8_R	31,310	6,700	7,230	600	4,674	1,677	52,191	4,892
91T_Utility_Cl6-7_MP	22,126	4,236	7,141	600	2,489	1,677	38,268	3,457
92T_Utility_Cl6-7_R	23,779	4,236	7,141	600	2,489	1,677	39,922	3,716
93T_Utility_Cl4-5_MP	14,390	5,093	7,051	600	-	1,677	28,811	2,248
94T_Utility_Cl2b-3_MP	13,651	5,093	7,006	600	-	1,677	28,027	2,133
95T_Utility_Cl4-5_R	15,382	5,093	7,051	600	-	1,677	29,803	2,403
96T_Utility_Cl2b-3_R	15,382	5,093	7,006	600	-	1,677	29,758	2,403
97T_Utility_Cl8_U	30,009	6,700	7,230	600	4,674	1,677	50,891	4,689
98T_Utility_Cl6-7_U	20,841	4,236	7,141	600	2,489	1,677	36,984	3,256
99T_Utility_Cl4-5_U	13,567	5,093	7,051	600	-	1,677	27,988	2,120
100T_Utility_Cl2b-3_U	12,718	5,093	7,006	600	-	1,677	27,094	1,987
101Tractor_DC_Cl8	33,513	10,997	7,230	600	3,858	3,354	59,553	5,236

Table 2-58 Direct Manufacturing BEV Costs Including IRA Tax Credit for MY 2030 (2022$)

Vehicle ID	Battery Cost without IRA Battery Tax Credit ($/unit)	Motor Cost ($/unit)	Power Converter and Electric Accessories ($/unit)	Charger ($/unit)	Gearbox ($/unit)	Final Drive ($/unit)	BEV PT DMC without IRA Battery Tax Credit ($/veh)	Battery Tax Credit ($/veh)
01V_Amb_Cl4-5_MP	12,320	4,374	6,056	515	-	1,660	24,926	4,035
02V_Amb_Cl2b-3_MP	11,631	4,374	6,017	515	-	1,660	24,198	3,809
03V_Amb_Cl4-5_U	11,479	4,374	6,056	515	-	1,660	24,085	3,759
04V_Amb_Cl2b-3_U	10,765	4,374	6,017	515	-	1,660	23,332	3,525
05T_Box_Cl8_MP	25,121	5,755	6,210	515	4,014	1,660	43,276	8,227
06T_Box_Cl8_R	25,949	5,755	6,210	515	4,014	1,660	44,103	8,498
07T_Box_Cl6-7_MP	17,342	3,638	6,133	515	2,222	1,660	31,510	5,679
08T_Box_Cl6-7_R	18,862	3,638	6,133	515	2,222	1,660	33,030	6,177
09T_Box_Cl8_U	24,339	5,755	6,210	515	4,014	1,660	42,493	7,970
10T_Box_Cl6-7_U	16,711	3,638	6,133	515	2,222	1,660	30,880	5,473
11T_Box_Cl2b-3_U	10,307	4,374	6,056	515	-	1,660	22,912	3,375
12T_Box_Cl2b-3_R	12,153	4,374	6,056	515	-	1,660	24,758	3,980
13T_Box_Cl2b-3_MP	11,189	4,374	6,056	515	-	1,660	23,794	3,664
14T_Box_Cl4-5_U	10,307	4,374	6,056	515	-	1,660	22,912	3,375
15T_Box_Cl4-5_R	12,153	4,374	6,056	515	-	1,660	24,758	3,980
16T_Box_Cl4-5_MP	11,189	4,374	6,056	515	-	1,660	23,794	3,664
17B_Coach_Cl8_R	73,221	5,755	6,402	515	2,290	1,660	89,843	23,978
19C_Mix_Cl8_MP	44,074	5,755	6,210	515	4,014	1,660	62,228	14,433
20T_Dump_Cl8_U	29,123	5,755	6,210	515	4,014	1,660	47,277	9,537
21T_Dump_Cl8_MP	29,499	5,755	6,210	515	4,014	1,660	47,653	9,660
22T_Dump_Cl6-7_MP	28,563	3,638	6,133	515	2,138	1,660	42,647	9,354
23T_Dump_Cl8_U	29,123	5,755	6,210	515	4,014	1,660	47,277	9,537
24T_Dump_Cl6-7_U	26,735	3,638	6,133	515	2,138	1,660	40,818	8,755
25T_Fire_Cl8_MP	30,969	5,755	6,210	515	4,014	1,660	49,123	10,141
26T_Fire_Cl8_U	31,034	5,755	6,210	515	4,014	1,660	49,188	10,163
27T_Flat_Cl6-7_MP	17,342	3,638	6,133	515	2,138	1,660	31,426	5,679
28T_Flat_Cl6-7_R	18,862	3,638	6,133	515	2,138	1,660	32,946	6,177
29T_Flat_Cl6-7_U	16,004	3,638	6,133	515	2,138	1,660	30,088	5,241
30Tractor_DC_Cl8	36,186	9,445	6,210	515	3,887	3,321	59,563	11,850
31Tractor_DC_Cl7	32,703	6,563	6,133	515	2,112	3,321	51,346	10,709
32Tractor_SC_Cl8	100,269	7,152	6,248	515	4,681	3,321	122,186	32,835
33Tractor_DC_Cl8	54,739	9,857	6,133	515	2,112	3,321	76,676	17,926
34T_Ref_Cl8_MP	36,556	5,755	6,248	515	3,114	1,660	53,849	11,971
35T_Ref_Cl6-7_MP	29,839	3,638	6,133	515	2,138	1,660	43,923	9,772
36T_Ref_Cl8_U	36,556	5,755	6,248	515	3,114	1,660	53,849	11,971
37T_Ref_Cl6-7_U	29,445	3,638	6,133	515	2,138	1,660	43,529	9,642
38RV_Cl8_R	58,103	5,755	6,402	515	2,290	1,660	74,725	19,027
39RV_Cl6-7_R	61,775	3,638	6,325	515	2,084	1,660	75,998	20,230
40RV_Cl4-5_R	39,301	4,374	6,056	515	-	1,660	51,906	12,870
42RV_Cl8_MP	58,103	5,755	6,402	515	2,290	1,660	74,725	19,027

Vehicle ID	Battery Cost without IRA Battery Tax Credit ($/unit)	Motor Cost ($/unit)	Power Converter and Electric Accessories ($/unit)	Charger ($/unit)	Gearbox ($/unit)	Final Drive ($/unit)	BEV PT DMC without IRA Battery Tax Credit ($/veh)	Battery Tax Credit ($/veh)
43RV_Cl6-7_MP	56,634	3,638	6,325	515	2,084	1,660	70,856	18,546
44RV_Cl4-5_MP	36,021	4,374	6,056	515	-	1,660	48,627	11,796
46B_School_Cl8_MP	27,440	5,755	6,402	515	2,290	1,660	44,063	8,986
47B_School_Cl6-7_MP	16,534	3,638	6,325	515	2,084	1,660	30,756	5,414
48B_School_Cl4-5_MP	12,320	4,374	6,056	515	-	1,660	24,926	4,035
49B_School_Cl2b-3_MP	11,631	4,374	6,133	515	-	1,660	24,313	3,809
50B_School_Cl8_U	25,991	5,755	6,402	515	2,290	1,660	42,614	8,512
51B_School_Cl6-7_U	16,534	3,638	6,325	515	2,084	1,660	30,756	5,414
52B_School_Cl4-5_U	11,479	4,374	6,056	515	-	1,660	24,085	3,759
53B_School_Cl2b-3_U	10,765	4,374	6,133	515	-	1,660	23,447	3,525
54Tractor_SC_Cl8	119,922	7,152	6,248	515	4,681	3,321	141,839	39,271
55B_Shuttle_Cl2b-3_MP	16,914	4,374	6,133	515	-	1,660	29,596	5,539
56B_Shuttle_Cl4-5_U	16,311	4,374	6,056	515	-	1,660	28,916	5,341
57B_Shuttle_Cl2b-3_U	15,596	4,374	6,133	515	-	1,660	28,278	5,107
58B_Shuttle_Cl6-7_MP	27,178	3,638	6,325	515	2,084	1,660	41,400	8,900
59B_Shuttle_Cl6-7_U	25,213	3,638	6,325	515	2,084	1,660	39,435	8,257
60S_Plow_Cl6-7_MP	20,543	3,638	6,133	515	2,138	1,660	34,627	6,727
61S_Plow_Cl8_MP	40,629	5,755	6,210	515	4,014	1,660	58,784	13,305
62S_Plow_Cl6-7_U	19,244	3,638	6,133	515	2,138	1,660	33,328	6,302
63S_Plow_Cl8_U	39,943	5,755	6,210	515	4,014	1,660	58,097	13,080
64V_Step_Cl6-7_MP	17,468	3,638	6,133	515	2,079	1,660	31,494	5,720
65V_Step_Cl4-5_MP	11,189	4,374	6,056	515	-	1,660	23,794	3,664
66V_Step_Cl2b-3_MP	11,189	4,374	6,017	515	-	1,660	23,756	3,664
67V_Step_Cl6-7_U	16,120	3,638	6,133	515	2,079	1,660	30,145	5,279
68V_Step_Cl4-5_U	10,307	4,374	6,056	515	-	1,660	22,912	3,375
69V_Step_Cl2b-3_U	10,307	4,374	6,017	515	-	1,660	22,874	3,375
70S_Sweep_Cl6-7_U	18,755	3,638	6,133	515	2,138	1,660	32,839	6,142
71T_Tanker_Cl8_R	27,769	5,755	6,210	515	4,014	1,660	45,923	9,094
72T_Tanker_Cl8_MP	27,255	5,755	6,210	515	4,014	1,660	45,409	8,925
73T_Tanker_Cl8_U	27,113	5,755	6,210	515	4,014	1,660	45,267	8,879
74T_Tow_Cl8_R	42,563	5,755	6,210	515	4,014	1,660	60,718	13,938
75T_Tow_Cl6-7_R	30,969	3,638	6,133	515	2,138	1,660	45,053	10,141
76T_Tow_Cl8_U	41,205	5,755	6,210	515	4,014	1,660	59,360	13,494
77T_Tow_Cl6-7_U	26,851	3,638	6,133	515	2,138	1,660	40,935	8,793
78Tractor_SC_Cl8	85,931	7,152	6,248	515	4,681	3,321	107,848	28,140
80Tractor_DC_Cl8	66,668	8,046	6,210	515	4,014	3,321	88,774	21,832
81Tractor_DC_Cl7	54,736	6,563	6,133	515	2,112	3,321	73,380	17,925
82Tractor_DC_Cl8	65,451	9,445	6,202	515	4,689	3,321	89,623	21,433
83Tractor_DC_Cl7	47,320	6,563	6,133	515	2,112	3,321	65,963	15,496
84Tractor_DC_Cl8	36,719	9,445	6,210	515	3,313	3,321	59,523	12,025
85B_Transit_Cl8_MP	48,634	5,755	6,402	515	2,290	1,660	65,256	15,926
86B_Transit_Cl6-7_MP	38,411	3,638	6,325	515	2,084	1,660	52,633	12,579
87B_Transit_Cl8_U	48,634	5,755	6,402	515	2,290	1,660	65,256	15,926
88B_Transit_Cl6-7_U	35,184	3,638	6,325	515	2,084	1,660	49,406	11,522

Vehicle ID	Battery Cost without IRA Battery Tax Credit ($/unit)	Motor Cost ($/unit)	Power Converter and Electric Accessories ($/unit)	Charger ($/unit)	Gearbox ($/unit)	Final Drive ($/unit)	BEV PT DMC without IRA Battery Tax Credit ($/veh)	Battery Tax Credit ($/veh)
89T_Utility_Cl8_MP	26,225	5,755	6,210	515	4,014	1,660	44,379	8,588
90T_Utility_Cl8_R	26,890	5,755	6,210	515	4,014	1,660	45,045	8,806
91T_Utility_Cl6-7_MP	19,003	3,638	6,133	515	2,138	1,660	33,087	6,223
92T_Utility_Cl6-7_R	20,423	3,638	6,133	515	2,138	1,660	34,507	6,688
93T_Utility_Cl4-5_MP	12,359	4,374	6,056	515	-	1,660	24,964	4,047
94T_Utility_Cl2b-3_MP	11,724	4,374	6,017	515	-	1,660	24,291	3,839
95T_Utility_Cl4-5_R	13,211	4,374	6,056	515	-	1,660	25,816	4,326
96T_Utility_Cl2b-3_R	13,211	4,374	6,017	515	-	1,660	25,778	4,326
97T_Utility_Cl8_U	25,773	5,755	6,210	515	4,014	1,660	43,928	8,440
98T_Utility_Cl6-7_U	17,900	3,638	6,133	515	2,138	1,660	31,983	5,862
99T_Utility_Cl4-5_U	11,652	4,374	6,056	515	-	1,660	24,257	3,816
100T_Utility_Cl2b-3_U	10,922	4,374	6,017	515	-	1,660	23,489	3,577
101Tractor_DC_Cl8	28,783	9,445	6,210	515	3,313	3,321	51,587	9,426

Table 2-59 Direct Manufacturing BEV Costs and IRA Tax Credit for MY 2032 (2022$)

Vehicle ID	Battery Cost without IRA Battery Tax Credit ($/unit)	Motor Cost ($/unit)	Power Converter and Electric Accessories ($/unit)	Charger ($/unit)	Gearbox ($/unit)	Final Drive ($/unit)	BEV PT DMC without IRA Battery Tax Credit ($/veh)	Battery Tax Credit ($/veh)
01V_Amb_Cl4-5_MP	11,542	4,097	5,673	483	-	1,644	23,438	1,345
02V_Amb_Cl2b-3_MP	10,896	4,097	5,637	483	-	1,644	22,756	1,270
03V_Amb_Cl4-5_U	10,754	4,097	5,673	483	-	1,644	22,650	1,253
04V_Amb_Cl2b-3_U	10,084	4,097	5,637	483	-	1,644	21,945	1,175
05T_Box_Cl8_MP	23,533	5,391	5,817	483	3,761	1,644	40,628	2,742
06T_Box_Cl8_R	24,309	5,391	5,817	483	3,761	1,644	41,404	2,833
07T_Box_Cl6-7_MP	16,246	3,408	5,745	483	2,082	1,644	29,606	1,893
08T_Box_Cl6-7_R	17,670	3,408	5,745	483	2,082	1,644	31,030	2,059
09T_Box_Cl8_U	22,800	5,391	5,817	483	3,761	1,644	39,895	2,657
10T_Box_Cl6-7_U	15,655	3,408	5,745	483	2,082	1,644	29,016	1,824
11T_Box_Cl2b-3_U	9,655	4,097	5,673	483	-	1,644	21,552	1,125
12T_Box_Cl2b-3_R	11,385	4,097	5,673	483	-	1,644	23,282	1,327
13T_Box_Cl2b-3_MP	10,481	4,097	5,673	483	-	1,644	22,378	1,221
14T_Box_Cl4-5_U	9,655	4,097	5,673	483	-	1,644	21,552	1,125
15T_Box_Cl4-5_R	11,385	4,097	5,673	483	-	1,644	23,282	1,327
16T_Box_Cl4-5_MP	10,481	4,097	5,673	483	-	1,644	22,378	1,221
17B_Coach_Cl8_R	68,592	5,391	5,997	483	2,145	1,644	84,252	7,993
19C_Mix_Cl8_MP	41,288	5,391	5,817	483	3,761	1,644	58,383	4,811
20T_Dump_Cl8_U	27,282	5,391	5,817	483	3,761	1,644	44,377	3,179
21T_Dump_Cl8_MP	27,634	5,391	5,817	483	3,761	1,644	44,729	3,220

Vehicle ID	Battery Cost without IRA Battery Tax Credit ($/unit)	Motor Cost ($/unit)	Power Converter and Electric Accessories ($/unit)	Charger ($/unit)	Gearbox ($/unit)	Final Drive ($/unit)	BEV PT DMC without IRA Battery Tax Credit ($/veh)	Battery Tax Credit ($/veh)
22T_Dump_Cl6-7_MP	26,758	3,408	5,745	483	2,003	1,644	40,040	3,118
23T_Dump_Cl8_U	27,282	5,391	5,817	483	3,761	1,644	44,377	3,179
24T_Dump_Cl6-7_U	25,045	3,408	5,745	483	2,003	1,644	38,326	2,918
25T_Fire_Cl8_MP	29,011	5,391	5,817	483	3,761	1,644	46,106	3,380
26T_Fire_Cl8_U	29,072	5,391	5,817	483	3,761	1,644	46,167	3,388
27T_Flat_Cl6-7_MP	16,246	3,408	5,745	483	2,003	1,644	29,527	1,893
28T_Flat_Cl6-7_R	17,670	3,408	5,745	483	2,003	1,644	30,951	2,059
29T_Flat_Cl6-7_U	14,992	3,408	5,745	483	2,003	1,644	28,274	1,747
30Tractor_DC_Cl8	33,898	8,848	5,817	483	3,641	3,287	55,974	3,950
31Tractor_DC_Cl7	30,636	6,148	5,745	483	1,978	3,287	48,277	3,570
32Tractor_SC_Cl8	93,931	6,700	5,853	483	4,385	3,287	114,639	10,945
33Tractor_DC_Cl8	51,279	9,234	5,745	483	1,978	3,287	72,006	5,975
34T_Ref_Cl8_MP	34,246	5,391	5,853	483	2,917	1,644	50,533	3,990
35T_Ref_Cl6-7_MP	27,953	3,408	5,745	483	2,003	1,644	41,235	3,257
36T_Ref_Cl8_U	34,246	5,391	5,853	483	2,917	1,644	50,533	3,990
37T_Ref_Cl6-7_U	27,584	3,408	5,745	483	2,003	1,644	40,865	3,214
38RV_Cl8_R	54,430	5,391	5,997	483	2,145	1,644	70,090	6,342
39RV_Cl6-7_R	57,871	3,408	5,925	483	1,952	1,644	71,282	6,743
40RV_Cl4-5_R	36,817	4,097	5,673	483	-	1,644	48,713	4,290
42RV_Cl8_MP	54,430	5,391	5,997	483	2,145	1,644	70,090	6,342
43RV_Cl6-7_MP	53,054	3,408	5,925	483	1,952	1,644	66,465	6,182
44RV_Cl4-5_MP	33,744	4,097	5,673	483	-	1,644	45,641	3,932
46B_School_Cl8_MP	25,706	5,391	5,997	483	2,145	1,644	41,366	2,995
47B_School_Cl6-7_MP	15,489	3,408	5,925	483	1,952	1,644	28,900	1,805
48B_School_Cl4-5_MP	11,542	4,097	5,673	483	-	1,644	23,438	1,345
49B_School_Cl2b-3_MP	10,896	4,097	5,745	483	-	1,644	22,864	1,270
50B_School_Cl8_U	24,348	5,391	5,997	483	2,145	1,644	40,008	2,837
51B_School_Cl6-7_U	15,489	3,408	5,925	483	1,952	1,644	28,900	1,805
52B_School_Cl4-5_U	10,754	4,097	5,673	483	-	1,644	22,650	1,253
53B_School_Cl2b-3_U	10,084	4,097	5,745	483	-	1,644	22,053	1,175
54Tractor_SC_Cl8	112,341	6,700	5,853	483	4,385	3,287	133,049	13,090
55B_Shuttle_Cl2b-3_MP	15,845	4,097	5,745	483	-	1,644	27,814	1,846
56B_Shuttle_Cl4-5_U	15,280	4,097	5,673	483	-	1,644	27,176	1,780
57B_Shuttle_Cl2b-3_U	14,610	4,097	5,745	483	-	1,644	26,579	1,702
58B_Shuttle_Cl6-7_MP	25,460	3,408	5,925	483	1,952	1,644	38,872	2,967
59B_Shuttle_Cl6-7_U	23,620	3,408	5,925	483	1,952	1,644	37,031	2,752
60S_Plow_Cl6-7_MP	19,245	3,408	5,745	483	2,003	1,644	32,526	2,242
61S_Plow_Cl8_MP	38,061	5,391	5,817	483	3,761	1,644	55,156	4,435

Vehicle ID	Battery Cost without IRA Battery Tax Credit ($/unit)	Motor Cost ($/unit)	Power Converter and Electric Accessories ($/unit)	Charger ($/unit)	Gearbox ($/unit)	Final Drive ($/unit)	BEV PT DMC without IRA Battery Tax Credit ($/veh)	Battery Tax Credit ($/veh)
62S_Plow_Cl6-7_U	18,028	3,408	5,745	483	2,003	1,644	31,310	2,101
63S_Plow_Cl8_U	37,418	5,391	5,817	483	3,761	1,644	54,513	4,360
64V_Step_Cl6-7_MP	16,364	3,408	5,745	483	1,948	1,644	29,591	1,907
65V_Step_Cl4-5_MP	10,481	4,097	5,673	483	-	1,644	22,378	1,221
66V_Step_Cl2b-3_MP	10,481	4,097	5,637	483	-	1,644	22,342	1,221
67V_Step_Cl6-7_U	15,101	3,408	5,745	483	1,948	1,644	28,328	1,760
68V_Step_Cl4-5_U	9,655	4,097	5,673	483	-	1,644	21,552	1,125
69V_Step_Cl2b-3_U	9,655	4,097	5,637	483	-	1,644	21,516	1,125
70S_Sweep_Cl6-7_U	17,569	3,408	5,745	483	2,003	1,644	30,851	2,047
71T_Tanker_Cl8_R	26,013	5,391	5,817	483	3,761	1,644	43,108	3,031
72T_Tanker_Cl8_MP	25,532	5,391	5,817	483	3,761	1,644	42,627	2,975
73T_Tanker_Cl8_U	25,399	5,391	5,817	483	3,761	1,644	42,494	2,960
74T_Tow_Cl8_R	39,873	5,391	5,817	483	3,761	1,644	56,968	4,646
75T_Tow_Cl6-7_R	29,011	3,408	5,745	483	2,003	1,644	42,293	3,380
76T_Tow_Cl8_U	38,601	5,391	5,817	483	3,761	1,644	55,696	4,498
77T_Tow_Cl6-7_U	25,154	3,408	5,745	483	2,003	1,644	38,436	2,931
78Tractor_SC_Cl8	80,499	6,700	5,853	483	4,385	3,287	101,208	9,380
80Tractor_DC_Cl8	62,454	7,538	5,817	483	3,761	3,287	83,339	7,277
81Tractor_DC_Cl7	51,277	6,148	5,745	483	1,978	3,287	68,918	5,975
82Tractor_DC_Cl8	61,314	8,848	5,810	483	4,393	3,287	84,134	7,144
83Tractor_DC_Cl7	44,329	6,148	5,745	483	1,978	3,287	61,970	5,165
84Tractor_DC_Cl8	34,398	8,848	5,817	483	3,104	3,287	55,937	4,008
85B_Transit_Cl8_MP	45,560	5,391	5,997	483	2,145	1,644	61,220	5,309
86B_Transit_Cl6-7_MP	35,983	3,408	5,925	483	1,952	1,644	49,394	4,193
87B_Transit_Cl8_U	45,560	5,391	5,997	483	2,145	1,644	61,220	5,309
88B_Transit_Cl6-7_U	32,960	3,408	5,925	483	1,952	1,644	46,372	3,841
89T_Utility_Cl8_MP	24,567	5,391	5,817	483	3,761	1,644	41,662	2,863
90T_Utility_Cl8_R	25,190	5,391	5,817	483	3,761	1,644	42,285	2,935
91T_Utility_Cl6-7_MP	17,802	3,408	5,745	483	2,003	1,644	31,083	2,074
92T_Utility_Cl6-7_R	19,132	3,408	5,745	483	2,003	1,644	32,414	2,229
93T_Utility_Cl4-5_MP	11,578	4,097	5,673	483	-	1,644	23,475	1,349
94T_Utility_Cl2b-3_MP	10,983	4,097	5,637	483	-	1,644	22,844	1,280
95T_Utility_Cl4-5_R	12,376	4,097	5,673	483	-	1,644	24,272	1,442
96T_Utility_Cl2b-3_R	12,376	4,097	5,637	483	-	1,644	24,236	1,442
97T_Utility_Cl8_U	24,144	5,391	5,817	483	3,761	1,644	41,239	2,813
98T_Utility_Cl6-7_U	16,768	3,408	5,745	483	2,003	1,644	30,050	1,954
99T_Utility_Cl4-5_U	10,916	4,097	5,673	483	-	1,644	22,812	1,272
100T_Utility_Cl2b-3_U	10,232	4,097	5,637	483	-	1,644	22,093	1,192
101Tractor_DC_Cl8	26,964	8,848	5,817	483	3,104	3,287	48,503	3,142

2.4.3.5 Qualified Commercial Clean Vehicle Tax Credits

IRA section 13403, “Qualified Commercial Clean Vehicles,” (codified in the Internal Revenue Code as section 45W) creates a tax credit for the purchase or lease of a qualified commercial clean vehicle.[1037] In our HD TRUCS analysis, we included in our quantitative analysis the IRA battery tax credit described in RIA Chapter 2.4.3.1 and this vehicle tax credit. As described in Section II.E.4 of the preamble, RIA Chapter 1, RIA Chapter 2.4.3.1, and RIA Chapter 2.6.2.1.2, there are several other provisions in the IRA that we expect will support electrification of the HD vehicle fleet.

IRA section 13403 creates a tax credit applicable to each purchase of a qualified commercial clean vehicle. These vehicles must be on-road vehicles (or mobile machinery) that are propelled to a significant extent by a battery-powered electric motor. The battery must have a capacity of at least 15 kWh (or 7 kWh if it is Class 3 or below) and must be rechargeable from an external source of electricity. This limits the qualified vehicles to BEVs, plug-in hybrid electric vehicles (PHEVs) and FCEVs (see RIA Chapter 2.5.2.3).

The credit is available from CY 2023 through 2032, which overlaps with the model years for which we are finalizing standards (MYs 2027–2032), so we included the tax credit in our calculations for each of those years in HD TRUCS. For BEVs, the tax credit is equal to the lesser of: (A) 30 percent of the BEV cost, or (B) the incremental cost of a BEV when compared to a comparable ICE vehicle. The limit of this tax credit is $40,000 for Class 4–8 commercial vehicles and $7,500 for commercial vehicles Class 3 and below. For example, if a BEV costs $350,000 and a comparable ICE vehicle costs $150,000[1038] the tax credit would be the lesser of: (A) 30 percent × $350,000 = $105,000 or (B) $350,000 - $150,000 = $200,000. (A) is less than (B), but (A) exceeds the limit of $40,000, so the tax credit would be $40,000.

In order to estimate the impact of this tax credit in our feasibility analysis for BEVs, we first applied a retail price equivalent to our direct manufacturing costs for BEVs, FCEVs, and ICE vehicles. Note that the direct manufacturing costs of BEVs were reduced by the amount of the battery tax credit in IRA section 13502, as described previously and in Chapter 2.4.3.1. We calculated the purchaser’s incremental cost of BEVs compared to ICE vehicles and not the full cost of vehicles in our analysis. We based our calculation of the tax credit on this incremental cost. When the incremental cost exceeded the tax credit limitation (determined by gross vehicle weight rating as described in the previous paragraph), we decreased the incremental cost by the tax credit limitation. When the incremental cost was between $0 and the tax credit limitation, we reduced the incremental cost to $0 (i.e., the tax credit received by the purchaser was equal to the incremental cost). When the incremental cost was negative (i.e., the BEV was cheaper to purchase than the ICE vehicle), no tax credit was given. In order for this calculation to be appropriate, we determined that all Class 4–8 BEVs must cost more than $133,333 such that 30 percent of the cost is at least $40,000 (or $25,000 and $7,500, respectively, for BEVs Class 3 and

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[1037] Inflation Reduction Act of 2022, Pub. L. No. 117-169, 136 Stat. 1818 (2022). Available online: https://www.congress.gov/117/bills/hr5376/BILLS-117hr5376enr.pdf.

[1038] Sharpe, B., Basma, H. "A meta-study of purchase costs for zero-emission trucks". International Council on Clean Transportation. February 17, 2022. Available online: https://theicct.org/wp-content/uploads/2022/02/purchase-cost-ze-trucks-feb22-1.pdf.

below), and determined that this assumption is reasonable based on our review of the literature on the costs of BEVs.[1039]

2.4.3.6 State Sales Tax and Federal Excise Tax

As explained in RIA Chapter 2.3.2.2 above, the NPRM version of HD TRUCS did not include estimates for state sales taxes on the purchase of a vehicle or Federal Excise Tax (FET). In response to comments, we have added these values to the final version of HD TRUCS. Sales tax and FET are calculated by first applying a retail price equivalent (RPE) factor[1040] to the BEV powertrain DMC costs. One industry commenter recommended using a state sales tax rate of 5.02%, an average of the 50 state sales tax values, which we assessed and confirmed was appropriate.[1041] This rate was applied to the upfront costs (RPE) for all HD TRUCS vehicles for the final rule analysis. A Federal Excise tax of 12% was applied to the upfront costs (RPE) for all Class 8 (heavy heavy-duty) vehicles and all tractors.[1042] The results of this analysis for MY 2032 as an example year are shown in Table 2-60.

Table 2-60 BEV Powertrain (PT) RPE, Sales Tax and FET for MY 2032 (2022$)

Vehicle ID	PT DMC without Battery Tax Credit ($/veh)	PT RPE with Battery Tax Credit ($/veh)	FET ($/veh)	State Sales Tax ($/veh)
01V_Amb_Cl4-5_MP	23,438	31,938	-	1,603
02V_Amb_Cl2b-3_MP	22,756	31,044	-	1,558
03V_Amb_Cl4-5_U	22,650	30,911	-	1,552
04V_Amb_Cl2b-3_U	21,945	29,987	-	1,505
05T_Box_Cl8_MP	40,628	54,950	6,594	2,759
06T_Box_Cl8_R	41,404	55,961	6,715	2,809
07T_Box_Cl6-7_MP	29,606	40,148	-	2,015
08T_Box_Cl6-7_R	31,030	42,004	-	2,109
09T_Box_Cl8_U	39,895	53,995	6,479	2,711
10T_Box_Cl6-7_U	29,016	39,378	-	1,977
11T_Box_Cl2b-3_U	21,552	29,479	-	1,480
12T_Box_Cl2b-3_R	23,282	31,733	-	1,593
13T_Box_Cl2b-3_MP	22,378	30,556	-	1,534
14T_Box_Cl4-5_U	21,552	29,479	-	1,480
15T_Box_Cl4-5_R	23,282	31,733	-	1,593
16T_Box_Cl4-5_MP	22,378	30,556	-	1,534
17B_Coach_Cl8_R	84,252	111,645	13,397	5,605
19C_Mix_Cl8_MP	58,383	78,093	9,371	3,920
20T_Dump_Cl8_U	44,377	59,836	7,180	3,004
21T_Dump_Cl8_MP	44,729	60,296	7,235	3,027
22T_Dump_Cl6-7_MP	40,040	53,738	-	2,698
23T_Dump_Cl8_U	44,377	59,836	7,180	3,004

[1039] Burnham, A., Gohlke, D., Rush, L., Stephens, T., Zhou, Y., Delucchi, M. A., Birky, A., Hunter, C., Lin, Z., Ou, S., Xie, F., Proctor, C., Wiryadinata, S., Liu, N., Boloor, M. "Comprehensive Total Cost of Ownership Quantification for Vehicles with Different Size Classes and Powertrains". Argonne National Laboratory. April 1, 2021. Available at https://publications.anl.gov/anlpubs/2021/05/167399.pdf.

[1040] See Chapter 3.2 for a discussion of RPE.

[1041] See page 38 of docket number EPA-HQ-OAR-2022-0985-2668-A1.

[1042] U.S. Internal Revenue Service. 26 USC 4051. Available at http://uscode.house.gov/view.xhtml?req=granuleid:USC-prelim-title26-section4051&num=0&edition=prelim

Vehicle ID	PT DMC without Battery Tax Credit ($/veh)	PT RPE with Battery Tax Credit ($/veh)	FET ($/veh)	State Sales Tax ($/veh)
24T_Dump_Cl6-7_U	38,326	51,505	-	2,586
25T_Fire_Cl8_MP	46,106	62,091	7,451	3,117
26T_Fire_Cl8_U	46,167	62,170	7,460	3,121
27T_Flat_Cl6-7_MP	29,527	40,036	-	2,010
28T_Flat_Cl6-7_R	30,951	41,892	-	2,103
29T_Flat_Cl6-7_U	28,274	38,402	-	1,928
30Tractor_DC_Cl8	55,974	75,533	9,064	3,792
31Tractor_DC_Cl7	48,277	64,983	7,798	3,262
32Tractor_SC_Cl8	114,639	151,842	18,221	7,622
33Tractor_DC_Cl8	72,006	96,273	11,553	4,833
34T_Ref_Cl8_MP	50,533	67,766	8,132	3,402
35T_Ref_Cl6-7_MP	41,235	55,297	-	2,776
36T_Ref_Cl8_U	50,533	67,766	8,132	3,402
37T_Ref_Cl6-7_U	40,865	54,815	-	2,752
38RV_Cl8_R	70,090	93,186	11,182	4,678
39RV_Cl6-7_R	71,282	94,477	-	4,743
40RV_Cl4-5_R	48,713	64,883	-	3,257
42RV_Cl8_MP	70,090	93,186	11,182	4,678
43RV_Cl6-7_MP	66,465	88,199	-	4,428
44RV_Cl4-5_MP	45,641	60,878	-	3,056
46B_School_Cl8_MP	41,366	55,744	6,689	2,798
47B_School_Cl6-7_MP	28,900	39,233	-	1,970
48B_School_Cl4-5_MP	23,438	31,938	-	1,603
49B_School_Cl2b-3_MP	22,864	31,198	-	1,566
50B_School_Cl8_U	40,008	53,974	6,477	2,710
51B_School_Cl6-7_U	28,900	39,233	-	1,970
52B_School_Cl4-5_U	22,650	30,911	-	1,552
53B_School_Cl2b-3_U	22,053	30,140	-	1,513
54Tractor_SC_Cl8	133,049	175,840	21,101	8,827
55B_Shuttle_Cl2b-3_MP	27,814	37,649	-	1,890
56B_Shuttle_Cl4-5_U	27,176	36,810	-	1,848
57B_Shuttle_Cl2b-3_U	26,579	36,040	-	1,809
58B_Shuttle_Cl6-7_MP	38,872	52,231	-	2,622
59B_Shuttle_Cl6-7_U	37,031	49,832	-	2,502
60S_Plow_Cl6-7_MP	32,526	43,945	-	2,206
61S_Plow_Cl8_MP	55,156	73,887	8,866	3,709
62S_Plow_Cl6-7_U	31,310	42,359	-	2,126
63S_Plow_Cl8_U	54,513	73,048	8,766	3,667
64V_Step_Cl6-7_MP	29,591	40,113	-	2,014
65V_Step_Cl4-5_MP	22,378	30,556	-	1,534
66V_Step_Cl2b-3_MP	22,342	30,505	-	1,531
67V_Step_Cl6-7_U	28,328	38,466	-	1,931
68V_Step_Cl4-5_U	21,552	29,479	-	1,480
69V_Step_Cl2b-3_U	21,516	29,428	-	1,477
70S_Sweep_Cl6-7_U	30,851	41,761	-	2,096
71T_Tanker_Cl8_R	43,108	58,183	6,982	2,921
72T_Tanker_Cl8_MP	42,627	57,555	6,907	2,889
73T_Tanker_Cl8_U	42,494	57,382	6,886	2,881
74T_Tow_Cl8_R	56,968	76,248	9,150	3,828
75T_Tow_Cl6-7_R	42,293	56,675	-	2,845

Vehicle ID	PT DMC without Battery Tax Credit ($/veh)	PT RPE with Battery Tax Credit ($/veh)	FET ($/veh)	State Sales Tax ($/veh)
76T_Tow_Cl8_U	55,696	74,590	8,951	3,744
77T_Tow_Cl6-7_U	38,436	51,648	-	2,593
78Tractor_SC_Cl8	101,208	134,335	16,120	6,744
80Tractor_DC_Cl8	83,339	111,064	13,328	5,575
81Tractor_DC_Cl7	68,918	91,888	11,027	4,613
82Tractor_DC_Cl8	84,134	112,326	13,479	5,639
83Tractor_DC_Cl7	61,970	82,832	9,940	4,158
84Tractor_DC_Cl8	55,937	75,423	9,051	3,786
85B_Transit_Cl8_MP	61,220	81,623	9,795	4,097
86B_Transit_Cl6-7_MP	49,394	65,947	-	3,311
87B_Transit_Cl8_U	61,220	81,623	9,795	4,097
88B_Transit_Cl6-7_U	46,372	62,007	-	3,113
89T_Utility_Cl8_MP	41,662	56,298	6,756	2,826
90T_Utility_Cl8_R	42,285	57,110	6,853	2,867
91T_Utility_Cl6-7_MP	31,083	42,064	-	2,112
92T_Utility_Cl6-7_R	32,414	43,798	-	2,199
93T_Utility_Cl4-5_MP	23,475	31,985	-	1,606
94T_Utility_Cl2b-3_MP	22,844	31,159	-	1,564
95T_Utility_Cl4-5_R	24,272	33,025	-	1,658
96T_Utility_Cl2b-3_R	24,236	32,974	-	1,655
97T_Utility_Cl8_U	41,239	55,746	6,690	2,798
98T_Utility_Cl6-7_U	30,050	40,717	-	2,044
99T_Utility_Cl4-5_U	22,812	31,122	-	1,562
100T_Utility_Cl2b-3_U	22,093	30,179	-	1,515
101Tractor_DC_Cl8	48,503	65,732	7,888	3,300

2.4.4 BEV Operating Costs

Operating costs for HD vehicles encompass a variety of costs, such as labor, insurance, registration fees, charging, maintenance and repair (M&R), and other costs. For this analysis, we are primarily interested in costs that could differ for a comparable diesel-powered ICE vehicle and a ZEV. These operational cost differences are used to calculate an estimated payback period in HD TRUCS. We focus on charging costs, M&R costs, insurance costs, and ZEV state registration fees[1043] because we expect these costs to be different for ZEVs than for comparable ICE vehicles.

For each BEV in HD TRUCS, the 10-year average annual operating costs are as shown in Table 2-61 and described in the sections below. As discussed in Chapter 2.2.1.1.3, for the final version for HD TRUCS, we have assessed each year of operation using the appropriate changes that occur over time for inputs such as VMT, maintenance and repair, and fuel costs; however, we are continuing to show a 10-year average values in tables such as the one below, as a single value point of comparison. Note that the annual insurance cost represents the incremental

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[1043] Insurance costs and ZEV registration fees were not included in the proposal; EPA added these costs to the final version of HD TRUCS after consideration of comments. See RIA Chapter 2.4.4.3 and 2.4.4.4.

insurance cost of the BEV powertrain only, not the total insurance cost for the complete BEV. Appendix A to this RIA includes each year of a 10-year schedule for VMT.

Table 2-61 BEV Operating Costs for a MY 2032 Vehicle (2022$, 10-Year Average)

Vehicle ID	Annual BEV M&R ($/year)	Annual Charging Cost ($/year)	Annual Powertrain Insurance Cost[1044] + $100 annual ZEV Reg. Fee ($/year)
01V_Amb_Cl4-5_MP	1418	1063	1378
02V_Amb_Cl2b-3_MP	2065	1461	1321
03V_Amb_Cl4-5_U	1634	1141	1378
04V_Amb_Cl2b-3_U	1662	1088	1321
05T_Box_Cl8_MP	2759	4216	2535
06T_Box_Cl8_R	2683	4271	2535
07T_Box_Cl6-7_MP	1666	1757	1471
08T_Box_Cl6-7_R	1620	1874	1471
09T_Box_Cl8_U	2759	4085	2253
10T_Box_Cl6-7_U	1625	1579	1471
11T_Box_Cl2b-3_U	2481	1555	1301
12T_Box_Cl2b-3_R	2481	1834	1301
13T_Box_Cl2b-3_MP	2481	1688	1301
14T_Box_Cl4-5_U	1593	999	1305
15T_Box_Cl4-5_R	1593	1178	1305
16T_Box_Cl4-5_MP	1593	1084	1305
17B_Coach_Cl8_R	6534	15516	2016
19C_Mix_Cl8_MP	3735	10014	2253
20T_Dump_Cl8_U	1672	2666	2535
21T_Dump_Cl8_MP	1672	2700	2535
22T_Dump_Cl6-7_MP	2348	2619	1463
23T_Dump_Cl8_U	1672	2666	2253
24T_Dump_Cl6-7_U	2348	2452	1463
25T_Fire_Cl8_MP	1672	2835	2535
26T_Fire_Cl8_U	1672	2841	2253
27T_Flat_Cl6-7_MP	1666	1757	1463
28T_Flat_Cl6-7_R	1666	1911	1463
29T_Flat_Cl6-7_U	1666	1621	1463
30Tractor_DC_Cl8	3875	6345	2666
31Tractor_DC_Cl7	3876	5306	2118
32Tractor_SC_Cl8	17603	35944	2762
33Tractor_DC_Cl8	8617	18972	2142
34T_Ref_Cl8_MP	2237	4170	2126
35T_Ref_Cl6-7_MP	4028	6129	1463
36T_Ref_Cl8_U	2237	4170	2126
37T_Ref_Cl6-7_U	4028	6048	1463
38RV_Cl8_R	513	521	1525
39RV_Cl6-7_R	513	554	1467
40RV_Cl4-5_R	513	353	1279
42RV_Cl8_MP	513	521	1525
43RV_Cl6-7_MP	513	508	1467
44RV_Cl4-5_MP	513	323	1279
46B_School_Cl8_MP	1985	3275	1525

[1044] As described at the beginning of Chapter 2.3, this analysis is examining the incremental cost differences between a comparable ICE vehicle and ZEV technologies; therefore, insurance costs are estimated based on the upfront cost of powertrain components that are expected to differ for a comparable ICE vehicle and ZEV.s.

Vehicle ID	Annual BEV M&R ($/year)	Annual Charging Cost ($/year)	Annual Powertrain Insurance Cost[1044] + $100 annual ZEV Reg. Fee ($/year)
47B_School_Cl6-7_MP	2113	2101	1467
48B_School_Cl4-5_MP	1985	1471	1279
49B_School_Cl2b-3_MP	1985	1388	1336
50B_School_Cl8_U	1985	3102	1525
51B_School_Cl6-7_U	2113	2101	1467
52B_School_Cl4-5_U	1985	1370	1279
53B_School_Cl2b-3_U	1985	1285	1336
54Tractor_SC_Cl8	17603	42990	2762
55B_Shuttle_Cl2b-3_MP	4868	3301	1336
56B_Shuttle_Cl4-5_U	4868	3183	1279
57B_Shuttle_Cl2b-3_U	4868	3043	1336
58B_Shuttle_Cl6-7_MP	4868	5304	1467
59B_Shuttle_Cl6-7_U	4868	4920	1467
60S_Plow_Cl6-7_MP	1666	1874	1463
61S_Plow_Cl8_MP	1849	2934	2535
62S_Plow_Cl6-7_U	1666	1755	1463
63S_Plow_Cl8_U	1849	2884	2253
64V_Step_Cl6-7_MP	2546	2685	1460
65V_Step_Cl4-5_MP	1593	1084	1279
66V_Step_Cl2b-3_MP	2412	1656	1321
67V_Step_Cl6-7_U	2546	2477	1460
68V_Step_Cl4-5_U	1593	999	1279
69V_Step_Cl2b-3_U	2412	1525	1321
70S_Sweep_Cl6-7_U	2107	2404	1463
71T_Tanker_Cl8_R	2157	3644	2535
72T_Tanker_Cl8_MP	2157	3576	2253
73T_Tanker_Cl8_U	2157	3558	2253
74T_Tow_Cl8_R	2692	4452	2612
75T_Tow_Cl6-7_R	2344	2821	1463
76T_Tow_Cl8_U	2692	4310	2253
77T_Tow_Cl6-7_U	2344	2446	1463
78Tractor_SC_Cl8	12573	30805	2762
80Tractor_DC_Cl8	4431	10002	2792
81Tractor_DC_Cl7	8615	18971	2118
82Tractor_DC_Cl8	8615	22685	2762
83Tractor_DC_Cl7	4807	6544	2118
84Tractor_DC_Cl8	4794	12727	2598
85B_Transit_Cl8_MP	5612	8078	2016
86B_Transit_Cl6-7_MP	3312	3486	1467
87B_Transit_Cl8_U	5612	8078	1993
88B_Transit_Cl6-7_U	3312	3193	1467
89T_Utility_Cl8_MP	1116	1780	2535
90T_Utility_Cl8_R	1116	1825	2535
91T_Utility_Cl6-7_MP	2057	2377	1463
92T_Utility_Cl6-7_R	2057	2555	1463
93T_Utility_Cl4-5_MP	2057	1546	1378
94T_Utility_Cl2b-3_MP	941	671	1321
95T_Utility_Cl4-5_R	2000	1621	1378
96T_Utility_Cl2b-3_R	2000	1621	1321
97T_Utility_Cl8_U	1116	1749	2253
98T_Utility_Cl6-7_U	2057	2239	1463
99T_Utility_Cl4-5_U	2057	1458	1378

Vehicle ID	Annual BEV M&R ($/year)	Annual Charging Cost ($/year)	Annual Powertrain Insurance Cost[1044] + $100 annual ZEV Reg. Fee ($/year)
100T_Utility_Cl2b-3_U	941	625	1321
101Tractor_DC_Cl8	2412	3954	2598

2.4.4.1 Maintenance and Repair

Data on real-world maintenance and repair costs for heavy-duty BEVs is sparse due to limited heavy-duty BEV technology adoption today. We expect the overall maintenance costs to be lower for heavy-duty BEVs than for a comparable ICE vehicle for several reasons. First, an electric powertrain has fewer moving parts that accrue wear or need regular adjustments. Second, BEVs do not require fluids such as engine oil or DEF, nor do they require exhaust filters to reduce particulate matter or other pollutants. Third, the per-mile rate of brake wear is expected to be lower for BEVs due to regenerative braking systems. Several literature sources apply a scaling factor to diesel vehicle maintenance costs to estimate BEV maintenance costs.[1045,1046,1047] We followed this approach and, for the proposal, applied a repair cost scaling factor of 0.71 to the maintenance and repair costs for diesel-fueled ICE vehicles. The 0.71 scaling factor was based on an analysis from Wang et al. 2022, that estimates a future BEV HD vehicle would have a 29 percent reduction compared to a diesel-powered HD vehicle.[1048]

Commenters noted the potential need to retrain technicians to work on BEVs. We agree that there may be a transition period during which costs for maintaining and repairing BEVs will not be at their full savings potential due to the need to train more of the workforce to maintain and repair BEVs. To account for this period, in this final rule EPA has phased in the BEV scaling factors for maintenance and repair. Specifically, instead of applying a single scaling factor for every year commencing in 2027 as at proposal, EPA is starting with a higher scaling factor and gradually decreasing it (i.e., gradually increasing the projected cost savings) from calendar year 2027-2032. The initial higher scaling factor (0.88) also comes from Wang et al. and reflects estimates for 2022. EPA's approach of applying this factor commencing in 2027 is consequently conservative given that technicians in those later years will be more experienced than they were in 2022. These values, shown in Table 2-62, are multiplied by the annual diesel maintenance and repair costs by calendar year in order to assess the costs for BEV vehicle maintenance and repair.

[1045] Burnham, A., Gohlke, D., Rush, L., Stephens, T., Zhou, Y., Delucchi, M. A., Birky, A., Hunter, C., Lin, Z., Ou, S., Xie, F., Proctor, C., Wiryadinata, S., Liu, N., Boloor, M. "Comprehensive Total Cost of Ownership Quantification for Vehicles with Different Size Classes and Powertrains". Argonne National Laboratory. April 1, 2021. Available online: https://publications.anl.gov/anlpubs/2021/05/167399.pdf.

[1046] Hunter, Chad, Michael Penev, Evan Reznicek, Jason Lustbader, Alicia Birkby, and Chen Zhang. "Spatial and Temporal Analysis of the Total Cost of Ownership for Class 8 Tractors and Class 4 Parcel Delivery Trucks". National Renewable Energy Lab. September 2021. Available online: https://www.nrel.gov/docs/fy21osti/71796.pdf.

[1047] Burke, Andrew, Marshall Miller, Anish Sinha, et. al. "Evaluation of the Economics of Battery-Electric and Fuel Cell Trucks and Buses: Methods, Issues, and Results". August 1, 2022. Available online: https://escholarship.org/uc/item/1g89p8dn.

[1048] Wang, G., Miller, M., and Fulton, L." Estimating Maintenance and Repair Costs for Battery Electric and Fuel Cell Heavy Duty Trucks, 2022. Available online: https://escholarship.org/content/qt36c08395/qt36c08395_noSplash_589098e470b036b3010eae00f3b7b618.pdf?t=r6zwjb.

Table 2-62 Maintenance and Repair Scaling Factors for BEV CY 2027 – 2032+

CY	2027	2028	2029	2030	2031	2032+
Factor	0.88	0.846	0.812	0.778	0.744	0.71

In our payback analysis in HD TRUCS, we did not account for potential diesel engine rebuild costs for ICE vehicles, potential replacement battery costs for BEVs, or potential replacement fuel cell stack costs for FCEVs because our payback analysis typically covers a shorter period of time than the expected life of these components. Typical battery warranties being offered by HD BEV manufacturers range between 8 and 15 years today.[1049] A BEV battery replacement may be practically necessary over the life of a vehicle if the battery deteriorates to a point where the vehicle range no longer meets the vehicle's operational needs. We believe that proper vehicle and battery maintenance and management can extend battery life, and our use of 2,000 cycles for battery sizing in HD TRUCS is a conservative means of assuring that no battery replacement is needed for the first 10 years of a vehicle at issue in our HD TRUCS analysis. See RIA Chapter 2.4.1.1.4. For example, manufacturers can utilize battery management system to maintain the temperature of the battery[1050] as well active battery balancing to extend the life of the battery.[1051,1052] Likewise, pre-conditioning has also shown to extend the life of the battery as well.[1053] Furthermore, research suggests that battery life is expected to improve with new batteries over time as battery chemistry and battery charging strategies improve, such that newer MY BEVs will have longer battery life.

2.4.4.2 Charging Costs

The annual charging cost is a function of the electricity price, daily energy consumption of a BEV, and number of operating days in a year. There are energy losses between the meter and the battery associated with the AC/DC converter and battery charge and discharge that are in addition to the losses accounted for in the electrified powertrain (as described in RIA Chapter 2.4.1.1.3) so the electrical power purchased (as measured at the meter) is greater than the electrical power applied at the axle. For the AC/DC converter we used an efficiency value of 94% and a value of 95% for battery charge and discharge efficiency, consistent with the values used in MOVES.

For the final rule, we differentiate between depot charging and public charging when assigning charging costs. We have also expanded the scope of what is covered in these costs to more accurately capture the cost of charging. The charging costs we use for both charging types

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[1049] Type C BEV school bus battery warranty range five to fifteen years according to https://www.nyapt.org/resources/Documents/WRI_ESB-Buyers-Guide_US-Market_2022.pdf. The Freightliner electric walk-in van includes an eight year battery warranty according to https://www.electricwalkinvan.com/wp-content/uploads/2022/05/MT50e-specifications-2022.pdf.

[1050] Basma, Hussein, Charbel Mansour, Marc Haddad, Maroun Nemer, Pascal Stabat. "Comprehensive energy modeling methodology for battery electric buses". Energy: Volume 207, 15 September 2020, 118241. Available online: https://www.sciencedirect.com/science/article/pii/S0360544220313487.

[1051] Bae, SH., Park, J.W., Lee, S.H. "Optimal SOC Reference Based Active Cell Balancing on a Common Energy Bus of Battery" Available online: http://koreascience.or.kr/article/JAKO201709641401357.pdf.

[1052] Azad, F.S., Ahasan Habib, A.K.M., Rahman, A., Ahmed I. "Active cell balancing of Li-Ion batteries using single capacitor and single LC series resonant circuit." https://beei.org/index.php/EEI/article/viewFile/1944/1491.

[1053] Prejean, Louis. "How to Improve EV Battery Performance in Cold Weather" Accessed on March 31, 2023. https://www.worktruckonline.com/10176367/how-to-improve-ev-battery-performance-in-cold-weather.

include the cost of electricity as charged by the utility (cents/kWh) as well as costs for EVSE maintenance and grid distribution upgrades (expressed in cents/kWh).[1054] Our public charging price additionally includes the amortized cost of public charging equipment, land costs for the station and other costs described below; we project that third parties may install and operate these stations and pass costs onto BEV owners via charging costs.

To estimate charging costs, we start by modeling future electricity prices, as charged by utilities, that account for the costs of BEV charging demand and the associated distribution system upgrade costs. We do this in three steps: 1) we model future power generation using the Integrated Planning Model (IPM), 2) we estimate the cost of distribution system upgrades associated with charging demand through the DOE Transportation Electrification Impact Study (TEIS),[1055] and 3) we use the Retail Price Model to project electricity prices accounting for both (1) and (2).

As described in RIA Chapter 4.2, IPM models the power sector, including changes to power generation based on future demand scenarios. In order to capture the potential future impacts on the power sector from ZEVs, we ran IPM for a scenario that combined electricity demand from an interim version of the final standards case and EPA's proposed rulemaking "Multi-Pollutant Emissions Standards for Model Years 2027 and Later Light-Duty and Medium-Duty Vehicles."[1056],[1057] The same demand scenario was used as the action case for the TEIS.[1058] The TEIS research team modeled how many new or upgraded substations, feeders, and transformers would be needed to meet projected electricity demand from transportation, including demand from residential workplace, depot, and public charging to support projected light-, medium-, and heavy-duty plug-in electric vehicles. For all public and workplace charging, vehicles were assumed to charge at full power upon arrival. At homes and depot charging stations—where vehicles have longer dwell times—a conservative managed charging scenario was developed to spread out charging and reduce peak power (vehicles arriving at charging locations minimize charging power such that the session is completed when the vehicle departs).[1059] (See RIA Chapter 1.6.5 for a discussion of the potential benefits of managed charging to fleet owners.)

[1054] While EVSE maintenance costs associated with depot charging infrastructure may be borne directly by the fleet owner, it will occur over the lifetime of the EVSE rather than as an upfront capital cost. Therefore, we have accounted for it as part of our operating cost analysis rather than as part of the upfront depot EVSE costs discussed in RIA Chapter 2.6.2.

[1055] National Renewable Energy Laboratory, Lawrence Berkeley National Laboratory, Kevala Inc., and U.S. Department of Energy. "Multi-State Transportation Electrification Impact Study: Preparing the Grid for Light-, Medium-, and Heavy-Duty Electric Vehicles". DOE/EE-2818. U.S. Department of Energy. March 2024.

[1056] Multi-Pollutant Emissions Standards for Model Years 2027 and Later Light-Duty and Medium-Duty Vehicles (88 FR 29184, May 5, 2023)

[1057] Electricity demand for heavy-duty ZEVs was based on the interim control case described in RIA Chapter 4.2.4 and for light- and medium-duty vehicles was based Alternative 3 from the proposed "Multipollutant Emissions Standards for Model Years 2027 and Later Light-Duty and Medium-Duty Vehicles." See the TEIS report for more information on the modeled ('Action', 'Managed') scenario, and how demand was allocated by region and time of day.

[1058] National Renewable Energy Laboratory, Lawrence Berkeley National Laboratory, Kevala Inc., and U.S. Department of Energy. "Multi-State Transportation Electrification Impact Study: Preparing the Grid for Light-, Medium-, and Heavy-Duty Electric Vehicles". DOE/EE-2818. U.S. Department of Energy. March 2024 at 3.

[1059] TEIS at 4.

The changes to power generation in our modeled IPM scenario and the distribution cost estimates from TEIS[1060] were then input to the Retail Price Model (RPM).[1061] The RPM developed by ICF generates estimates for average electricity prices over consumer classes accounting for the regional distribution of electricity demand. The resulting national average retail prices, which include distribution upgrade costs, were used as a basis for the charging costs in HD TRUCS and are shown in Table 2-63. For comparison purposes, we also estimated retail prices for the same demand scenario without including the distribution upgrades costs associated with charging demand. We find that electricity prices would be 11.1 (rather than 11.3) cents/kWh in 2030 and 9.8 (rather than 10.4) cents/kWh in 2050 showing the cost of distribution upgrades increased electricity prices between about two percent and six percent over this timeframe. As described in RTC Section 7, for comparison purposes, we also ran IPM and RPM for a no action case with unmanaged charging.[1062] We think this is a reasonable comparison to make given the considerable economic benefits of managed charging, particularly in light of the increased EV adoption associated with the modeled potential compliance pathway of the final rule, which provides an extremely strong economic incentive for market actors to adopt managed charging practices. Our analysis projects that there is almost no difference in retail electricity prices in 2030 and the difference in 2050 is only about 2.5 percent.

Table 2-63 Retail Electricity Prices for select years (2022 cents/kWh) [1063,1064]

2027	2028	2030	2035	2040	2045	2050	2055
11.8	11.8	11.3	11.2	11.1	10.8	10.4	10.4

To estimate depot charging costs in HD TRUCS, we add 0.52 cents/kWh to the RPM results in Table 2-63 (and for intermediate years) to account for EVSE maintenance costs. This value is from a recent ICCT study[1065] which was suggested in public comments (see RTC Section 6). For public charging, we project an electricity price of 19.6 cents/kWh for 2027 and adjust it for future years according to the results of the IPM Retail Price Model discussed above. The initial value from the same ICCT study[1066] reflects costs for public charging at stations designed for

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[1060] Electricity demand for heavy-duty ZEVs was based on the interim control case described in RIA Chapter 4.2.4 and for light- and medium-duty vehicles was based Alternative 3 from the proposed "Multipollutant Emissions Standards for Model Years 2027 and Later Light-Duty and Medium-Duty Vehicles." See the TEIS report for more information on the modeled ('Action', 'Managed') scenario, and how demand was allocated by region and time of day.

[1061] ICF. "Documentation of the Retail Price Model. Draft." 2019. Available online: https://www.epa.gov/sites/default/files/2019-06/documents/rpm_documentation_june2019.pdf.

[1062] This scenario is the TEIS 'No Action', 'Unmanaged' scenario, see TEIS 2-4 for details.

[1063] IPM and the RPM were run for select years between 2028 and 2050. We used linear interpolation for electricity prices between model run years from 2028–2050. We kept electricity prices constant for 2050+ and assumed the 2027 price was the same as 2028. We converted outputs of the RPM from 2019$ to 2022$.

[1064] The results from the RPM (along with input files used for power sector modeling) discussed here are available in the docket. (See Evan Murray. Memorandum to Docket EPA-HQ-OAR-2022-0985. "Files from IPM Runs Supporting FRM Modeling." March 2024.)

[1065] Hussein Basma, Claire Buysee, Yuanrong Zhou, and Felipe Rodriguez. "Total Cost of Ownership of Alternative Powertrain Technologies for Class 8 Long-haul Trucks in the United States." April 2023. Available online: https://theicct.org/wp-content/uploads/2023/04/tco-alt-powertrain-long-haul-trucks-us-apr23.pdf.

[1066] Hussein Basma, Claire Buysee, Yuanrong Zhou, and Felipe Rodriguez. "Total Cost of Ownership of Alternative Powertrain Technologies for Class 8 Long-haul Trucks in the United States." April 2023. Available online: https://theicct.org/wp-content/uploads/2023/04/tco-alt-powertrain-long-haul-trucks-us-apr23.pdf.

long-haul vehicles. Stations are assumed to have seventeen 1 MW EVSE ports and twenty 150 kW EVSE ports for a total peak power capacity of 20 MW. The 19.6 cents/kWh price includes the amortized cost of this charging equipment, land costs, both electricity prices (cents/kWh) and demand charges (cents/kW) associated with high peak power, distribution upgrade costs for substations, feeders, and transformers, and EVSE maintenance costs. As discussed in Chapter 2.6.2.1.2, we expect the 30C tax credit[1067] to significantly reduce the costs for procuring and installing EVSE where applicable. DOE assessed the average value of this tax credit for both depot and public charging infrastructure serving HD BEVs taking into account the potential share of EVSE in eligible census tracts, 30C prevailing wage and apprenticeship requirements and the $100,000 per item cap.[1068] DOE estimated average value of this tax credit for public charging infrastructure to be 27 percent of the installed costs for EVSE under 1 MW, and 19 percent for 1 MW or higher EVSE. However, we did not reduce the amortized cost of public charging infrastructure (which was sourced from the ICCT study) to account for this tax credit, and therefore, these costs may be considered conservative.

We apply public electricity prices to long-haul vehicles, some longer-range day cab tractors and coach buses. Overall, our charging costs used in the final rule analysis are higher than those used in the NPRM analysis, particularly since those costs now reflect maintenance, grid distribution upgrades, and public charging costs.

Table 2-64 Charging Costs (2022$)

CY	Depot (cents/kWh)	Public (cents/kWh)
2027	12.36	19.60
2028	12.36	19.60
2029	12.09	19.33
2030	11.83	19.07
2031	11.81	19.05
2032	11.79	19.03
2033	11.77	19.02
2034	11.76	19.00
2035	11.74	18.98
2036	11.72	18.97
2037	11.71	18.95
2038	11.70	18.94
2039	11.68	18.92
2040	11.67	18.91
2041	11.61	18.85

2.4.4.3 Insurance Cost

In the NPRM analysis, we did not take into account the cost of insurance on the ZEV purchaser. A few commenters suggested we should consider the addition of insurance cost because the incremental cost of insurance for the ZEVs will be higher than for ICE vehicles. We

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[1067] IRA Section 13404, “Alternative Fuel Refueling Property Credit” under section 26 U.S. Code §30C, referred to as 30C in this document.

[1068] U.S. DOE, “Estimating Federal Tax Incentives for Heavy Duty Electric Vehicle Infrastructure and for Acquiring Electric Vehicles Weighing Less Than 14,000 Pounds,” Memorandum, March 2024.

agree that insurance costs may differ between these vehicle types and that this is a cost that will be seen by the operator. Therefore, for the final rule analysis in HD TRUCS, we included the incremental insurance costs of a ZEV relative to an ICE vehicle by incorporating an annual insurance cost. A commenter recommended using an insurance rate of 3%, based originally on an ICCT April 2023 paper on ZEV TCO.[1069] We have reviewed the comment and the ICCT White Paper and consider the 3% insurance rate to be reasonable. Similar to sales tax and the FET, insurance costs are calculated as a percentage, after applying the RPE, to the upfront costs shown in Table 2-60; however, unlike the sales tax and FET, the insurance costs are added to operating costs each year in HD TRUCS, as part of the payback calculation. See Table 2-61 for MY 2032 BEV insurance costs.

2.4.4.4 ZEV Registration Fee

Some states have adopted ZEV registration fees. Though 18 states do not have an additional ZEV registration fee, of the 32 states that do, the registration fees are generally between $50 and $225 per year.[1070] While EPA cannot predict whether and to what extent other states will enact ZEV registration fees, we have nonetheless conservatively added an annual registration fee of $100 to all ZEV vehicles in our final HD TRUCS analysis. See RTC Section 3 for further discussion.

2.5 Fuel Cell Electric Vehicle Technology

We considered HD FCEVs for select applications that travel long distances and/or have heavy loads. Our analysis in HD TRUCS evaluates a FCEV as having similar components as a BEV plus a fuel cell and an onboard hydrogen storage tank, with variations in the sizing of key components. Rather than focusing on depot hydrogen fueling infrastructure costs that would be incurred upfront, we included infrastructure costs in our per-kilogram retail price of hydrogen.[1071] This approach is consistent with the method we use in HD TRUCS for ICE vehicles, where the equivalent diesel fuel costs are included in the diesel fuel price instead of accounting for the costs of fuel stations separately, and consistent as well with our inclusion of public charging infrastructure costs within the price of charging (see RIA Chapter 2.4.4.2 above).

To compare ICE and heavy-duty FCEV technology costs and performance, this section explains how we characterize heavy-duty FCEVs based on the performance and use criteria in RIA Chapter 2.2. First, we determined the size of key FCEV components based on power requirements and the hydrogen fuel amount required to meet the energy and daily operational needs of each vehicle, and projected energy and fuel use for each FCEV application (kWh/mi) on an annual basis. Then, we estimated upfront DMC of FCEV components. Next, the upfront DMC costs are presented as RPE costs, and state sales tax and excise taxes are added, where applicable. Lastly, we projected the hydrogen fueling costs, maintenance and repair costs, insurance costs, and an annual ZEV registration fee for each vehicle type for the first ten years of vehicle operation. Table 2-65 shows the technical properties for four vehicle types that travel

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[1069] Basma, Hussein, et.al. “Total Cost of Ownership of Alternative Powertrain Technologies for Class 8 Long-Haul Trucks in the United States.” April 2023. Page 17. Available online: https://theicct.org/wp-content/uploads/2023/04/tco-alt-powertrain-long-haul-trucks-us-apr23.pdf

[1070] National Conference of State Legislatures. “Special Fees on Plug-In Hybrid and Electric Vehicles” March 2023, Available at: https://www.ncsl.org/energy/special-fees-on-plug-in-hybrid-and-electric-vehicles..

[1071] Retail price of hydrogen is the total price of hydrogen when it becomes available to the end user, including the costs of production, distribution, storage, and dispensing at a fueling station.

long distances (e.g., for duty cycles where the volume or weight of a BEV battery may impact payload).[1072] The FCEV properties analyzed in HD TRUCS as part of the compliance pathway to support the final standards include power output of the fuel cell and e-motor, battery energy, hydrogen fuel tank capacity, and daily hydrogen fuel use.

Table 2-65 Technical Properties of the FCEV for MY 2032

Vehicle ID	Fuel Cell Size (kW)	E-Motor Peak Power (kW)	Battery Energy (kWh)	H2 Fuel Tank Capacity (kg)	Daily H2 Fuel Use (kg)
18B_Coach_Cl8_MP	182	322	33	53	16
41Tractor_DC_Cl7_R	190	367	67	38	20
45Tractor_DC_Cl8_R	265	528	98	45	24
79Tractor_SC_Cl8_R	285	400	58	51	44

2.5.1 Fuel Cell Electric Vehicle Component Sizing

To compare HD FCEV technology costs and performance to a comparable ICE vehicle in HD TRUCS, this section explains how we define HD FCEVs based on the performance and use criteria. We determined the e-motor, fuel cell system, and battery pack sizes to meet the power requirements for each of the four FCEVs represented in HD TRUCS, as described in the following subsections. We also estimated the size of the onboard fuel tank needed to store the fuel, in the form of hydrogen, required to meet typical range and duty cycle needs. Finally, based on component sizing, we determined the cost of these vehicles.

2.5.1.1 Component Sizing Based on Power Needs

2.5.1.1.1 E-Motor

As discussed in Chapter 2.4.1.2, the e-motor is part of the electric drive system that converts the electric power from the battery or fuel cell into mechanical power to move the wheels of the vehicle. In HD TRUCS, the e-motor was sized for a FCEV like it was sized for a BEV (see RIA Chapter 2.4.1.2) – to meet peak power needs of a vehicle, which is the maximum requirement to drive the ARB transient cycle, meet the maximum time to accelerate from 0 to 30 mph, meet the maximum time to accelerate from 0 to 60 mph, and maintain a set speed up a six-percent grade.

2.5.1.1.2 Fuel Cell System

Vehicle power in a FCEV comes from a combination of the fuel cell stack and the battery pack. The fuel cell converts chemical energy stored in the hydrogen fuel into electrical energy. The battery is charged by power derived from regenerative braking, as well as excess power from the fuel cell. Some FCEVs are designed to rely on the fuel cell stack to produce the necessary power, with the battery primarily used to capture energy from regenerative braking. This is the type of HD FCEV that we modeled in HD TRUCS for the MY 2030 to 2032

[1072] This does not mean that a BEV with large battery weight and volume is not technically feasible. Rather, this is an acknowledgement that as battery size increases, cost is likely to increase, which can affect purchase price and payback.

timeframe in order to meet the longer distance requirements of select vehicle applications.[1073,1074,1075]

While much of FCEV design is dependent on the use case of the vehicle, manufacturers also balance the cost of components such as the FC stack, the battery, and the hydrogen fuel storage tanks. For the purposes of this HD TRUCS analysis, we focused on proton-exchange membrane (PEM) fuel cells that use batteries with energy cells (described in RIA Chapter 1.7.2), where the fuel cell and the battery were sized based on the demands of the vehicle. In HD TRUCS, the fuel cell system (i.e., fuel cell stacks plus balance of plant, or BOP) was sized at either the 90th percentile of power required for driving the ARB transient cycle or to maintain a constant highway speed of 75 mph with 80,000-pound gross combined vehicle weight (GCVW). The 90th percentile power requirement was used to size the fuel cells of vocational vehicles and day cab tractors, and the 75-mph power requirement was used to size the fuel cells of sleeper cab tractors.[1076]

As explained below, we revised our sizing methodology for the fuel cell system in the final rule version of HD TRUCS.

To avoid undersizing the fuel cell system, we oversized the fuel cell stack by an additional 25 percent to allow for occasional scenarios where the vehicle requires more power (e.g., to accelerate when the battery state of charge is low, to meet unusually long grade requirements, or to meet other infrequent extended high loads like a strong headwind) and so the fuel cell can operate within an efficient region. This size increase we included in the final rule version of HD TRUCS can also improve fuel cell stack durability and ensure the fuel cell stack can meet the power needs throughout the useful life. This is the system's net peak power, or the amount available to power the wheels.[1077] The fuel cell stack generates power, but some power is consumed to operate the fuel cell system before it gets to the e-motor. Therefore, we increased

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[1073] Islam, Ehsan Sabri, Ram Vijayagopal, Aymeric Rousseau. "A Comprehensive Simulation Study to Evaluate Future Vehicle Energy and Cost Reduction Potential",Report to the U.S. Department of Energy, Contract ANL/ESD-22.6, October 2022. See Full report. Available online: https://anl.app.box.com/s/an4nx0v2xpudxtpsnkhd5peimzu4j1hk/file/1406494585829.

[1074] Note that ANL's analysis defines a fuel cell hybrid EV (FCHEV) as a battery-dominant vehicle with a large energy battery pack and a small fuel cell, and a fuel cell EV (FCEV) as a fuel cell-dominant vehicle with a large fuel cell and a smaller power battery. Ours is a slightly different approach because we consider a fuel cell-dominant vehicle with a large battery with energy cells. The approach we took is intended to cover a wide range of vehicle applications however it results in a conservative design, as it relies on a large fuel cell and a larger energy battery. As manufacturers design FCEV for specific HD applications, they will likely end up with a more optimized lower cost designs. Battery-dominant FCHEVs and fuel cell-dominant technologies with power batteries may also be feasible in this timeframe but were not evaluated for the FRM.

[1075] FEV Consulting. "Heavy Duty Commercial Vehicles Class 4 to 8: Technology and Cost Evaluation for Electrified Powertrains—Final Report". Prepared for EPA. March 2024.

[1076] In the NPRM version of HD TRUCS, we inadvertently used the 90th percentile of the ARB transient cycle to size the sleeper and day cab tractors and the power required to drive at 75 mph to size the vocational vehicles. This error is corrected in the final version of HD TRUCS.

[1077] Net system power is the gross stack power minus balance of plant losses. This value can be called the rated power.

the size of the system by an additional 20 percent[1078] to account for operation of balance of plant components that ensure that gases entering the system are at the appropriate temperature, pressure, and humidity and remove heat generated by the stack. This is the fuel cell stack gross power.

The larger fuel cell can allow the system to operate more efficiently based on its daily needs, which results in less wasted energy and lower fuel consumption. This additional size also adds durability, which is important for commercial vehicles, by allowing for some degradation over time. We determined that with this upsizing, there is no need for a fuel cell system replacement within the 10-year period at issue in the HD TRUCS analysis.

2.5.1.1.3 Battery Pack

In HD TRUCS, the battery power accounts for the difference between the peak power of the e-motor and the continuous power output of the fuel cell system. We sized the battery to meet these power needs in excess of the fuel cell's capability only when the fuel cell cannot provide sufficient power. In our analysis, the remaining power needs are sustained for a duration of 10 minutes (e.g., to assist with a climb up a steep hill).

Since a FCEV operates like a hybrid vehicle, where instantaneous power comes from a combination of the fuel cell stack and the battery, the battery is sized smaller than a battery in a BEV, which can result in more cycling of the FCEV battery. Thus, we reduced the FCEV battery's depth of discharge from 80 percent in the NPRM to 60 percent in the final rule version of HD TRUCS to reflect the usage of a hybrid battery more accurately. This means the battery is oversized by in HD TRUCS to account for potential battery degradation over time.[1079]

2.5.1.2 Onboard Hydrogen Storage Tank Sizing Based on Energy Needs

A FCEV is re-fueled like a gasoline or diesel-fueled ICE vehicle. We determined the capacity of the onboard hydrogen energy storage system using an approach like the BEV methodology for battery pack sizing in RIA Chapter 2.4.1.1, but we based the amount of hydrogen needed on the daily energy consumption needs of a FCEV.

Daily energy consumption is a summation of ZEV baseline energy and powertrain-specific energy. A detailed description of ZEV baseline energy, which includes the energy used at the axle to move the vehicle, regenerative braking, and PTO load, can be found in RIA Chapter 2.2.2.1. The powertrain-specific energy demand includes energy losses associated with the fuel cell system (based on fuel cycle efficiency) as well as energy used for HVAC and battery conditioning.

Hydrogen fuel in the tank enters the fuel cell stacks, where an electrochemical reaction converts the hydrogen into electricity. During the conversion process, energy from the hydrogen fuel is lost as heat or otherwise does not go towards producing electricity. The remaining energy is used to operate the fuel cell system. Based on consideration of comments, we agree the fuel

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[1078] Huya-Kouadio, Jennie and Brian D. James. "Fuel Cell Cost and Performance Analysis: Presentation for the DOE Hydrogen Program; 2023 Annual Merit Review and Peer Evaluation Meeting". Strategic Analysis. June 6, 2023. Available online: https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/review23/fc353_james_2023_o-pdf.pdf.

[1079] Ceschia, et. al. "Optimal Sizing of Fuel Cell Hybrid Power Sources with Reliability Consideration". Energies, Volume 13, Issue 13. 2020. Available online: https://www.mdpi.com/1996-1073/13/13/3510.

cell efficiency values used in the NPRM were too high and therefore reduced them, as described in RIA Chapter 2.5.1.2.1.

For the final rule, we combined the revised fuel cell system efficiency value with the BEV powertrain efficiencies (i.e., the combined inverter, gearbox, and e-motor efficiencies from Table 2-44). Table 2-66 includes the estimated total FCEV powertrain efficiencies to account for losses that take place before the remaining energy arrives at the axle. The final FCEV powertrain efficiencies were used to size the hydrogen storage tanks and to determine the hydrogen usage and related costs.

The ZEV baseline energy loads from RIA Chapter 2.2.2 and the powertrain-specific energy loads are reported in terms of kWh/mi, which we converted into kWh/day using the daily sizing VMT. This daily energy consumption was then used to size the hydrogen fuel tank and eventually to estimate its cost. Since literature frequently provides cost of a hydrogen fuel tank in terms of $ per kg of hydrogen, to determine the hydrogen tank size, we converted the energy demand of each vehicle in HD TRUCS (kWh) into) into hydrogen weight using an energy content of 33.33 kWh per kg of hydrogen. In our analysis, 95 percent of the hydrogen in the tank ("usable H2") can be accessed. This is based on targets for light-duty vehicles, where a 700-bar hydrogen fuel tank with a capacity of 5.9 kg has 5.6 kg of usable hydrogen.[1080] Furthermore, we added 10 percent to the tank to avoid complete depletion of hydrogen from the tank.

2.5.1.2.1 Fuel Cell System Efficiency

Fuel cell system efficiency is an important factor for sizing the hydrogen tank. For the NPRM, we used the DOE fuel cell efficiency target values that ranged between 64.5 and 66 percent and requested comment on these values. We received comments suggesting that the NPRM did not accurately reflect how a fuel cell operates because we relied on peak fuel cell efficiency rather than average operating efficiency. One commenter noted that FCEVs would benefit from BEV component efficiency gains and observed that we did not utilize the DOE targets for peak fuel cell efficiency in HD TRUCS, implying that fuel cells could be more efficient than we assumed in the NPRM because a more efficient stack would require less cooling, which could lead to compounded gains over time. Three commenters suggested that the fuel cell efficiency values used in the NPRM were too high. One commenter pointed out that we considered peak efficiency estimates in error rather than average operating efficiencies. The same commenter and another offered ranges for operating efficiency at power levels typical for commercial vehicles and suggested that we revise our fuel cell efficiency estimates. One of the same commenters noted that fuel cell performance degrades over time, generally due to impurities in hydrogen fuel that cause efficiencies to drop significantly from beginning of life to end of life. We evaluated these comments and find those about considering fuel cell efficiencies at more average rather than peak operating conditions to be persuasive. Accordingly, we have made revisions consistent with the commenters' suggestions.

[1080] U.S. DRIVE Partnership. "Target Explanation Document: Onboard Hydrogen Storage for Light-Duty Fuel Cell Vehicles". U.S. Department of Energy. 2017. Available online: https://www.energy.gov/sites/prod/files/2017/05/f34/fcto_targets_onboard_hydro_storage_explanation.pdf.

Figure 2-8 (which is shared to be illustrative) shows the shape of an efficiency curve for a fuel cell system in a HD FCEV in terms of normalized net power. A typical fuel cell system operates most efficiently at lower or partial power loads. For example, the figure demonstrates a peak efficiency of about 65 percent at roughly 10 percent power load compared to an efficiency of around 55 percent at full power on a normalized scale.

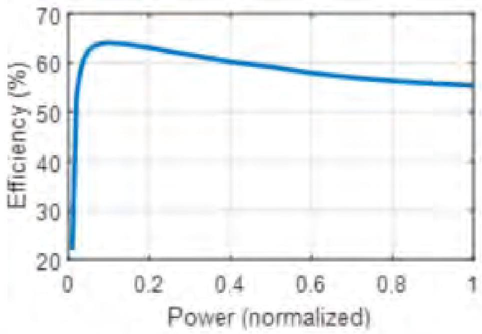

FIGURE 2-11 Operating efficiency of the fuel cell plotted against the normalized net power output

Figure 2-8: Operating Efficiency of a Fuel Cell[1081]

Based on a review of comments, we agree that the fuel cell system efficiency values used in the NPRM were too high and should not be based on peak performance at low power, since fuel cells typically do not operate long in that range. We therefore reduced them by eight percent to reflect an average operating efficiency instead of peak efficiency. This was based on a review of DOE’s 2019 Class 8 Fuel Cell Targets. DOE has an ultimate target for peak efficiency of 72 percent, which corresponds to an ultimate fuel cell drive cycle efficiency of 66 percent. This equates to an 8 percent difference between peak efficiency and drive cycle efficiency at a more typical operating power. Therefore, to reflect system efficiency more accurately at a typical operating power, we applied the 8 percent difference to the peak efficiency estimate in the NPRM. For the final rule, the operational efficiency of the fuel cell system (i.e., represented by drive cycle efficiency) is about 61 percent.

[1081] Islam, Ehsan Sabri, Ram Vijayagopal, Aymeric Rousseau. “A Comprehensive Simulation Study to Evaluate Future Vehicle Energy and Cost Reduction Potential”, Report to the U.S. Department of Energy, Contract ANL/ESD-22.6, October 2022. Available online: https://anl.app.box.com/s/an4nx0v2xpudxtpsnkhd5peimzu4j1hk/file/1406494585829.

Table 2-66 Powertrain Efficiencies for FCEV

GEM Energy ID	Combined inverter, gearbox, e-motor and FC system efficiency
C7_DC_HR	56%
C8_DC_HR	56%
C8_HH	56%
C8_SC_HR	57%
C8_SC_HR_CdA036	57%
C8_DC_HR_CdA036	56%
C7_DC_HR_CdA036	56%
HHD_R	56%
HHD_M	54%
HHD_U	51%
MHD_R	54%
MHD_M	52%
MHD_U	51%
LHD_R	54%
LHD_M	52%
LHD_U	51%
RV	54%
School Bus	51%
Coach Bus	56%
Emergency	51%
Concrete Mixer	51%
Transit Bus	51%
Refuse Truck	51%

More information on ambient temperature impact on powertrain-specific energy demand can be found in the following section.

2.5.1.2.2 HVAC and Battery Conditioning

Fuel cell stacks produce excess heat during the conversion of hydrogen to electricity, like an engine during combustion. This excess heat can be used to heat the interior cabin of the vehicle. In HD TRUCS, no additional energy consumption is applied to FCEVs for heating operation, and we already accounted for the energy loads due to ventilation in the axle loads. Therefore, for FCEV energy consumption, we only include additional energy requirements for air conditioning.[1082] As described in RIA Chapter 2.4.1.1.1, we assigned a power demand of 3.32 kW for powering the air conditioner on a Class 8 bus. The HVAC loads are then scaled by the cabin volume for other vehicle applications in HD TRUCS and applied to the VMT fraction that requires cooling.

Since the batteries in FCEVs have the same characteristics as batteries for BEVs, for battery conditioning, we used the methodology described in RIA Chapter 2.4.1.1.2 for BEVs to estimate the energy consumption of the battery.

[1082] We assume that FCEVs use waste heat from the fuel cell for heating, and that ventilation operates the same as it does for an ICE vehicle.

2.5.2 FCEV Components Costs

FCEVs and BEVs include many of the same components such as a battery pack, e-motor, power converter and electric accessories, gearbox unit, and final drive. Therefore, we used the same costs across vehicles for the same applications; for detailed descriptions of these components, see RIA Chapter 2.4.3. In this subsection, we present the costs for components for FCEVs that are different from a BEV. These components include the fuel cell system and hydrogen fuel tank. The same energy cell battery costs used for BEVs are used for FCEVs, but the battery size of a comparable FCEV is smaller.[1083] Table 2-67 shows the component level and total powertrain direct manufacturing costs for the eight FCEVs for MY 2032, which are described in more detail in the following subsections.

As described in Chapter 1.3.2, the IRA provides a tax credit to reduce the cost of producing qualified batteries (battery tax credit) and to reduce the cost of purchasing qualified ZEVs (vehicle tax credit).[1084] The battery tax credit is considered in HD TRUCS before determining the total incremental RPE, as described in RIA Chapter 2.4.3.1.

Table 2-67 FCEV Direct Manufacturing Costs and IRA Tax Credit for MY 2032 (2022$)

Vehicle ID	FC Stack ($/unit)	E-Motor ($/unit)	H2 Fuel Tank ($/unit)	Battery without IRA Battery Tax Credit ($/unit)	Power Converter and Electric Accessorie s($/unit)	Gearb ox ($/unit)	Final Drive ($/unit)	FCEV PT Cost ($/veh)	IRA Tax Credit ($/unit)
18B_Coach_Cl8_MP	$29,096	$ 5,391	$32,525	$3,158	$5,997	$2,415	$1,644	$79,956	$368
41Tractor_DC_Cl7	$30,381	$6,148	$23,310	$6,442	$5,745	$1,978	$3,287	$77,291	$751
45Tractor_DC_Cl8	$42,353	$8,848	$27,919	$9,423	$5,810	$4,393	$3,287	$102,033	$1,098
79Tractor_SC_Cl8	$45,497	$6,700	$31,675	$5,633	$5,853	$4,385	$3,287	$103,030	$656

It is important to note that, as described in the subsequent sections, the cost of FCEV components will depend heavily on manufacturing volumes and economies of scale. Modeling of compliance pathways for this rulemaking conducted using HD TRUCS yielded estimates of roughly 10,000 FCEVs per year by 2032. This manufacturing volume informed estimates of component costs, but may be conservative, particularly if research and development (R&D) success toward DOE targets is achieved or if large-scale infrastructure deployments occur faster than assumed. Analysis that informed DOE's National Clean Hydrogen Strategy and Roadmap identified scenarios where 10 to 14 percent of the truck stock in 2050 could utilize hydrogen and

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[1083] Sharpe, Ben and Hussein Basma. "A Meta-Study of Purchase Costs for Zero-Emission Trucks". The International Council on Clean Transportation. February 2022. Available online: https://theicct.org/publication/purchase-cost-ze-trucks-feb22/.

[1084] Inflation Reduction Act of 2022, Pub. L. No. 117-169, 136 Stat. 1818 (2022). Available online: https://www.congress.gov/117/bills/hr5376/BILLS-117hr5376enr.pdf.

fuel cells (representing annual sales of ~40,000 trucks per year in 2032), if hydrogen fuel is available at $4 per kg and DOE's targets for technology cost are achieved.[1085,1086,1087]

2.5.2.1 Fuel Cell System Costs

The fuel cell stack is the most expensive component of a fuel cell system,[1088] which is the most expensive part of a heavy-duty FCEV, primarily due to the technological requirements of manufacturing rather than raw material costs.[1089] Fuel cells for the heavy-duty sector are expected to be more expensive than fuel cells for the light-duty sector because they operate at higher average continuous power over their lifespan, which requires a larger fuel cell stack size, and because they have more stringent durability requirements (i.e., to travel more hours and go longer distances).[1090]

Projected costs vary widely in the literature. They are expected to decrease as manufacturing matures. Larger production volumes are anticipated as global demand increases for fuel cell systems for HD vehicles, which could improve economies of scale.[1091] Costs are also anticipated to decline as durability improves.[1092]

For the NPRM, we relied on an average of costs from an ICCT meta-study that found a wide variation in fuel cell costs in the literature.[1093] The costs we used in the NPRM ranged from $200

[1085] U.S. Department of Energy. "U.S. National Clean Hydrogen Strategy and Roadmap". June 2023. Available online: https://www.hydrogen.energy.gov/library/roadmaps-vision/clean-hydrogen-strategy-roadmap, https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/us-national-clean-hydrogen-strategy-roadmap.pdf.

[1086] Marcinkoski, Jason et. al. "Hydrogen Class 8 Long Haul Truck Targets". U.S. Department of Energy. October 31, 2019. Available online: https://www.hydrogen.energy.gov/pdfs/19006_hydrogen_class8_long_haul_truck_targets.pdf.

[1087] Ledna, et. al. "Decarbonizing Medium- & Heavy-Duty On-Road Vehicles: Zero-Emission Vehicles Cost Analysis". National Renewable Energy Laboratory. March 2022. Available online: https://www.nrel.gov/docs/fy22osti/82081.pdf.

[1088] Papageorgopoulos, Dimitrios. "Fuel Cell Technologies Overview". U.S. Department of Energy. June 6, 2023. Available online: https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/review23/fc000_papageorgopoulos_2023_o.pdf.

[1089] Deloitte China and Ballard. "Fueling the Future of Mobility: Hydrogen and fuel cell solutions for transportation, Volume 1". 2020. Available online: https://www2.deloitte.com/content/dam/Deloitte/cn/Documents/finance/deloitte-cn-fueling-the-future-of-mobility-en-200101.pdf.

[1090] Marcinkoski, Jason et. al. "Hydrogen Class 8 Long Haul Truck Targets". U.S. Department of Energy. October, 31, 2019. Available online: https://www.hydrogen.energy.gov/pdfs/19006_hydrogen_class8_long_haul_truck_targets.pdf.

[1091] Deloitte China and Ballard. "Fueling the Future of Mobility: Hydrogen and fuel cell solutions for transportation, Volume 1". 2020. Available online: https://www2.deloitte.com/content/dam/Deloitte/cn/Documents/finance/deloitte-cn-fueling-the-future-of-mobility-en-200101.pdf.

[1092] Deloitte China and Ballard. "Fueling the Future of Mobility: Hydrogen and fuel cell solutions for transportation, Volume 1". 2020. Available online: https://www2.deloitte.com/content/dam/Deloitte/cn/Documents/finance/deloitte-cn-fueling-the-future-of-mobility-en-200101.pdf.

[1093] Sharpe, Ben and Hussein Basma. "A meta-study of purchase costs for zero-emission trucks". International Council on Clean Transportation, Working Paper 2022-09. February 2022. Available online: https://theicct.org/publication/purchase-cost-ze-trucks-feb22/.

per kW in MY 2030 to $185 per kW in MY 2032. We requested comment and cost data projections in the proposal.

Several commenters addressed EPA's estimates for fuel cell costs. CARB agreed with EPA's estimates, noting they used similar estimated values in their Advanced Clean Fleets rule proceeding. One commenter thought the NPRM fuel cell cost estimates were too high, particularly if they represent the fuel cell stack alone, based on targets published by the European Joint Undertaking. Another commenter stated that fuel stack technology is too nascent to make any type of realistic cost estimate. They noted that existing component technologies still need to be adapted for the HD market and that fuel cell stacks are not being produced now, and they stated that they do not believe accurate HD FCEV technology costs can be predicted now. Several commenters said that EPA's estimates were too low and referred to fuel cell costs from a more recent (2023) ICCT White Paper[1094] that updated the ICCT meta-study referenced in the NPRM.[1095] See RTC Section 3.4.3 for additional details.

We reviewed the ICCT paper that several commenters referenced. Also, due to the wide range of projected costs in the literature, EPA contracted with FEV[1096] to independently evaluate direct manufacturing costs of heavy-duty vehicles with alternative powertrain technologies and EPA conducted an external peer review of the final FEV report.[1097] In the report, FEV estimated costs associated with a Class 8 FCEV-dominated long-haul tractor with graphite fuel cell stacks, which are more durable than stainless steel stacks typically used in light-duty vehicle applications. FEV leveraged a benchmark study of a commercial vehicle fuel cell stack from a supplier that serves the Class 8 market. They also built prototype vehicles in-house and relied on existing expertise to validate their sizing of tanks and stacks.[1098] Please see RTC Section 3.4.3 for additional detail.

For the final rule, we established MY 2032 fuel cell system DMCs using cost projections from FEV and ICCT. We weighted FEV's work twice as much as ICCT's because it was primary research and because some of the volumes associated with the costs in ICCT's analysis were not transparent. We note that this method of weighting primary research more heavily than secondary research is generally appropriate for assessing predictive studies of this nature; indeed, it is consistent with what ICCT itself did. For FEV's work, we selected costs that align with the HD FCEV production volume that we project in our modeled potential compliance pathway's technology packages developed for this final rule, which is roughly 10,000 units per year in MY 2032, for a DMC of $89 per kW. For ICCT's work, we used the 2030 value of $301 per kW for

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[1094] Xie, et. al. "Purchase costs of zero-emission trucks in the United States to meet future Phase 3 GHG standards". International Council of Clean Transportation, Working Paper 2023-10. March 2023. Available online: https://theicct.org/wp-content/uploads/2023/03/cost-zero-emission-trucks-us-phase-3-mar23.pdf.

[1095] Sharpe, Ben and Hussein Basma. "A meta-study of purchase costs for zero-emission trucks". International Council on Clean Transportation, Working Paper 2022-09. February 2022. Available online: https://theicct.org/publication/purchase-cost-ze-trucks-feb22/.

[1096] FEV Consulting. "Heavy Duty Commercial Vehicles Class 4 to 8: Technology and Cost Evaluation for Electrified Powertrains—Final Report". Prepared for EPA. March 2024.

[1097] ICF. "Peer Review of HD Vehicles, Industry Characterization, Technology Assessment and Costing Report". September 15, 2023

[1098] FEV Consulting. "Heavy Duty Commercial Vehicles Class 4 to 8: Technology and Cost Evaluation for Electrified Powertrains—Final Report". Prepared for EPA. March 2024.

MY 2032, since 2030 was the latest year of values referenced by ICCT from literature. Our weighted average yielded a MY 2032 fuel cell system DMC of $160 per kW. In order to project DMCs from MY 2032 for earlier MYs, we used our learning rates shown in RIA Chapter 3.2.1. This yielded the MYs 2030 and 2031 DMCs shown in Table 2-68.

Table 2-68 Fuel Cell System Direct Manufacturing Costs (2022$)

Year	**MY 2030**	**MY 2031**	**MY 2032**
FC System	$170/kW	$165/kW	$160/kW

2.5.2.2 Onboard Hydrogen Fuel Tank Costs

Onboard hydrogen storage cost projections also vary widely in the literature. For the NPRM, we relied on an average of costs from the same ICCT meta-study that we used for fuel cell costs.[1099] The values we used in the NPRM analysis ranged between $660/kg in MY 2030 and $612/kg in MY 2032. We requested comment and cost data projections in the proposal.

There were few comments on hydrogen fuel tank costs. Two commenters referred to ICCT's revised meta-study.[1100] One commenter suggested that onboard liquid hydrogen will be required for long-distance ranges of over 500 miles in the longer-term and suggested that it is too soon to offer cost estimates for liquid tanks. See RTC Section 3.4.3 for details about the meta-study.

Given our assessment of technology readiness for the NPRM, liquid storage tanks were not included in the potential compliance pathway that supports the feasibility and appropriateness of our standards.

Like fuel cell costs, onboard gaseous hydrogen tank costs are dependent on manufacturing volume. We reviewed the ICCT paper that several commenters referenced and contracted with FEV[1101] to independently evaluate onboard hydrogen storage tanks costs for 2027 (2022$) based on manufacturing volume, and EPA conducted an external peer review of the final FEV report.[1102] Please see RTC Section 3.4.3 for additional detail.

Using the same approach taken for fuel cell system costs, as described in RIA Chapter 2.5.2.2, we established MY 2032 onboard storage tank DMCs using cost projections from FEV and ICCT. We weighted FEV's work twice as much as ICCT's because it was primary research and because some of the volumes associated with the costs in ICCT's analysis were not transparent. We note that this method of weighting primary research more heavily than secondary research is generally appropriate for assessing predictive studies of this nature; indeed, it is consistent with

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[1099] Sharpe, Ben and Hussein Basma. "A meta-study of purchase costs for zero-emission trucks". International Council on Clean Transportation, Working Paper 2022-09. February 2022. Available online: https://theicct.org/publication/purchase-cost-ze-trucks-feb22/.

[1100] Xie, et. al. "Purchase costs of zero-emission trucks in the United States to meet future Phase 3 GHG standards". International Council of Clean Transportation, Working Paper 2023-10. March 2023. Available online: https://theicct.org/wp-content/uploads/2023/03/cost-zero-emission-trucks-us-phase-3-mar23.pdf.

[1101] FEV Consulting. "Heavy Duty Commercial Vehicles Class 4 to 8: Technology and Cost Evaluation for Electrified Powertrains—Final Report". Prepared for EPA. March 2024.

[1102] ICF. "Peer Review of HD Vehicles, Industry Characterization, Technology Assessment and Costing Report". September 15, 2023 what ICCT itself did. For FEV's work, we selected costs for approximately 10,000 units per year in MY 2032, for a DMC of $504 per kg. For ICCT's work, we used the 2030 value of $844 per kW for MY 2032, since 2030 was the latest year of values referenced by ICCT from literature. Our weighted average yielded a MY 2032 fuel cell system DMC of $617 per kW. Please see RTC Section 3.4.3 for additional detail. In order to project DMCs for earlier MYs, we used our learning rates shown in RIA Chapter 3.2.1. This yielded the MYs 2030 and 2031 DMCs shown in Table 2-69.

Table 2-69: Onboard Hydrogen Tank Direct Manufacturing Costs (2022$)

Year	MY 2030	MY 2031	MY 2032
Onboard H2 Tank	$659/kg	$636/kg	$617/kg

2.5.2.3 Vehicle Tax Credits

We applied the IRA section 13403 vehicle tax credit to FCEVs in HD TRUCS exactly how we applied it to BEVs, as described in RIA Chapter 2.4.3.5.

2.5.2.4 State Sales Tax and Federal Excise Tax

As explained in RIA Chapter 2.3.2.2, the NPRM version of HD TRUCS did not include estimates for state sales taxes on the purchase of a vehicle or Federal Excise Tax (FET). After consideration of comments, we have added these values to the final version of HD TRUCS. Sales tax and FET are calculated by first applying a retail price equivalent (RPE) factor[1103] to the upfront powertrain DMC costs. One industry commenter recommended using a state sales tax rate of 5.02%, an average of the 50 state sales tax values, which we assessed and confirmed was appropriate.[1104] This rate was applied to the upfront costs (RPE) for all HD TRUCS vehicles for the final rule analysis. A Federal Excise tax of 12% was applied to the upfront costs (RPE) for all Class 8 (heavy heavy-duty) vehicles and all tractors.[1105] The results of this analysis for MY 2032 as an example year are shown in Table 2-70.

Table 2-70 FCEV Powertrain (PT) RPE, Sales Tax and FET for MY 2032 (2022$)

Vehicle ID	PT DMC ($/unit)	Battery Tax Credit ($/unit)	PT RPE ($/unit)	FET ($/unit)	State Sales Tax ($/unit)
18B_Coach_Cl8_MP	$ 79,956	$368	$113,169	$13,580	$5,681
41Tractor_DC_Cl7	$77,291	$751	$109,002	$13,080	$5,472
45Tractor_DC_Cl8	$102,033	$1,098	$143,789	$17,255	$7,218
79Tractor_SC_Cl8	$103,030	$656	$145,647	$17,478	$7,311

[1103] See Chapter 3.2 for a discussion of RPE.

[1104] See page 38 of docket number EPA-HQ-OAR-2022-0985-2668-A1.

[1105] U.S. Internal Revenue Service. 26 USC 4051. Available at http://uscode.house.gov/view.xhtml?req=granuleid:USC-prelim-title26-section4051&num=0&edition=prelim

2.5.3 FCEV Operating Costs

The annual operating cost for FCEVs is the annual hydrogen fuel cost plus the maintenance and repair cost, powertrain insurance cost, and annual ZEV registration fee.[1106] RIA Chapter 2.5.3.1 discusses hydrogen fuel price and how the annual hydrogen cost of operating a FCEV is computed, and RIA Chapter 2.5.3.2 discusses maintenance and repair costs for FCEVs. RIA Chapter 2.5.3.3 describes the insurance cost for FCEV vehicles, and RIA Chapter 2.5.3.4 describes an annual ZEV registration fee. For each FCEV in HD TRUCS, the 10-year average annual operating costs are as shown in Table 2-71 and described in the sections below. As discussed in RIA Chapter 2.2.1.1.3, for the final version for HD TRUCS, we have assessed each year of operation using the appropriate changes that occur over time for inputs such as VMT, maintenance and repair, and fuel costs; however, we are continuing to show a 10-year average values in tables such as the one below, as a single value point of comparison. Appendix A to this RIA includes each year of a 10-year schedule for VMT.

Table 2-71 FCEV Operating Costs for a MY 2032 Vehicle (2022$), 10 Year Average

Vehicle ID	Annual FCEV M&R ($/year)	Annual Hydrogen Cost ($/year)	Annual Powertrain Insurance Cost [1107] + $100 Annual ZEV Reg. Fee ($/year)
18B_Coach_Cl8_MP	7073	14593	3395
41Tractor_DC_Cl7	9339	18252	3370
45Tractor_DC_Cl8	9339	21865	4414
79Tractor_SC_Cl8	19058	41425	4469

2.5.3.1 Annual Hydrogen Fuel Cost

The annual hydrogen cost is a function of the hydrogen price, daily energy consumption of a FCEV (which includes the efficiency of the powertrain), and number of operating days in a year.

For the purposes of the HD TRUCS analysis, rather than focusing on depot hydrogen fueling infrastructure costs that would be incurred upfront, we included infrastructure costs in our per-kilogram retail price of hydrogen. The retail price of hydrogen is the total price of hydrogen when it becomes available to the end user, including the costs of production, distribution, storage, and dispensing at a fueling station. This price per kilogram of hydrogen includes the amortization of the station capital costs. This approach is consistent with the method we use in HD TRUCS for ICE vehicles, where the equivalent diesel fuel costs are included in the diesel fuel price instead of accounting for the costs of fuel stations separately, as well as for BEVs with public charging infrastructure costs within the price of charging.

We acknowledge that this market is still emerging and that hydrogen fuel providers will likely pursue a diverse range of business models. For example, some businesses may sell hydrogen to fleets through a negotiated contract rather than at a flat market rate on a given day. Others may

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[1106] Insurance costs and an annual ZEV registration fee were not included in the proposal; EPA added these costs to the final version of HD TRUCS after consideration of comments. See RIA Chapter 2.5.3.3 and 2.5.3.4.

[1107] As described at the beginning of Chapter 2.3, this analysis is examining the incremental cost differences between a comparable ICE vehicle and ZEV technologies; therefore, insurance costs are estimated based on the upfront cost of powertrain components that are expected to differ for a comparable ICE vehicle and ZEV.

offer to absorb the infrastructure development risk for the consumer, in exchange for the ability to sell excess hydrogen to other customers and more quickly amortize the cost of building a fueling station. FCEV manufacturers may offer a "turnkey" solution to fleets, where they provide a vehicle with fuel as a package deal. This level of granularity is not reflected in our hydrogen price estimates presented in the RIA.

As discussed in RIA Chapters 1.3.2 and 1.8, large federal incentives are in place that could impact the price of hydrogen. In June 2021, DOE launched a Hydrogen Shot goal to reduce the cost of clean hydrogen production by 80 percent to $1 per kilogram in one decade.[1108] The BIL and IRA included funding for several hydrogen programs to accelerate progress towards the Hydrogen Shot and jumpstart the hydrogen market in the U.S.

For the NPRM analysis, we included a hydrogen price based on analysis from ANL using BEAN. One commenter highlighted several reports that indicate large potential for the hydrogen price to rapidly drop, particularly on the production side. Several commenters expressed concern about the hydrogen price assumption in the NPRM or said that prices cannot be predicted at this time and urged that EPA's projection be regularly evaluated as the market develops. Some commenters referred to an ICCT analysis of hydrogen pricing that indicated a lack of cost-competitiveness for hydrogen-fueled trucks before 2035. Another commenter noted that the price of $4 to 5 per kg (that EPA referenced) is described by DOE as a "willingness to pay" that reflects the total price at which hydrogen must be available to the HD vehicle end user for uptake to occur, or the point at which FCEVs could reach cost parity with diesel vehicles. They stated that it cannot represent the real market and offered a bottom-up analysis to understand what fleet owners would pay at the hydrogen refueling stations.

For the final rule HD TRUCS analysis, in consideration of the comments, we re-evaluated our assumption about the retail price of hydrogen, in consultation with DOE. We determined the estimates for hydrogen price based on 2030 cost scenarios for hydrogen from DOE's Pathways to Commercial Liftoff report[1109] that are in line with estimates from a previous DOE analysis of market uptake of HD ZEVs, including FCEVs.[1110] Several cost trajectories in the report identified paths for around $6 per kg in 2030, depending on the method of hydrogen production and cost of the station. For 2030, we looked at the average of the sums of low and high pathway estimates for hydrogen produced using steam methane reforming (SMR) with carbon capture and sequestration (CCS) and water electrolysis, considering varying incentives from the IRA hydrogen production tax credit (PTC). Distribution, storage, and dispensing costs are based on DOE estimates if advances in distribution and storage technology are commercialized and at scale. Our scenario selections presume that in the near-term, delivery of hydrogen in liquid form

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[1108] U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office. "Hydrogen Shot". Available online: https://www.energy.gov/eere/fuelcells/hydrogen-shot.

[1109] U.S. Department of Energy. "Pathways to Commercial Liftoff: Clean Hydrogen". March 2023. Available online: https://liftoff.energy.gov/wp-content/uploads/2023/05/20230523-Pathways-to-Commercial-Liftoff-Clean-Hydrogen.pdf. See Figure 10.

[1110] Ledna, et. al. "Decarbonizing Medium- & Heavy-Duty On-Road Vehicles: Zero-Emission Vehicles Cost Analysis". National Renewable Energy Laboratory. March 2022. Available online: https://www.nrel.gov/docs/fy22osti/82081.pdf.

is likely, due to the limited capacity of gaseous tube trailers and limited availability of pipelines. Table 2-72 shows the range of costs presented in Figure 10 of the Liftoff Report.[1111]

Table 2-72 Projected Hydrogen Costs from DOE's Liftoff Report

DOE Liftoff Report (2030 $/kg)	**Low**	**High**
SMR w/$0.75/kg PTC (including cost of CCS)	0.4	0.85
Liquefaction	2.7	2.7
Liquid H2 storage	0.2	0.2
Liquid H2 trucking	0.2	0.3
Next gen fuel dispensing at high use*	1	3.6
SUM	**4.5**	**7.65**
Water electrolysis w/$3/kg PTC	0.4	0.4
Liquefaction	2.7	2.7
Liquid H2 storage	0.2	0.2
Liquid H2 trucking	0.2	0.3
Next gen fuel dispensing at high use*	1	3.6
SUM	**4.5**	**7.2**

**Greater than or equal to 70% utilization, assumes line fill at high pressure

Cost reductions to $4 per kg are considered feasible by 2035 with next generation fuel dispensing technologies, reductions in the cost of hydrogen production due to IRA incentives, and possibly the use of pipelines for hydrogen delivery.[1112]

To evaluate our estimates further, and in response to comments, the National Renewable Energy Laboratory (NREL) conducted a bottom-up analysis that explores the potential range of levelized costs of dispensed hydrogen (LCOH)[1113] from hydrogen refueling stations for HD FCEVs in 2030. Bracci et. al[1114] evaluates breakeven costs along the full supply chain from hydrogen production to dispensing, including station costs by technology component and delivery costs by distance delivered. The authors vary hydrogen delivery distances, station sizes, station utilization rates, and economies of scale. They assume that hydrogen is dispensed in gaseous form at 700 bar pressure and is either delivered via liquid tanker trucks or produced onsite in gaseous form. The assumed production cost of $1.50 per kg is based on costs of production today using steam methane reforming (SMR), though the paper acknowledges that many factors are at play that could impact the cost and method of hydrogen production in 2030 such as the rate of economies of scale; the impacts of policy incentives (e.g, the 45V production

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[1111] U.S. Department of Energy. "Pathways to Commercial Liftoff: Clean Hydrogen". March 2023. Available online: https://liftoff.energy.gov/wp-content/uploads/2023/05/20230523-Pathways-to-Commercial-Liftoff-Clean-Hydrogen.pdf. See Figure 10.

[1112] Ledna, et. al. "Decarbonizing Medium- & Heavy-Duty On-Road Vehicles: Zero-Emission Vehicles Cost Analysis". National Renewable Energy Laboratory. March 2022. Available online: https://www.nrel.gov/docs/fy22osti/82081.pdf.

[1113] LCOH is described as the total annualized capital costs plus annual feedstock, variable, and fixed operating costs, divided by the annual hydrogen flow through the supply chain.

[1114] Bracci, Justin, Mariya Koleva, and Mark Chung. "Levelized Cost of Dispensed Hydrogen for Heavy-Duty Vehicles". National Renewable Energy Laboratory. NREL/TP-5400-88818. March 2024. Available online: https://www.nrel.gov/docs/fy24osti/88818.pdf.

tax credit);[1115] and the success of research, development, and deployment efforts. Most capital and operating costs are derived from Argonne National Laboratory's Hydrogen Delivery Scenario Analysis Model (HDSAM) Version 4.5.[1116]

The authors conclude that the overall system LCOH for stations in 2030 is estimated to range from ~\$3.80/kg-H_2 to ~\$12.60/kg-H_2, depending on the size of stations and method of hydrogen supply.[1117] This cost range is not the same as a retail price, but we assume that any retail markup at the station is minimal.[1118,1119] Importantly, it does not consider any tax incentives or other state or federal incentive policies that may further reduce the retail price that consumers see at a fueling station in 2030.[1120,1121] Therefore, we conclude that our retail price of hydrogen is within a reasonable range of anticipated values.

We took a closer look at the ICCT analysis referenced by several commenters.[1122] ICCT assessed near-term charging and refueling needs for Class 4 to 8 vehicles for scenarios before and after IRA tax incentives are in place, including incentives for renewable electricity (45 and 45Y) and clean hydrogen (45V). They assumed that hydrogen fuel is green, meaning that it is produced onsite using electrolysis powered by renewable energy. Thus, their retail price includes production and refueling station costs but not distribution costs. ICCT's study found that HD FCEVs would account for less than one percent of total sales overall through 2035,[1123] and that neither HD FCEVs nor H2-ICEVs would be cost-competitive due to hydrogen prices, despite

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[1115] The authors indicate that relevant incentives include but are not limited to the Alternative Fuel Refueling Property Credit (30C), the Credit of Production of Clean Hydrogen (45V), the Qualified Advanced Energy Project Credit (48C), and the Credit for Qualified Commercial Clean Vehicles (45W).

[1116] Bracci, Justin, Mariya Koleva, and Mark Chung. "Levelized Cost of Dispensed Hydrogen for Heavy-Duty Vehicles". National Renewable Energy Laboratory. NREL/TP-5400-88818. March 2024. Available online: https://www.nrel.gov/docs/fy24osti/88818.pdf.

[1117] Bracci, Justin, Mariya Koleva, and Mark Chung. "Levelized Cost of Dispensed Hydrogen for Heavy-Duty Vehicles". National Renewable Energy Laboratory. NREL/TP-5400-88818. March 2024. Available online: https://www.nrel.gov/docs/fy24osti/88818.pdf.

[1118] West Virginia Oil Marketers and Grocers Association. "How Much Money Do Businesses Make on Fuel Purchases?" Available online: https://www.omegawv.com/faq/140-how-much-money-do-businesses-make-on-fuel-purchases.html#:~:text=Retailers%20Make%20Very%20Little%20Selling,cents%20per%20gallon%20in%20profit.

[1119] Kinnier, Alex. "I've analyzed the profit margins of 30,000 gas stations. Here's the proof fuel retailers are not to blame for high gas prices". Fortune. August 9, 2022. Available online: https://fortune.com/2022/08/09/energy-profit-margins-gas-stations-proof-fuel-retailers-high-gas-prices-alex-kinnier/.

[1120] The authors indicate that relevant incentives include but are not limited to the Alternative Fuel Refueling Property Credit (30C), the Credit of Production of Clean Hydrogen (45V), the Qualified Advanced Energy Project Credit (48C), and the Credit for Qualified Commercial Clean Vehicles (45W).

[1121] U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office. "Financial Incentives for Hydrogen and Fuel Cell Projects". Available online: https://www.energy.gov/eere/fuelcells/financial-incentives-hydrogen-and-fuel-cell-projects.

[1122] Slowik, Peter, et. al. "White Paper: Analyzing the Impact of the Inflation Reduction Act on Electric Vehicle Uptake in the United States". International Council on Clean Transportation and Energy Innovation Policy & Technology LLC. January 2023. Available online: https://theicct.org/wp-content/uploads/2023/01/ira-impact-evs-us-jan23-2.pdf.

[1123] The HD FCEV component costs used in this ICCT study are from Xie et. al, which we also considered in RIA Chapter 2.5.2.

IRA incentives.[1124] Their levelized costs for new green hydrogen production plants started at $5.59 per kg in 2020 and did not go below $4.50 through 2035 with or without tax credits. This cost is higher than the clean hydrogen production costs in DOE's Liftoff Report and the production cost in Bracci et. al, which assumed $1.50 per kg based on the cost of hydrogen production today. ICCT's production costs are from a paper on hydrogen production in Europe, where about 500 kg of hydrogen is produced onsite at a station per day to meet the needs of a station.[1125] This is a smaller station size than used in the bottom-up analysis conducted in support of this rule. For example, Bracci et. al evaluated hydrogen refueling stations in the U.S.—considering gaseous stations that produce hydrogen onsite, but also centralized production pathways—that would dispense between 2 and 18 million tons of hydrogen per day per station. The larger station size is based on the size of operating and planned hydrogen refueling stations for HD FCEVs in the U.S.[1126]

Then, ICCT relied on a 2017 study for a refueling station cost of $6 per kg in 2020, decreasing linearly to $2.30 per kg by 2050. This equates to about $4.77 in 2030. Their station costs are closer to the range of costs for refueling stations with onsite production in Bracci et. al, which vary depending on the rate of utilization. We note that Bracci et. al also considers the cost of liquid hydrogen delivery to stations in the LCOH.

The ICCT authors reduced the station costs by four percent due to the IRA tax credit for eligible hydrogen refueling stations of up to $100,000 (30C), which we did not quantify. Applying this four percent to the LCOH range in Bracci et. al would drop their estimated LCOH costs to between ~$3.65 to $12.10 per kg. ICCT also accounted for competition between hydrogen suppliers to estimate a total market price "at-the-pump" that includes a retail markup. We did not add a retail markup to the LCOH, given that gas and diesel fuel retailers generally make very little selling fuel.[1127,1128]

[1124] ICCT used a discounted cash flow model, which they said is necessary to estimate annual tax liability and accurately reflect the impact of the PTC. For example, since the PTC ends in 2030, they used the model to account for the impact of the credit for a limited time during the life of a plant (e.g., only for two years for a plant that starts producing hydrogen in 2030 and then operates for 30 years). They included additional effects of IRA policies (i.e., a separate PTC for renewable electricity, "direct pay", and tax transferability provisions).

[1125] Zhou, Yuanrong and Stephanie Searle. "White Paper: Cost of Renewable Hydrogen Produced Onsite at Hydrogen Refueling Stations in Europe". International Council on Clean Transportation. February 2022. Available online: https://theicct.org/wp-content/uploads/2022/02/fuels-eu-cost-renew-H-produced-onsite-H-refueling-stations-europe-feb22.pdf.

[1126] Bracci, Justin, Mariya Koleva, and Mark Chung. "Levelized Cost of Dispensed Hydrogen for Heavy-Duty Vehicles". National Renewable Energy Laboratory. NREL/TP-5400-88818. March 2024. Available online: https://www.nrel.gov/docs/fy24osti/88818.pdf.

[1127] West Virginia Oil Marketers and Grocers Association. "How Much Money Do Businesses Make on Fuel Purchases?" Available online: https://www.omegawv.com/faq/140-how-much-money-do-businesses-make-on-fuel-purchases.html#:~:text=Retailers%20Make%20Very%20Little%20Selling,cents%20per%20gallon%20in%20profit.

[1128] Kinnier, Alex. "I've analyzed the profit margins of 30,000 gas stations. Here's the proof fuel retailers are not to blame for high gas prices". Fortune. August 9, 2022. Available online: https://fortune.com/2022/08/09/energy-profit-margins-gas-stations-proof-fuel-retailers-high-gas-prices-alex-kinnier/.

The high green hydrogen production cost assumed by ICCT is a main driver of their estimated retail price in 2030 of $9.50 per kg.[1129] We recognize that ICCT's results are also within the range of values presented in Bracci et al's analysis of the LCOH in 2030, but our approach for the FRM is based on projections about a U.S. clean hydrogen market that may or may not be "green" during the 2030 to 2032 timeframe but is incentived to reduce emissions over time. (See RIA Chapter 4.8 for a comparative emissions analysis of potential hydrogen production methods in this timeframe.) As indicated in RIA Chapter 1.8.3, there is $9.5 billion in BIL and IRA investment to quickly ramp up production and reduce the cost of hydrogen. Our retail price estimates are lower than ICCT's without directly accounting for these incentives, so any potential beneficial impact from them would be additional.

We identified few other bottom-up assessments of hydrogen price available since the NPRM. The authors used differing analytical approaches and assumptions and only two included production, delivery, and dispensing costs. For example, Fulton et. al evaluated hydrogen end use scenarios in the state of California, aligned with the state's vision for a hydrogen hub (the "ARCH2ES" or Alliance for Renewable Clean Hydrogen Energy Systems) that was awarded $1.2 billion from DOE. They considered eight approaches to producing electrolytic hydrogen and delivering it to refueling stations in California and determined that, given strong transportation demand growth, a levelized cost of $5 to 6.25 per kg could be achievable for a scaled system by 2030.[1130] Their analysis of longer-term (e.g., 2030-35) costs included reduced operating and capital costs due to scale and learning. They assumed electricity generation from low-cost renewables in this timeframe. Hydrogen production costs ranged from roughly $2.60 to 3.70 per kg; distribution and storage costs ranged widely based on volumes and distance moved; and refueling station costs ranged from just $1 to 2 per kg to about $3.80 per kg, with lower costs for larger liquid hydrogen stations.[1131] Their analysis represents potential cost ranges for a single H2Hub region.

A Ricardo study for the Truck and Engine Manufacturers Association investigated the feasibility of the EPA NPRM Phase 3 GHG standards for Medium Heavy-Duty Vehicles, so their hydrogen demand levels were higher than we are including in the final FRM. Their hydrogen price projections were based on a review of costs for production, delivery, and dispensing from various literature sources. They chose the costs in Table 2-73 for their analysis and applied an annual reduction rate of three percent:

Table 2-73 EMA H2 Cost Projections

Type	Option	Cost (2030)
Production	Blue hydrogen	$1.50/kg
	Green hydrogen	$5/kg

[1129] Slowik, Peter, et. al. "White Paper: Analyzing the Impact of the Inflation Reduction Act on Electric Vehicle Uptake in the United States". International Council on Clean Transportation and Energy Innovation Policy & Technology LLC. January 2023. Available online: https://theicct.org/wp-content/uploads/2023/01/ira-impact-evs-us-jan23-2.pdf.

[1130] Fulton, Lew, et. al. "California Hydrogen Analysis Project: The Future Role of Hydrogen in a Carbon-Neutral California: Final Synthesis Modeling Report". UC Davis Institute of Transportation Studies. April 19, 2023. Available online: https://escholarship.org/uc/item/27m7g841.

[1131] Fulton, Lew, et. al. "California Hydrogen Analysis Project: The Future Role of Hydrogen in a Carbon-Neutral California: Final Synthesis Modeling Report". UC Davis Institute of Transportation Studies. April 19, 2023. Available online: https://escholarship.org/uc/item/27m7g841.

Delivery	Gas tube trailer	$1.50/kg
	Liquid tankers	$1.20/kg
	Dedicated pipeline	$0.50/kg
	Repurposed pipeline	$0.30/kg
Dispensing	Based on 2020 levelized refueling station cost and 25-30% reduction in green hydrogen production cost	$3.50/kg

Their assessment of four scenarios (e.g., based on different fuel types and delivery options) found that hydrogen costs could range from $5.50 to 10 per kg in 2030.[1132]

After consideration of comments and this assessment, we project the price of hydrogen in 2030 will be $6/kg and fall to $4/kg in 2035 and beyond, as shown in Table 2-74.

Table 2-74 Retail Price of Hydrogen for CYs 2030-2035+ (2022$) used in Final Version of HD TRUCS

	2030	2031	2032	2033	2034	2035 and beyond
$/kg H2	6.00	5.60	5.20	4.80	4.40	4.00

2.5.3.2 Maintenance and Repair

Like BEVs, data on real-world maintenance and repair costs for heavy-duty FCEVs is limited. We expect the overall maintenance costs to be lower for a heavy-duty FCEV than a comparable diesel- fueled ICE vehicle for several reasons. First, a FCEV powertrain has fewer moving parts that accrue wear or need regular adjustments. Second, FCEVs do not require regular replacement of certain fluids such as engine oil, nor do they require exhaust filters to reduce particulate matter and other pollutants. Third, the per-mile rate of brake wear is expected to be lower for FCEVs due to regenerative braking systems.

Fuel cell vehicles share many BEV components, with fuel cell vehicles also having fuel cell stacks and hydrogen tanks; based on this, it is reasonable to assume that, since a FCEV has more components than a BEV (e.g., a fuel cell and a hydrogen storage tank), a FCEV will have slightly higher maintenance and repair costs than a BEV. Several literature sources apply a scaling factor to diesel vehicle maintenance costs to estimate FCEV maintenance costs.[1133,1134,1135] We followed this approach for the proposal and applied a repair cost scaling factor of 0.75 to the maintenance and repair costs for diesel-fueled ICE vehicles. This scaling factor is slightly higher than the BEV scaling factor of 0.71. The 0.75 FCEV scaling factor is

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[1132] Kuhn, et. al. “Feasibility study of EPA NPRM Phase 3 GHG standards for Medium Heavy-Duty Vehicles: Version 3.0”. Ricardo, Prepared for Truck and Engine Manufacturers Association. July 19, 2023.

[1133] Burnham, A., Gohlke, D., Rush, L., Stephens, T., Zhou, Y., Delucchi, M. A., Birky, A., Hunter, C., Lin, Z., Ou, S., Xie, F., Proctor, C., Wiryadinata, S., Liu, N., Boloor, M. "Comprehensive Total Cost of Ownership Quantification for Vehicles with Different Size Classes and Powertrains". Argonne National Laboratory. April 1, 2021. Available online: https://publications.anl.gov/anlpubs/2021/05/167399.pdf.

[1134] Hunter, Chad, Michael Penev, Evan Reznicek, Jason Lustbader, Alicia Birkby, and Chen Zhang. “Spatial and Temporal Analysis of the Total Cost of Ownership for Class 8 Tractors and Class 4 Parcel Delivery Trucks”. National Renewable Energy Lab. September 2021. Available online: https://www.nrel.gov/docs/fy21osti/71796.pdf.

[1135] Burke, Andrew, Marshall Miller, Anish Sinha, et. al. “Evaluation of the Economics of Battery-Electric and Fuel Cell Trucks and Buses: Methods, Issues, and Results”. August 1, 2022. Available online: https://escholarship.org/uc/item/1g89p8dn.

based on an analysis from Wang et al. 2022, that estimates a future FCEV HD vehicle would have a 25 percent reduction compared to a diesel-powered HD vehicle truck.[1136]

Commenters noted the potential need to retrain technicians to work on ZEVs. As similarly noted in RIA Chapter 2.4.4.1 above with respect to BEVs, we agree that there may be a transition period during which costs for maintaining and repairing FCEVs will not be at their full savings potential due to the need to train more of the workforce to maintain and repair FCEVs. To account for this period, in this final rule, EPA has phased in the FCEV scaling factors for maintenance and repair. Specifically, instead of applying a single scaling factor for every year commencing in 2027 as at proposal, EPA is starting with a higher scaling factor and gradually decreasing it (i.e., gradually increasing the projected cost savings) from calendar year 2030-2035. The initial higher scaling factor (1.0) also comes from Wang et al. and reflects estimates for 2022. EPA's approach of applying this factor commencing in 2030 is consequently conservative given that technicians in those later years will be more experienced than they were in 2022. These values, shown in Table 2-75, are multiplied by the annual diesel maintenance and repair costs by calendar year in order to assess the costs for FCEV vehicle maintenance and repair.

Table 2-75 Maintenance and Repair Scaling Factors for FCEV CY 2030 – 2035+

CY	**2030**	**2031**	**2032**	**2033**	**2034**	**2035+**
Factor	1.0	0.95	0.90	0.85	0.80	0.75

Consistent with our approach for ICEs and BEVS, we did not include the costs for fuel cell system replacement within our analysis. We upsized the fuel cell system such that the addition of cells add durability so that replacement will not be necessary in the 10-year assessment period considered in the HD TRUCS analysis.[1137]

2.5.3.3 Insurance cost

In the NPRM analysis, we did not take into account the cost of insurance on the ZEV purchaser. A few commenters suggested we should consider the addition of insurance cost because the incremental cost of insurance for the ZEVs will be higher than for ICE vehicles. We agree that insurance costs may differ between these vehicle types and that this is a cost that will be seen by the operator. Therefore, for the final rule analysis in HD TRUCS, we included the incremental insurance costs of a ZEV relative to an ICE vehicle by incorporating an annual insurance cost. A commenter recommended using an insurance rate of 3%, based originally on an ICCT April 2023 paper on ZEV TCO.[1138] We have reviewed the comment and the ICCT White Paper and consider the 3% insurance rate to be reasonable. Similar to sales tax and the FET, insurance costs are calculated as a percentage, after applying the RPE, to the upfront costs

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[1136] Wang, G., Miller, M., and Fulton, L." Estimating Maintenance and Repair Costs for Battery Electric and Fuel Cell Heavy Duty Trucks, 2022. Available online: https://escholarship.org/content/qt36c08395/qt36c08395_noSplash_589098e470b036b3010eae00f3b7b618.pdf?t=r6zwjb.

[1137] The interim target fuel cell system lifetime for a Class 8 tractor-trailer is 25,000 hours, which is equivalent to more than 10 years if a vehicle operates for 45 hours a week for 52 weeks a year.

[1138] Basma, Hussein, et.al. "Total Cost of Ownership of Alternative Powertrain Technologies for Class 8 Long-Haul Trucks in the United States." International Council on Clean Transportation. April 2023. Page 17. Available online: https://theicct.org/wp-content/uploads/2023/04/tco-alt-powertrain-long-haul-trucks-us-apr23.pdf shown in Table 2-70; however, unlike the sales tax and FET, the insurance costs are added to operating costs each year in HD TRUCS, as part of the payback calculation. See Table 2-71 for MY 2032 FCEV powertrain insurance costs.

2.5.3.4 ZEV Registration Fee

Some states have adopted ZEV registration fees. Though 18 states do not have an additional ZEV registration fee, of the 32 states that do, the registration fees are generally between $50 and $225 per year.[1139] While EPA cannot predict whether and to what extent other states will enact ZEV registration fees, we have nonetheless conservatively added an annual registration fee of $100 to all ZEV vehicles in our final HD TRUCS analysis. See RTC Section 3 for further discussion.

2.6 BEV Charging Infrastructure

Charging infrastructure will be needed to support the growing fleet of heavy-duty BEVs. This section describes how we accounted for costs associated with charging infrastructure in our analysis of heavy-duty BEV technologies for our technology packages to support the feasibility of the standards and extent of use of HD BEV technologies in the potential compliance pathway for MYs 2027 through 2032.

2.6.1 Scope

As discussed in Chapter 1, we project future charging infrastructure will include a combination of (1) depot charging—with infrastructure installed in parking depots, warehouses, and other private locations where vehicles are parked off-shift (when not in use), and (2) public charging, which provides additional electricity for vehicles during their operating hours or en-route.

For this final rule HD TRUCS analysis, we project that most vocational vehicles and certain day cab tractors—those with return-to-base operations— will rely on depot charging. We estimate upfront capital hardware and installation costs for depot charging to fulfill each BEV's daily charging needs off-shift with the appropriately sized EVSE.[1140] This approach reflects our expectation that many heavy-duty BEV owners will opt to purchase and install sufficient EVSE ports at or near the time of vehicle purchase to ensure that operational needs are met. Starting in MY 2030 in our final rule HD TRUCS analysis we project en-route charging at public stations will be used by eight BEV types: long-haul vehicles (both sleeper cab and long-range day cab tractors) and coach buses. MY 2030 is the year when we project there will be sufficient public charging infrastructure for HD vehicles for the projected utilization of such technologies under the modeled potential compliance pathway. See RIA Chapter 1.6. We assign higher charging costs to vehicles using public charging stations to reflect our expectation that upfront capital costs and operating expenses for public EVSE[1141] will be passed onto customers, in addition to the electricity prices.

[1139] National Conference of State Legislatures. "Special Fees on Plug-In Hybrid and Electric Vehicles". March 27, 2023. Available online: https://www.ncsl.org/energy/special-fees-on-plug-in-hybrid-and-electric-vehicles.

[1140] We sized EVSE to meet vehicles' daily electricity consumption (kWh/day) based on the sizing VMT, as described in RIA Chapter 2.2.1.2.2.

[1141] En-route charging could occur at public or private charging stations though, for simplicity, we often refer to en-route charging as occurring at public stations in the RIA.

We acknowledge that even vehicles which predominantly rely on depot charging may utilize some public charging, for example on high travel days. This could allow fleet owners to purchase lower-power EVSE and reduce upfront depot infrastructure costs. In addition, we recognize that not all BEV owners may choose to procure and install their own EVSE. Some fleets may opt for lease agreements or alternative business models such as charging as a service, in which a third-party provider owns, operates, and maintains the charging equipment for a monthly (or other recurring) fee. Given the uncertainty around uptake and costs of these alternatives to depot charging at this early market stage, we chose to account for the hardware and installation costs of EVSE sized to meet BEV needs upfront in our analysis.

Depot and public charging infrastructure will vary depending on the number of vehicles that stations are designed to accommodate and their expected duty cycles, site conditions, and the charging preferences of BEV owners. The subsequent sections describe how we considered these factors and estimated the associated costs for each vehicle type in our analysis.

2.6.2 Depot Charging Analysis

2.6.2.1 EVSE Costs

Vehicle owners with return-to-base (or "depot") operations who choose to install privately-owned charging equipment have many equipment options from which to select. This includes AC or DC charging, power level[1142], number of ports and connectors, connector type(s), communications protocols, and additional features such as vehicle-to-grid capability (which allows the vehicle to supply energy back to the grid). Many of these selections will impact EVSE hardware and installation costs. For example, an ICCT paper found that hardware costs more than doubled between networked and non-networked[1143] Level 2 EVSE ports (with networked equipment costing more).[1144] Among networked EVSE with one or two ports per pedestal, ICCT found a roughly 10 percent difference in per-port hardware costs.[1145]

Power level of the EVSE is one of the most significant drivers of cost. While specific cost estimates vary across the literature, higher-power charging equipment is typically more expensive than lower-power units. For example, ICCT estimated hardware costs for a 350 kW DCFC port to be five times higher than for a 50 kW port.[1146] For this reason, we have evaluated

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[1142] Charging types are described in RIA Chapter 1.6.1.2.

[1143] Networked charging equipment is equipped with communications hardware such as WiFi or cellular.

[1144] Nicholas, Michael. "Estimating electric vehicle charging infrastructure costs across major U.S. metropolitan areas". The International Council on Clean Transportation. 2019. Available online: https://theicct.org/sites/default/files/publications/ICCT_EV_Charging_Cost_20190813.pdf.

[1145] Nicholas, Michael. "Estimating electric vehicle charging infrastructure costs across major U.S. metropolitan areas". The International Council on Clean Transportation. 2019. Available online: https://theicct.org/sites/default/files/publications/ICCT_EV_Charging_Cost_20190813.pdf.

[1146] Nicholas, Michael. "Estimating electric vehicle charging infrastructure costs across major U.S. metropolitan areas". The International Council on Clean Transportation. 2019. Available online: https://theicct.org/sites/default/files/publications/ICCT_EV_Charging_Cost_20190813.pdf.

infrastructure costs separately for four different, common power levels: AC Level 2 (19.2 kW) and 50 kW, 150 kW, and 350 kW DCFC.[1147]

Installation costs typically include labor and supplies, such as wire, conduit, and other hardware required for installation that is not supplied with the EVSE hardware purchase. Installation costs may also be incurred for permitting, taxes, and any upgrades or modifications to the on-site electrical service. These costs, especially those for labor and permitting can vary widely by region.[1148] Costs also vary by site conditions. The amount of land preparation and trenching needed will depend on the distance from where vehicles are parked (and the charging equipment is located) and the electrical panel.[1149] For example, a recent study found that average Level 2 installation costs at commercial locations increased by $20 for each extra foot of distance between the EVSE and power source.[1150] Another key factor is how many EVSE ports are installed. ICCT estimated that on a per-port basis, installation costs for 150 kW ports were about 2.5 times higher when only one port is installed compared to 6–20 per site.[1151] And as with hardware costs, installation costs may rise with power levels.

To reflect the diversity in anticipated depot infrastructure costs, we consider a range of hardware and installation costs for each charging type in our analysis. For the NPRM analysis, we developed the DCFC costs from a 2021 study (Borlaug et al. 2021) specific to heavy-duty electrification at charging depots. The study estimated the cost for procuring and installing 50 kW EVSE to be $30,000–$82,000 per port, the cost for 150 kW EVSE to be $94,000–$148,000 per port, and the cost for 350 kW EVSE to be $154,000–$216,000 per port.[1152,1153] In response to comments received and to reflect more recent literature, we are updating the cost ranges for 150 kW and 350 kW EVSE in the NPRM to those from a 2023 NREL report (Wood et al. 2023),[1154] which estimated combined hardware and installation costs to range from $112,200–$196,200 per

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[1147] Level 2 charging is available at a range of power levels. For simplicity, we have selected the upper end of the range to reflect our expectation that some heavy-duty fleets may opt for this power level. However, we acknowledge that some fleets may find that lower-power (e.g., 10 kW or 16.6 kW) Level 2 charging meets their needs and such fleets would therefore be likely to have lower infrastructure costs. Other DCFC power levels between 50 kW and 350 kW may also be available; this list is not intended to be comprehensive but is instead targeted to evaluate the range of potential costs.

[1148] U.S. Department of Energy. “Costs Associated with Non-Residential Electric Vehicle Supply Equipment”. 2015. Available online: https://afdc.energy.gov/files/u/publication/evse_cost_report_2015.pdf.

[1149] U.S. Department of Energy. “Costs Associated with Non-Residential Electric Vehicle Supply Equipment”. 2015. Available online: https://afdc.energy.gov/files/u/publication/evse_cost_report_2015.pdf.

[1150] Schey, Stephen, Kang-Ching Chu, and John Smart. “Breakdown of Electric Vehicle Supply Equipment Installation Costs. Idaho National Laboratory.” 2022. Accessed March 13, 2023. https://inldigitallibrary.inl.gov/sites/sti/sti/Sort_63124.pdf.

[1151] Nicholas, Michael. “Estimating electric vehicle charging infrastructure costs across major U.S. metropolitan areas”. The International Council on Clean Transportation. 2019. Available online: https://theicct.org/sites/default/files/publications/ICCT_EV_Charging_Cost_20190813.pdf.

[1152] Costs are expressed in 2019 dollars. We did not include the cost that may be incurred if a depot owner decides to install a separate meter for EVSE. These costs ($1,200–5,000) are relatively small compared to EVSE procurement and installation costs and would be even smaller on a per port basis if spread across multiple EVSE ports.

[1153] Borlaug, B., Muratori, M., Gilleran, M. et al. “Heavy-duty truck electrification and the impacts of depot charging on electricity distribution systems”. Nat Energy 6, 673–682 (2021). Available online: https://www.nature.com/articles/s41560-021-00855-0.

[1154] This report did not include costs for 50 kW EVSE ports.

150 kW EVSE port and from $180,100–$285,300 per 350 kW EVSE port.[1155] Considering the midpoints of these ranges, the EVSE costs in Wood et al. 2023 are about 25% higher than those in Borlaug et al. 2021.[1156] Most of the literature on Level 2 EVSE costs is for power levels common for light-duty vehicle charging. For example, the ICCT study previously discussed estimated hardware costs for networked 6.6 kW ports to be about $3,000 with approximately another $2,000–$4,000 per port for installation.[1157] We expect higher costs for higher-power Level 2 charging equipment. An RMI study showed a spread of hardware costs from $2,500 for a 7.7 kW charger to $4,900 for a 16.8 kW charger, with one outlier over $7,000 (for 14.4 kW).[1158] A guide by the Vermont Energy Investment Corporation (VEIC), which engaged in an electric school bus pilot, estimates that equipment and installation for high-powered Level 2 EVSE could range from $4,200 to over $21,000.[1159] Consistent with the NPRM analysis, we selected a range of $10,000 to $20,000 per EVSE port for our FRM final rule HD TRUCS analysis.

Table 2-76 summarizes the range of costs we considered for each charging type, adjusted to 2022 dollars.[1160]

Table 2-76 Combined Hardware and Installation Costs per EVSE Port (in 2022$)

Power level	Cost range
Level 2 (19.2 kW)	$11,327–$22,654
DC-50 kW	$33,981–$92,882
DC-150 kW	$112,200–$196,200
DC-350 kW	$180,100–$285,300

2.6.2.1.1 Will costs change over time?

The hardware and installation costs shown above generally reflect present day values. However, both could vary over time. For example, hardware costs could decrease due to manufacturing learning and economies of scale. Recent studies by ICCT assumed a 3 percent reduction in hardware costs for EVSE per year to 2030.[1161,1162] By contrast, installation costs

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[1155] Wood, Eric et al. “The 2030 National Charging Network: Estimating U.S. Light-Duty Demand for Electric Vehicle Charging Infrastructure.” 2023. Available online: https://driveelectric.gov/files/2030-charging-network.pdf.

[1156] Wood et al. 2023 cites multiple sources for EVSE cost ranges including Borlaug et al. 2021. The difference in EVSE costs was estimated from values as presented in the papers without adjusting for dollar years. Costs in Borlaug et al. are expressed in 2019 dollars whereas we treat values from Wood et al. as 2022 dollars.

[1157] Nicholas, Michael. “Estimating electric vehicle charging infrastructure costs across major U.S. metropolitan areas”. The International Council on Clean Transportation. 2019. Available online: https://theicct.org/sites/default/files/publications/ICCT_EV_Charging_Cost_20190813.pdf.

[1158] Nelder, Chris and Emily Rogers. “Reducing EV Charging Infrastructure Costs”. Rocky Mountain Institute. 2019. Available online: https://rmi.org/wp-content/uploads/2020/01/RMI-EV-Charging-Infrastructure-Costs.pdf.

[1159] Vermont Energy Investment Corporation. “Electric School Bus Charging Equipment Installation Guide”. August 2017. Available online: https://www.veic.org/Media/Default/documents/resources/reports/electric-school-bus-charging-equipment-installation-guide.pdf.

[1160] Values in the literature cited for Level 2 EVSE costs are assumed to be in 2019 dollars.

[1161] Bauer, Gordon, Chih-Wei Hsu, Mike Nicholas, and Nic Lutsey. “Charging Up America: Assessing the Growing Need for U.S. Charging Infrastructure Through 2030”. The International Council on Clean Transportation, July 2021. Available online: https://theicct.org/wp-content/uploads/2021/12/charging-up-america-jul2021.pdf.

[1162] Minjares, Ray, Felipe Rodriguez, Arijit Sen, and Caleb Braun. “Infrastructure to support a 100% zero-emission tractor-trailer fleet in the United States by 2040”. Working Paper 2021-33. ICCT, September 2021. Available online: https://theicct.org/sites/default/files/publications/ze-tractor-trailer-fleet-us-hdvs-sept21.pdf.

could increase due to growth in labor or material costs. As noted above, installation costs are also highly dependent on the specifics of the site including whether sufficient electric capacity exists to add charging infrastructure and how much trenching or other construction is required. If fleet owners choose to install charging stations at easier, and therefore, lower cost sites first, then installation costs could rise over time as stations are developed at more challenging sites. One of the ICCT studies discussed above[1163] found that these and other countervailing factors could result in the average cost of a 150 kW EVSE port in 2030 being similar (~3 percent lower) to that in 2021.

Due to the uncertainty on how costs may change over time, for this analysis we have kept combined hardware and installation costs per EVSE port constant, which could potentially be a conservative approach.

2.6.2.1.2 Tax Credit for Charging Infrastructure

As discussed in RIA Chapter 1.3.2, the IRA extends and modifies a federal tax credit under section 30C of the Internal Revenue Code that could cover up to 30 percent of the costs for businesses to procure and install EVSE on properties located in low-income or non-urban census tracts (subject to a total cap of $100,000 per item) if prevailing wage and apprenticeship requirements are met.[1164] The tax credit is available through 2032. To reflect our expectation that this tax credit—as well as grants, rebates, or other funding available through the IRA—could significantly reduce the overall infrastructure costs paid by BEV and fleet owners for depot charging, we used the low end of our EVSE cost ranges in the NPRM infrastructure cost analysis. After further consideration, including consideration of comments on this issue and availability of a new DOE analysis[1165] of the average value of the 30C tax credit for HD charging infrastructure, we have updated the depot EVSE costs in our final rule analysis to reflect a quantitative assessment of average savings from the tax credit.

As noted above, the 30C tax credit could cover up to 30 percent of the costs for fleets or other businesses to procure and install EVSE on properties located in low-income or non-urban census tracts if prevailing wage and apprenticeship requirements are met. DOE projects that businesses will meet prevailing wage and apprenticeship requirements in order to qualify for the full 30 percent tax credit[1166] and estimates that 60 percent[1167] of depots will be located in qualifying census tracts based on its assessment of where HD vehicles are currently registered, the location of warehouses and other transportation facilities that may serve as depots, and the share of the

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[1163] Bauer, Gordon, Chih-Wei Hsu, Mike Nicholas, and Nic Lutsey. “Charging Up America: Assessing the Growing Need for U.S. Charging Infrastructure Through 2030”. The International Council on Clean Transportation, July 2021. Available online: https://theicct.org/wp-content/uploads/2021/12/charging-up-america-jul2021.pdf.

[1164] IRA Section 13404, “Alternative Fuel Refueling Property Credit” under section 26 U.S. Code §30C, referred to as 30C in this document.

[1165] DOE. “Estimating Federal Tax Incentives for Heavy Duty Electric Vehicle Infrastructure and for Acquiring Electric Vehicles Weighting Less Than 14,000 Pounds.” Memorandum. March 11, 2024.

[1166] As noted in DOE’s assessment, the “good faith effort” clause applicable to the apprenticeship requirement suggests that it is unlikely that businesses will not be able to meet it and take advantage of the full 30 percent tax credit (if otherwise eligible).

[1167] This estimate may be conservative as DOE notes that its analysis did not factor in that fleets may choose to site depots at charging facilities in eligible census tracts to take further advantage of the tax credit. In addition, we note that DOE estimated 68 percent of heavy-duty vehicles are registered in qualifying census tracts suggesting the share of EVSE installations at depots that are eligible for the 30C tax credit could be higher.

population living in eligible census tracts. Taken together, DOE estimates an average value of this tax credit of 18 percent of the installed EVSE costs at depots. We apply this 18 percent average reduction to the EVSE costs used in HD TRUCS for the FRM.

As noted above, for the NPRM, we had used the low end of our EVSE cost ranges to reflect our expectation that the tax credit would significantly reduce EVSE costs to purchasers (i.e. we used the low end to reflect typical EVSE hardware and installation costs less savings from the tax credit). Since we explicitly model the tax credit reductions for the FRM analysis, we determined it was appropriate to switch from using the low to the midpoint of EVSE cost ranges for all EVSE types to better reflect typical hardware and installation costs before accounting for the tax credit savings. The resulting hardware and installation costs for EVSE are shown in Table 2-77 before and after applying the tax credit. We use values in the right column in our depot charging analysis.

Table 2-77 Combined Hardware and Installation EVSE Costs used in HD TRUCS (in 2022$)

Charging Type	Cost Before Tax Credit	Cost After Tax Credit
Level 2—19.2 kW	$16,991	$13,932
DCFC—50 kW	$63,432	$52,014
DCFC—150 kW	$154,200	$126,444
DCFC—350 kW	$232,700	$190,814

2.6.2.1.3 EVSE Sizing

In the preceding section, we described infrastructure costs for four different charging types that we think could be used at depots. To estimate the corresponding costs for each vehicle type, we considered the type and number of EVSE ports that different BEV owners may buy.

The choice of charging equipment will be based on the needs and preferences of each BEV or fleet owner. Fleet owners may work with OEMs, dealers, utilities, or charging equipment suppliers to analyze their charging options based on duty cycle requirements of the fleet and site-specific conditions of the depot, warehouse, or yard where EVSE will be installed. Some owners will likely opt for the lowest-power (and lowest-cost) EVSE type that is appropriate for the application. Other fleets may choose to install higher-power charging options that be shared among multiple BEVs in their fleet, or to prepare for future or additional vehicle purchases, resiliency, or evolving business needs.

For our depot charging analysis, we analyzed the scenario where BEV or fleet owners would opt for the lowest-cost EVSE option[1168] that could be used to charge the vehicle battery conservatively sized based on the 90th percentile VMT (as discussed in RIA Chapter 2.2.1.2.2 and 2.4.1.1) each day. While purchasers may make their own business decisions, we think analyzing the lowest-cost EVSE option that meets operational needs is a reasonable approach to estimating costs for the final rule. Two key inputs include (1) the amount of time a vehicle has to charge at the depot each day, and (2) how many vehicles can share charging equipment.

[1168] As discussed in Chapter 2.8.7.1.3, the lowest-cost EVSE option refers to the lowest cost on a per vehicle basis accounting for both EVSE port price and the number of vehicles that can share a port.

2.6.2.1.4 Depot Dwell Time

How long a vehicle is off-shift and parked at a depot, warehouse, or other home base each day is a key factor in determining what type of charging infrastructure could meet its needs. We refer to this as depot dwell time. This depot dwell time depends on a vehicle's duty cycle. For example, a school bus or refuse truck may be parked at a depot in the afternoon or early evening and remain there until the following morning whereas a transit bus may continue to operate throughout the evening. Even for a specific vehicle, off-shift depot dwell times may vary between weekends and weekdays, by season, or due to other factors that impact its operation.

The vehicles in our depot charging analysis span a wide range of vehicle types and duty cycles, and we expect their dwell times to vary accordingly. In the NPRM, we used a dwell time of 12 hours for every type of HD vehicle informed by our examination of start and idle activity data[1169] for 564 commercial vehicles.[1170] In order to better understand how depot dwell times might vary by vehicle application and class for our final rule analysis, we supported new data analysis by NREL through an interagency agreement between EPA and the U.S. Department of Energy. NREL analyzed several data sets for this effort: General Transit Feed Specification (GTFS) data for about 21,700 transit buses,[1171] operating data for nearly 300 school buses from NREL's FleetDNA database, and a set of fleet telematics data from Geotab's Altitude platform covering about 13,600 medium- and heavy-duty trucks in seven geographic zones[1172] selected to be nationally representative.[1173] The truck dataset includes a variety of classes and vocations. As described in Bruchon et al. 2024,[1174] NREL separately analyzed data for four class combinations (2b–3, 4–5, 6–7, and 8) and four vocations defined by vehicles' travel patterns (door to door, hub and spoke, local, and regional). This results in sixteen unique freight vehicle categories.[1175]

Across all vehicle categories, NREL provided national dwell time distributions that describe the number of hours vehicles spend at their primary domicile (or depot). For each of the sixteen freight categories as well as for school buses, these dwell durations reflect the total daily hours vehicles spent at their depots on operational weekday or weekend days regardless of whether the vehicles were parked for one continuous period or across multiple stops throughout the day. For transit buses, NREL estimated the typical time buses spent when parked at their depot overnight, i.e., the time between the end of the last shift of the day and the first shift the following service

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[1169] Zhang, Chen; Kotz, Andrew; Kelly, Kenneth "Heavy-Duty Vehicle Activity for EPA MOVES." National Renewable Energy Laboratory. 2021. Available online: https://data.nrel.gov/submissions/168.

[1170] The dataset had been analyzed as a joint effort between EPA and NREL to inform EPA's MOVES model.

[1171] Both GTFS schedule and real-time data were utilized along with information from the National Transit Database.

[1172] The seven zones are: San Jose-Sunnyvale-Santa Clara, CA; Pittsburgh, PA; Evansville, IN-KY; Lafayette, LA; Janesville-Beloit, WI; Southern ID non-Metropolitan Statistical Areas (MSA); Eastern GA non-MSAs. Data used was collected between September 7 and September 30, 2022. See Bruchon et al. 2024 for details on variables used to select the seven representative zones.

[1173] Bruchon, Matthew, Brennan Borlaug, Bo Liu, Tim Jonas, Jiayun Sun, Nhat Le, and Eric Wood. "Depot-based Vehicle Data for National Analysis of Medium- and Heavy-Duty Electric Vehicle Charging." NREL/TP-5400-88241. February 2024. Available online: https://www.nrel.gov/docs/fy24osti/88241.pdf.

[1174] Bruchon, Matthew, Brennan Borlaug, Bo Liu, Tim Jonas, Jiayun Sun, Nhat Le, and Eric Wood. "Depot-based Vehicle Data for National Analysis of Medium- and Heavy-Duty Electric Vehicle Charging." NREL/TP-5400-88241. February 2024. Available online: https://www.nrel.gov/docs/fy24osti/88241.pdf.

[1175] NREL's report also includes information on a long-distance vocation. However, we have excluded these from our depot charging analysis because, as noted in Bruchon et al. 2024, the long-distance trucks in the sample are less likely to meet the criteria for depot-based travel.

day with separate estimates for weekdays, Saturdays, and Sundays. Days on which vehicles were not operated were excluded from the samples.[1176]

There is a wide variation of dwell durations across vehicles and operating days. NREL provided tenth to ninetieth percentile dwell durations for each combination of class and vocation, where the tenth percentile values can be interpreted as the minimum depot dwell duration applicable to 90 percent of vehicle operating days in the sample, the twentieth percentile is the minimum dwell duration applicable to 80 percent of sampled vehicle days and so on. For our analysis, we selected the thirtieth percentile values for weekdays,[1177,1178] which corresponds to a minimum depot dwell duration applicable to 70 percent of sampled vehicle days. As described in RIA Chapter 2.7.2, we limited the maximum penetration of the ZEV technologies in HD TRUCS, and corresponding to our modeled potential compliance pathway, to 20 percent in MY 2027 and 70 percent in MY 2032 for any given vehicle type. Therefore, our use of the thirtieth percentile dwell times should cover the BEV technology in the projected technology packages developed to support the final standards and could be considered conservative for vehicle types or years with lower projected utilization of BEV technology.

We mapped the resulting dwell times[1179,1180] for the 18 unique combinations of vocation and class types (i.e., 16 freight vehicle categories plus transit and school buses) to the applicable vehicle types in our HD TRUCS model. We applied dwell times from NREL's school bus category to all eight school bus types in HD TRUCS and NREL's transit bus dwell times to all four transit buses in HD TRUCS. We mapped the freight vehicles as follows. For vocational vehicles in HD TRUCS, we assumed that those with an urban duty cycle corresponded to door-to-door vehicles in NREL's analysis, those with a multipurpose duty cycle corresponded to hub and spoke vehicles, and those with a regional duty cycle corresponded to either local or regional depending on whether daily operational VMT was (a) less than or equal to 150 miles or (b) greater than 150 miles, respectively.[1181] For tractors, we assumed all vehicle types in our analysis were either local or regional depending on the same daily operational VMT limits. There was one heavy-haul vehicle type that we assumed would use depot charging, but which did not

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[1176] In addition, total dwell durations for school buses were only considered during the school year and stops at the depot less than one hour were excluded.

[1177] The total time a vehicle spends at the depot on a weekday is typically shorter than on a weekend when some vehicles may operate for fewer hours. For this reason, we assumed fleet owners would size EVSE based on weekday driving needs.

[1178] NREL provided two sets of dwell durations for freight vehicles: 'fixed' and 'adjusted'. We selected the 'adjusted' values, which were more conservative than the corresponding 'fixed' values for the percentile selected. See Bruchon et al. 2024 for more details.

[1179] In NREL's "MHDV_Operations_Summaries.xlsx" data file, in the "Statistics" tab, see column V ('Domicile_Hours_p30').

[1180] Bruchon, Matthew, Brennan Borlaug, Bo Liu, Tim Jonas, Jiayun Sun, Nhat Le, and Eric Wood. 2024. "National Summary Statistics for Depot-Based Medium- and Heavy-Duty Vehicle Operations." NREL Data Catalog. Golden, CO: National Renewable Energy Laboratory. Last updated: March 8, 2024. Available online: https://data.nrel.gov/submissions/231. (See spreadsheet "MHDV_Operations_Summaries.xlsx".)

[1181] See Bruchon et al. 2024 for a description of vocations in the truck data set.

correspond to the vehicle types in NREL's analysis. For that vehicle type we assumed 8 hours consistent with a recent ICCT report.[1182]

The final dwell times assigned to each of the vehicle types in our analysis ranged from 7.4 hours to 14.5 hours and are shown in Table 2-78.

2.6.2.1.5 EVSE Sharing

Charging infrastructure can be shared across multiple vehicles in a variety of ways. An EVSE port with just one connector can be used sequentially by different vehicles. If those vehicles are parked at the depot at different times of day, drivers may plug in when they park. If vehicles have overlapping depot dwell times, employees may be tasked with swapping the connector among vehicles—though this may have tradeoffs in terms of convenience and may not be practical for all applications. Some EVSE ports are available for purchase with multiple connectors allowing vehicles to charge sequentially without the need to swap connectors.[1183]

Rated power can also be shared across EVSE ports by either decreasing the charging rate of vehicles charging simultaneously or charging vehicles one after another.[1184] For example, a dual port 150 kW DCFC unit could be configured to charge one vehicle at 150 kW or two vehicles at 75 kW. Some residential and commercial Level 2 charging equipment is also capable of power sharing (e.g., the Tesla Gen 3 Wall Connector).[1185] This can be accomplished through either a multi-connector charging unit, or use of multiple units on the same electrical circuit which communicate to limit the total power being delivered.

Sharing charging equipment or power may be attractive to fleet owners as it can reduce the upfront costs associated with procuring and installing EVSE at depots. And by spreading infrastructure costs across multiple vehicles, per-vehicle EVSE costs can decline. Of course, the decisions of whether to share EVSE ports and which types of sharing are selected will depend on the specific situation and operational needs of the fleet. For the NPRM, we assumed that each vehicle using Level 2 charging would have its own EVSE port, while up to two vehicles could share DCFC if charging needs could be met within the assumed dwell time. We received several comments that these constraints were too limiting. In our final rule HD TRUCS analysis, we updated our approach and project that up to two vocational vehicles can share one EVSE port if there is sufficient depot dwell time for all vehicles to meet their daily charging needs. For tractors, which tend to be part of larger fleets, we project up to four vehicles can share one EVSE port if there is sufficient daily depot dwell time for each vehicle to meet its charging needs. We note that for some of the vehicle types we evaluated, higher numbers of vehicles could share EVSE ports and still meet their daily electricity consumption needs. However, in our final rule HD TRUCS analysis we limit sharing to two vocational vehicles and four tractors per port, which could potentially be a conservative approach.

[1182] Ragon, Pierre-Louis et al., "Near-term Infrastructure Deployment to Support Zero-Emission Medium- and Heavy-Duty Vehicles in the United States," 2023. Available online: https://theicct.org/publication/infrastructure-deployment-mhdv-may23/.

[1183] Proterra. "New Proterra EV Charging Solutions Enable Full Fleet Electrification for Commercial Vehicles". October 28, 2020. See EPA-HQ-OAR-2022-0985-0705.

[1184] Agrawal, Ajay. "Charge More EVs with Power Management". ChargePoint, EV Charging Innovation: July 18, 2017. Available online: https://www.chargepoint.com/blog/charge-more-evs-power-management.

[1185] Tesla. "Power Sharing Overview". See EPA-HQ-OAR-2022-0985-0700.

2.6.2.2 Depot Summary

RIA Chapter 2.8.7 describes how EVSE are sized and per vehicle costs are assigned within HD TRUCS for each of the vehicle types that we assume use depot charging taking into account the vehicles' battery size, depot dwell time, and EVSE sharing constraints. The results are summarized in Table 2-78 which shows the charging type (designated in the table by its power level) assigned to each vehicle ID, how many vehicles can share the EVSE port, and the final per vehicle EVSE cost (reflecting upfront hardware and installation costs for depot charging accounting for the tax credit).[1186] The depot dwell time and battery size for each vehicle type are shown for reference.

Table 2-78 Summary of per vehicle EVSE costs (in 2022$)

Vehicle ID	Battery Size (kWh)	Dwell Time (hrs)	Charging Type (kW)	Vehicles per EVSE Port	EVSE Cost ($/vehicle)
01V_Amb_Cl4-5_MP	120	12.2	L2 (19.2 kW)	1	$13,932
02V_Amb_Cl2b-3_MP	113	12.5	L2 (19.2 kW)	2	$6,966
03V_Amb_Cl4-5_U	111	10.3	L2 (19.2 kW)	1	$13,932
04V_Amb_Cl2b-3_U	104	10.6	L2 (19.2 kW)	1	$13,932
05T_Box_Cl8_MP	244	11.6	DC - 50 kW	2	$26,007
06T_Box_Cl8_R	252	9.2	DC - 50 kW	1	$52,014
07T_Box_Cl6-7_MP	168	11.9	L2 (19.2 kW)	1	$13,932
08T_Box_Cl6-7_R	183	9.9	L2 (19.2 kW)	1	$13,932
09T_Box_Cl8_U	236	9.1	DC - 50 kW	1	$52,014
10T_Box_Cl6-7_U	162	10.2	L2 (19.2 kW)	1	$13,932
11T_Box_Cl2b-3_U	100	10.6	L2 (19.2 kW)	2	$6,966
12T_Box_Cl2b-3_R	118	7.9	L2 (19.2 kW)	1	$13,932
13T_Box_Cl2b-3_MP	109	12.5	L2 (19.2 kW)	2	$6,966
14T_Box_Cl4-5_U	100	10.3	L2 (19.2 kW)	1	$13,932
15T_Box_Cl4-5_R	118	9.7	L2 (19.2 kW)	1	$13,932
16T_Box_Cl4-5_MP	109	12.2	L2 (19.2 kW)	2	$6,966
17B_Coach_Cl8_R	710	NA	Public	0	$-
18B_Coach_Cl8_MP	1052	NA	NA	0	$-
19C_Mix_Cl8_MP	428	11.6	DC - 50 kW	1	$52,014
20T_Dump_Cl8_U	283	9.1	DC - 50 kW	1	$52,014
21T_Dump_Cl8_MP	286	11.6	DC - 50 kW	2	$26,007
22T_Dump_Cl6-7_MP	277	11.9	DC - 50 kW	2	$26,007
23T_Dump_Cl8_U	283	9.1	DC - 50 kW	1	$52,014
24T_Dump_Cl6-7_U	259	10.2	DC - 50 kW	1	$52,014
25T_Fire_Cl8_MP	300	11.6	DC - 50 kW	1	$52,014
26T_Fire_Cl8_U	301	9.1	DC - 50 kW	1	$52,014
27T_Flat_Cl6-7_MP	168	11.9	L2 (19.2 kW)	1	$13,932
28T_Flat_Cl6-7_R	183	9.9	DC - 50 kW	2	$26,007
29T_Flat_Cl6-7_U	155	10.2	L2 (19.2 kW)	1	$13,932
30Tractor_DC_Cl8	351	9.2	DC - 150 kW	3	$42,148

[1186] Note that all RV vehicle types have been assigned L2 EVSE with no sharing of EVSE ports. This was done to reflect the fact that RVs will generally be charged at residences and are likely to have a very long dwell time opportunity before the initial part of a trip. This assignment does not impact the HD TRUCS payback results because we are not setting new Optional Custom Chassis Standards for RVs, and RV vehicle types have zero percent ZEV adoption in the HD TRUCS results with this assignment.

Vehicle ID	Battery Size (kWh)	Dwell Time (hrs)	Charging Type (kW)	Vehicles per EVSE Port	EVSE Cost ($/vehicle)
31Tractor_DC_Cl7	317	9.9	DC - 150 kW	4	$31,611
32Tractor_SC_Cl8	973	NA	Public	0	$-
33Tractor_DC_Cl8	531	NA	Public	0	$-
34T_Ref_Cl8_MP	355	11.6	DC - 50 kW	1	$52,014
35T_Ref_Cl6-7_MP	290	11.9	DC - 50 kW	1	$52,014
36T_Ref_Cl8_U	355	9.1	DC - 50 kW	1	$52,014
37T_Ref_Cl6-7_U	286	10.2	DC - 50 kW	1	$52,014
38RV_Cl8_R	564	7.4	L2 (19.2 kW)	1	$13,932
39RV_Cl6-7_R	599	8.3	L2 (19.2 kW)	1	$13,932
40RV_Cl4-5_R	381	7.8	L2 (19.2 kW)	1	$13,932
41Tractor_DC_Cl7	744	NA	NA	0	$-
42RV_Cl8_MP	564	11.6	L2 (19.2 kW)	1	$13,932
43RV_Cl6-7_MP	550	11.9	L2 (19.2 kW)	1	$13,932
44RV_Cl4-5_MP	350	12.2	L2 (19.2 kW)	1	$13,932
45Tractor_DC_Cl8	891	NA	NA	0	$-
46B_School_Cl8_MP	266	14.5	DC - 50 kW	2	$26,007
47B_School_Cl6-7_MP	160	14.5	L2 (19.2 kW)	1	$13,932
48B_School_Cl4-5_MP	120	14.5	L2 (19.2 kW)	2	$6,966
49B_School_Cl2b-3_MP	113	14.5	L2 (19.2 kW)	2	$6,966
50B_School_Cl8_U	252	14.5	L2 (19.2 kW)	1	$13,932
51B_School_Cl6-7_U	160	14.5	L2 (19.2 kW)	1	$13,932
52B_School_Cl4-5_U	111	14.5	L2 (19.2 kW)	2	$6,966
53B_School_Cl2b-3_U	104	14.5	L2 (19.2 kW)	2	$6,966
54Tractor_SC_Cl8	1164	NA	Public	0	$-
55B_Shuttle_Cl2b-3_MP	164	12.5	L2 (19.2 kW)	1	$13,932
56B_Shuttle_Cl4-5_U	158	10.3	L2 (19.2 kW)	1	$13,932
57B_Shuttle_Cl2b-3_U	151	10.6	L2 (19.2 kW)	1	$13,932
58B_Shuttle_Cl6-7_MP	264	11.9	DC - 50 kW	2	$26,007
59B_Shuttle_Cl6-7_U	245	10.2	DC - 50 kW	1	$52,014
60S_Plow_Cl6-7_MP	199	11.9	L2 (19.2 kW)	1	$13,932
61S_Plow_Cl8_MP	394	11.6	DC - 50 kW	1	$52,014
62S_Plow_Cl6-7_U	187	10.2	DC - 50 kW	2	$26,007
63S_Plow_Cl8_U	388	9.1	DC - 50 kW	1	$52,014
64V_Step_Cl6-7_MP	169	11.9	L2 (19.2 kW)	1	$13,932
65V_Step_Cl4-5_MP	109	12.2	L2 (19.2 kW)	2	$6,966
66V_Step_Cl2b-3_MP	109	12.5	L2 (19.2 kW)	2	$6,966
67V_Step_Cl6-7_U	156	10.2	L2 (19.2 kW)	1	$13,932
68V_Step_Cl4-5_U	100	10.3	L2 (19.2 kW)	1	$13,932
69V_Step_Cl2b-3_U	100	10.6	L2 (19.2 kW)	1	$13,932
70S_Sweep_Cl6-7_U	182	10.2	L2 (19.2 kW)	1	$13,932
71T_Tanker_Cl8_R	269	9.2	DC - 50 kW	1	$52,014
72T_Tanker_Cl8_MP	264	11.6	DC - 50 kW	2	$26,007
73T_Tanker_Cl8_U	263	9.1	DC - 50 kW	1	$52,014
74T_Tow_Cl8_R	413	9.2	DC - 50 kW	1	$52,014
75T_Tow_Cl6-7_R	300	9.9	DC - 50 kW	1	$52,014
76T_Tow_Cl8_U	400	9.1	DC - 50 kW	1	$52,014
77T_Tow_Cl6-7_U	261	10.2	DC - 50 kW	1	$52,014
78Tractor_SC_Cl8	834	NA	Public	0	$-
79Tractor_SC_Cl8	1164	NA	NA	0	$-
80Tractor_DC_Cl8	647	8	DC - 350 kW	4	$47,704

Vehicle ID	Battery Size (kWh)	Dwell Time (hrs)	Charging Type (kW)	Vehicles per EVSE Port	EVSE Cost ($/vehicle)
81Tractor_DC_Cl7	531	NA	Public	0	$-
82Tractor_DC_Cl8	635	NA	Public	0	$-
83Tractor_DC_Cl7	459	9.9	DC - 150 kW	3	$42,148
84Tractor_DC_Cl8	356	NA	Public	0	$-
85B_Transit_Cl8_MP	472	8.1	DC - 150 kW	2	$63,222
86B_Transit_Cl6-7_MP	373	8.1	DC - 50 kW	1	$52,014
87B_Transit_Cl8_U	472	8.1	DC - 150 kW	2	$63,222
88B_Transit_Cl6-7_U	341	8.1	DC - 50 kW	1	$52,014
89T_Utility_Cl8_MP	254	11.6	DC - 50 kW	2	$26,007
90T_Utility_Cl8_R	261	9.2	DC - 50 kW	1	$52,014
91T_Utility_Cl6-7_MP	184	11.9	L2 (19.2 kW)	1	$13,932
92T_Utility_Cl6-7_R	198	9.9	DC - 50 kW	2	$26,007
93T_Utility_Cl4-5_MP	120	12.2	L2 (19.2 kW)	1	$13,932
94T_Utility_Cl2b-3_MP	114	12.5	L2 (19.2 kW)	1	$13,932
95T_Utility_Cl4-5_R	128	9.7	L2 (19.2 kW)	1	$13,932
96T_Utility_Cl2b-3_R	128	7.9	L2 (19.2 kW)	1	$13,932
97T_Utility_Cl8_U	250	9.1	DC - 50 kW	1	$52,014
98T_Utility_Cl6-7_U	174	10.2	L2 (19.2 kW)	1	$13,932
99T_Utility_Cl4-5_U	113	10.3	L2 (19.2 kW)	1	$13,932
100T_Utility_Cl2b-3_U	106	10.6	L2 (19.2 kW)	1	$13,932
101Tractor_DC_Cl8	279	9.2	DC - 150 kW	4	$31,611

2.6.3 Public Charging Analysis

As noted above, starting in MY 2030, we project eight BEV types: long-haul vehicles (both sleeper cab and some long-range day cab tractors) and BEV coach buses utilize public charging. The per-vehicle costs associated with public charging infrastructure will depend largely on the hardware and installation costs of the EVSE and station utilization. As discussed in RIA Chapter 1.6, recent studies have assumed different mixes of EVSE ports deployed at public stations, ranging from 125 kW to 2 MW. For our final rule analysis, we modeled station costs to reflect a 2023 ICCT study that examined public charging costs for Class 8 BEV trucks.[1187] The study assumed that a mix of 1 MW and 150 kW EVSE ports would meet BEV charging needs with each station capable of 20 MW power[1188] and utilization reaching 15% by 2035. The study estimated the mean levelized cost for trucks to charge at these stations to be 19.6 cents/kWh accounting for EVSE hardware and installation costs, EVSE maintenance, land costs, upgrades to the distribution infrastructure (see following section), electricity rates, demand charges, as well as financial costs and profit margins of station operators.

As discussed in RIA Chapter 2.4.4.2, we used this value as the basis of our public charging costs, which we then adjusted over time to reflect projected changes to electricity prices. This approach to incorporating public infrastructure costs reflects our expectation that upfront capital

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[1187] Hussein Basma, Claire Buysee, Yuanrong Zhou, and Felipe Rodriguez, “Total Cost of Ownership of Alternative Powertrain Technologies for Class 8 Long-haul Trucks in the United States.” April 2023. Available online: https://theicct.org/wp-content/uploads/2023/04/tco-alt-powertrain-long-haul-trucks-us-apr23.pdf.

[1188] Each station was assumed to have 17 one MW EVSE ports and 20 150 kW EVSE ports.

costs and operating expenses for public charging stations will be passed onto customers through the charging cost.

We analyzed the feasibility of public charging to meet the daily charging needs for the eight BEV vehicle types by assessing the time it would take to charge the energy needed for the daily operating VMT using a maximum of 2C power (up to 1 MW), as discussed in Chapter RIA 2.8.7.3. The results are shown in Table 2-79.[1189, 1190] All vehicles, except 54Tractor_SC_Cl8 (is not part of the technology package in the modeled potential compliance pathway), have approximate charging times of less than 60 minutes when charging at 2C or 1 MW.

Table 2-79 Time to Charge at 2C or 1 MW for Daily Operating VMT

Vehicle ID	Operating VMT (miles)	Time to Charge at 2C or 1 MW (minutes)
17B_Coach_Cl8_R	158	26
32Tractor_SC_Cl8	420	59
33Tractor_DC_Cl8	216	32
54Tractor_SC_Cl8	420	70
78Tractor_SC_Cl8	300	50
81Tractor_DC_Cl7	216	32
82Tractor_DC_Cl8	215	38
84Tractor_DC_Cl8	120	30

As discussed in RIA Chapter 2.2.1.2.2 and 2.2.1.2.3 and shown in Table 2-80, we also calculated the amount of time it would take to charge the battery at 2C or 1 MW to enable the vehicle to travel the 90th percentile daily VMT, assuming the vehicle has started the day charged to travel the operating VMT. All of the publicly-charged tractor vehicle types in our analysis have additional charging times of less than half an hour, which should allow drivers to charge during a 30 minute break. The BEV coach bus has an approximate additional charging time of less than an hour; however, since the sizing VMT for 17B_Coach_Cl8_R is 300 miles, if the coach bus starts the day with a full battery, an additional charge to reach the 90th percentile daily VMT would take less than 30 minutes.

[1189] The time to charge for operating VMT is based on year 0 of operation. Because VMT declines over time, we would also expect this time to correspondingly decline over time.

[1190] This calculation uses a uniform charging rate; however, charging rates may vary based on the state of charge of the battery.

Table 2-80 Additional Time to Charge at 2C or 1 MW to Travel the 90th Percentile VMT

Vehicle ID	Operating VMT (miles)	90th Percentile VMT (miles)	Additional Charging Time Needed for 90th Percentile Daily VMT at 2C or 1 MW (minutes)
17B_Coach_Cl8_R	158	450	48
32Tractor_SC_Cl8	420	571	21
33Tractor_DC_Cl8	216	349	20
54Tractor_SC_Cl8	420	571	25
78Tractor_SC_Cl8	300	300	0
81Tractor_DC_Cl7	216	349	20
82Tractor_DC_Cl8	215	349	24
84Tractor_DC_Cl8	120	120	0

2.6.4 Other considerations

While our depot and public charging analyses described above focus on EVSE needs and costs, we acknowledge that additional infrastructure costs associated with charging stations could be incurred. If the electrical grid distribution hosting capacity (power available for new use) is less than the charging station requires, investment will be needed to upgrade or “build out” that portion of the grid to enable the depot to draw power. While large BEV fleets or BEVs with high daily electricity consumption could force significant buildouts and associated expenditures, even lower power depots could drive some buildout if their need exceeds the grid capacity. As discussed in RTC section 7 (Distribution), we discuss demand posed by the phase 3 rule, assuming that the compliance pathway developed in support of the standards is followed. We see low demand at the national level, at the regional level in the high-volume freight corridors which are the most likely candidates for initial electrification, and at the localized parcel level. We also note that most (approximately 88%) of our projected depot ports will be Level 2, again reducing potential demand occasioning buildout. See RIA Chapter 2.10.3. In addition, as discussed in Chapter RIA 1.6.5, there are a variety of approaches by both utilities and BEV users that could reduce the need or scale of such upgrades. Utilities can factor, distribution system capacity into station siting decisions, and consider alternative charging solutions (e.g., mobile charging units or standalone charging canopies with integrated solar generation). In addition to charging at lower levels (as we project), fleets can engage in time of use and other managed charging to limit the instantaneous demand on the grid.

In the NPRM, we noted that in many cases, costs for distribution system upgrades will be borne by utilities and we did not model them in our analysis of EVSE or charging costs. In consideration of comments received (see RTC 7 (Distribution)), information from a new DOE analysis (described below), and from the literature, we have decided that it is appropriate to include the cost of distribution upgrades in our FRM analysis. See RIA Chapter 2.4.4.2 for a description of how we accounted for the costs associated with distribution upgrades for both depot and public charging in the charging costs used in the final rule analysis.

Our analysis for assessing the cost of potential distribution grid buildout posed by the final rule is informed by the DOE Multi-State Transportation Electrification Impact Study

("TEIS").[1191] It also provides information we have considered to inform questions of availability of infrastructure necessary to support the standards under the modeled potential compliance pathway within the rule's MY 2027-2032 and later time frame. The study focuses on 5 states (California, New York, Illinois, Oklahoma, and Pennsylvania) selected to capture diversity in population density (urban and rural areas), freight demand, BEV demand, state EV policies, utility type (i.e., investor owned, municipality, or cooperative) and distribution grid composition. The study is the first of its kind with respect to the combination of scale of the analysis, load and distribution spatial and asset granularity (parcel and feeder-level respectively), scope of the EV impacts, and time horizon. The study compares parcel level LMHD and HDV demand to parcel supply by photo-voltaic and grid capacity at each examined parcel. The TEIS used the five states to extrapolate a national demand for where and when upgrades will be needed to the electricity distribution system—including substations, feeders, and service transformers—due to BEV load under the EPA light- and heavy-duty rules (approximated) and under a no action case. The results from these five-states are extrapolated to the IPM regions that we use to represent the remaining 48 contiguous states within our power sector analysis. The Study also assesses the potential impact of simple, conservative limited time charging to reduce the needs and associated costs of distribution upgrades. This managed charging simply spreads the charging over the dwell time available rather than apply maximum charging as soon as the vehicle parks (starts dwell). The system peak power demand may still increase. With more sophisticated managed charging, the existing system peak would be avoided which suggests that demand and infrastructure savings could be a lower-end estimate compared to implementing more advanced control systems.[1192]

The TEIS evaluates demand from both the light- and heavy-duty sectors. The load profiles used for this analysis combine, for the first time, the load profiles for a No Action case and for both the Light- and Medium-Duty Multipollutant Standards rulemaking and this Phase 3 rule[1193] into a single power sector analysis. The load profiles from light-, medium- and heavy-duty are distributed into IPM regions using NREL's EVI-X suite of models for light-duty, LDVs, MDVs, and heavy-duty buses; and using LBNL's HEVI-LOAD model for all other heavy-duty applications. The resulting premise-level load profiles were aggregated up to electric utility service territories. The system-level grid impacts and costs of electricity service were determined based upon the profiles. Additional scenarios were modeled to evaluate the impact of both unmanaged charging and managed charging. In the unmanaged case, the study assumes that EVs are charged immediately when the vehicle returns to a charger. In contrast, managed charging spreads the charging out more evenly over the period when the vehicle is parked at the charger.

With respect to heavy-duty, the TEIS evaluates charging demand from heavy-duty vehicles using the Lawrence Berkely National Laboratory HEVI-LOAD modelling tool. HEVI-LOAD provides granular temporal and geospatial resolutions ranging from the station location level to traffic analysis zone, county, state, and freight corridors, to national scale. HEVI-LOAD's

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[1191] National Renewable Energy Laboratory, Lawrence Berkeley National Laboratory, Kevala Inc., and U.S. Department of Energy. "Multi-State Transportation Electrification Impact Study: Preparing the Grid for Light-, Medium-, and Heavy-Duty Electric Vehicles". DOE/EE-2818. U.S. Department of Energy. March 2024.

[1192] TEIS at 4, 76.

[1193] Electricity demand for heavy-duty ZEVs matches that of the interim control case as described in RIA Chapter 4.2.4 while demand from light- and medium-duty vehicles was based on Alternative 3 from the proposed "Multipollutant Emissions Standards for Model Years 2027 and Later Light-Duty and Medium-Duty Vehicles."

workflow consists of three major steps: data preprocess and scenario generation, agent-based simulation, and resulting output. Data preprocessing and scenario generation takes input data for travel demand, charging infrastructure, and road networks to create simulation scenarios. The post-scenario, post-analysis outputs are an energy demand analysis and an infrastructure assessment. More specifically, energy demand is considered on state/county/charging station locations. Charging infrastructure planning assesses charger quantity and power determination based on energy needs, charging session needs and charger utilization rate assumptions. The Study further sets out its methodology respecting HDC trip synthesis, vehicle and trip behavior, start time distribution, travel distance distribution, battery starting SOC distribution, charging infrastructure scenarios, and managed charging.[1194]

Additional infrastructure costs could also be incurred based on the choices of the fleet owner. For example, some fleet owners may opt to install battery energy storage or renewable energy such as solar panels at charging stations. While these choices add upfront costs, fleet owners can save on electricity costs over time. For example, as discussed in Chapter 1.6, by charging BEVs from onsite battery energy storage rather than directly from the grid, owners can reduce the amount of electricity purchased during peak hours (since battery energy storage can be replenished during off-peak periods). This can help fleet owners take advantage of lower-priced, time-of-use electricity rates, where applicable. Onsite battery energy storage can also be used to avoid large power draws from the grid, potentially reducing costly demand charges that are tied to peak power.[1195] ANL's paper on Innovative Charging solutions shares stationary battery strategies and analysis for Class 1-3 vehicles. While focused on LD and MD BEV, the positive aspects of the ICS may apply to some HD BEV users. ICS concepts may also allow LD and MD BEV users to implement stationary batteries and free up grid hardware needed for buildout for HD BEV users.[1196] Installing solar panels or other onsite renewables can support these strategies while also reducing the overall volume of electricity fleet owners need to purchase from utilities and potentially reducing the need for distribution upgrades described above. See also TEIS at 62 showing that in three of the five states analyzed, there are outright reductions in peak demand in 2032 between a no action case (reference case) and an action case with time-of-day adjustments, and significant projected decreases in peak demand in the action case (light-duty and heavy-duty standards) for the other two states in the study.

There is uncertainty about how many charging depots and public stations will incorporate these technologies over time, and how the incorporation of these technologies could impact site costs. The savings fleet owners may expect will also be highly variable based on local electricity rates and the charging load of the site. However, we generally expect that many fleet owners who choose to install onsite battery storage and renewables do so with the intent of recouping the upfront capital costs through electricity cost savings. For these reasons, we do not include these costs in our charging infrastructure cost estimates. Cost analysis for onsite battery systems is covered in a study, "Innovative Charging Solutions for Deploying The National Charging

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[1194] TEIS at 16-25.

[1195] National Renewable Energy Laboratory. "When Does Energy Storage Make Sense? It Depends." February 25, 2018. Available online: https://www.nrel.gov/state-local-tribal/blog/posts/when-does-energy-storage-make-sense-it-depends.html.

[1196] Poudel, Sajag, et. al. "Innovative Charging Solutions for Deploying the National Charging Network: Technoeconomic Analysis". Argonne National Laboratory. March 2024.

Network: Technoeconomic Analysis".[1197] This study looks at the levelized cost of charging (LCOC) to determine when onsite battery use drives net savings. Although the study is focused on LD Class 1-3 vehicles, the EVSE and BES (battery energy storage) is of sufficient size that it could apply to smaller HD BEV fleets. Directionally, this analysis supports that there will be scenarios where HD BEV users benefit from applying BES.

2.7 Technology Adoption

In the transportation sector, new technology adoption rates often follow an S shape. DRIA at 231. That is, the adoption rates for a specific technology are initially slow, followed by a rapid adoption period, then eventually levelling off as the market saturates. At proposal, we developed a method to project the rate at which utilization of ZEV technologies in the modeled technology packages could be accepted into the HD fleet. The schedule used in the NPRM was developed by EPA based on initial literature searches.[1198,1199,1200,1201,1202,1203,1204,1205] The adoption rate method used for the final rule includes updates to the proposal developed after considering methods in the literature to estimate adoption rates of ZEV technologies in the HD vehicle market as well as comments received after the proposed rule. The methods explored include the following: (1) the methods described in ACT Research's ChargeForward report,[1206] (2) NREL's Transportation Technology Total Cost of Ownership (T3CO) tool,[1207] (3) Oak Ridge National Laboratory's Market Acceptance of Advanced Automotive Technologies (MA3T) model,[1208] (4)

[1197] Poudel, Sajag, et. al. "Innovative Charging Solutions for Deploying the National Charging Network: Technoeconomic Analysis". Argonne National Laboratory. March 2024.

[1198] Oak Ridge National Laboratory. "MA3T-TruckChoice." June 2021. Available at: https://www.energy.gov/sites/default/files/2021-07/van021_lin_2021_o_5-28_1126pm_LR_FINAL_ML.pdf.

[1199] Oak Ridge National Laboratory. "Transportation Energy Evolution Modeling (TEEM) Program." https://www.energy.gov/eere/vehicles/articles/transportation-energy-evolution-modeling-teem-program-1

[1200] National Renewable Energy Laboratory. T3CO: Transportation Technology Total Cost of Ownership. Available at: https://www.nrel.gov/transportation/t3co.html.

[1201] Argonne National Laboratory. "ANL – ESD-2206 Report – BEAN Tool – MD HD Vehicle Techno-Economic Analysis.xlsm". Available online: https://anl.app.box.com/s/an4nx0v2xpudxtpsnkhd5peimzu4j1hk/folder/242640145714.

[1202] Pacific Northwest National Laboratory. GCAM: Global Change Analysis Model. https://gcims.pnnl.gov/modeling/gcam-global-change-analysis-model

[1203] Robo, Ellen and Dave Seamonds. Technical Memo to Environmental Defense Fund: Analysis of Alternative Medium- and Heavy-Duty Zero-Emission Vehicle Business-As-Usual Scenarios. ERM. August 19, 2022. Available online: https://www.erm.com/contentassets/154d08e0d0674752925cd82c66b3e2b1/edf-zev-baseline-technical-memo-16may2022.pdf.

[1204] ICCT and Energy Innovation. "Analyzing the Impact of the Inflation Reduction Act on Electric Vehicle Uptake in the United States". January 2023. Available online: https://theicct.org/wp-content/uploads/2023/01/ira-impact-evs-us-jan23-2.pdf.

[1205] Al-Alawi, Baha M., Owen MacDonnell, Cristiano Facanha. "Global Sales Targets for Zero-Emission Medium- and Heavy-Duty Vehicles—Methods and Application". February 2022. Available online: https://globaldrivetozero.org/site/wp-content/uploads/2022/02/CALSTART_Global-Sales_White-Paper.pdf.

[1206] Mitchell, George. Memorandum to docket EPA-HQ-OAR-2022-0985. " ACT Research Co. LLC. "Charging Forward" 2020-2040 BEV & FCEV Forecast & Analysis, updated December 2021.

[1207] National Renewable Energy Laboratory. T3CO: Transportation Technology Total Cost of Ownership. Available at: https://www.nrel.gov/transportation/t3co.html.

[1208] Oak Ridge National Laboratory. "MA3T-TruckChoice." June 2021. Available at: https://www.energy.gov/sites/default/files/2021-07/van021_lin_2021_o_5-28_1126pm_LR_FINAL_ML.pdf

Pacific Northwest National Laboratory's Global Change Analysis Model (GCAM),[1209] (5) ERM's market growth analysis done on behalf of EDF,[1210] (6) Energy Innovation's United States Energy Policy Simulator used in a January 2023 analysis by ICCT and Energy Innovation,[1211] and (7) CALSTART's Drive to Zero Market Projection Model.[1212]

The data we received in comments with respect to technology adoption rates relative to payback periods are plotted with the payback values we used in the NPRM, as shown in Figure 2-9. DTNA suggested a curve for Class 4-7 ZEVs and one for Class 8 ZEVs.[1213] EDF provided an alternate distribution of adoption rate based on payback period developed from their assessment of the inputs from a NREL study using the TEMPO Model.[1214] Energy Innovation provided payback versus adoption rate curves by vehicle segment.[1215] ICCT recommended a curve similar to TEMPO with a cap of 90% adoption.[1216] As shown in the figure, in general the adoption rate relative to the payback period follows a similar curve for all of the sources.

[1209] Pacific Northwest National Laboratory. GCAM: Global Change Analysis Model. https://gcims.pnnl.gov/modeling/gcam-global-change-analysis-model

[1210] Robo, Ellen and Dave Seamonds. Technical Memo to Environmental Defense Fund: Analysis of Alternative Medium- and Heavy-Duty Zero-Emission Vehicle Business-As-Usual Scenarios. ERM. August 19, 2022. Available online: https://www.erm.com/contentassets/154d08e0d0674752925cd82c66b3e2b1/edf-zev-baseline-technical-memo-16may2022.pdf.

[1211] ICCT and Energy Innovation. "Analyzing the Impact of the Inflation Reduction Act on Electric Vehicle Uptake in the United States". January 2023. Available online: https://theicct.org/wp-content/uploads/2023/01/ira-impact-evs-us-jan23-2.pdf.

[1212] Al-Alawi, Baha M., Owen MacDonnell, Cristiano Facanha. "Global Sales Targets for Zero-Emission Medium- and Heavy-Duty Vehicles—Methods and Application". February 2022. Available online: https://globaldrivetozero.org/site/wp-content/uploads/2022/02/CALSTART_Global-Sales_White-Paper.pdf.

[1213] Appendix E. Zero Emission Truck Market Assessment. CARB Advanced Clean Truck Regulations. October 22, 2019. Accessible at https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2019/act2019/appe.pdf

[1214] EDF Comments to Docket. EPA-HQ-OAR-2022-0985-1644-A1, p. 58-59.

[1215] See Comments of Energy Innovation. Docket EPA-HQ-OAR-2022-0985-1604 at pages 9-12.

[1216] See Comments of ICCT. Docket EPA-HQ-OAR-2022-0985-1553-A1, p. 7.

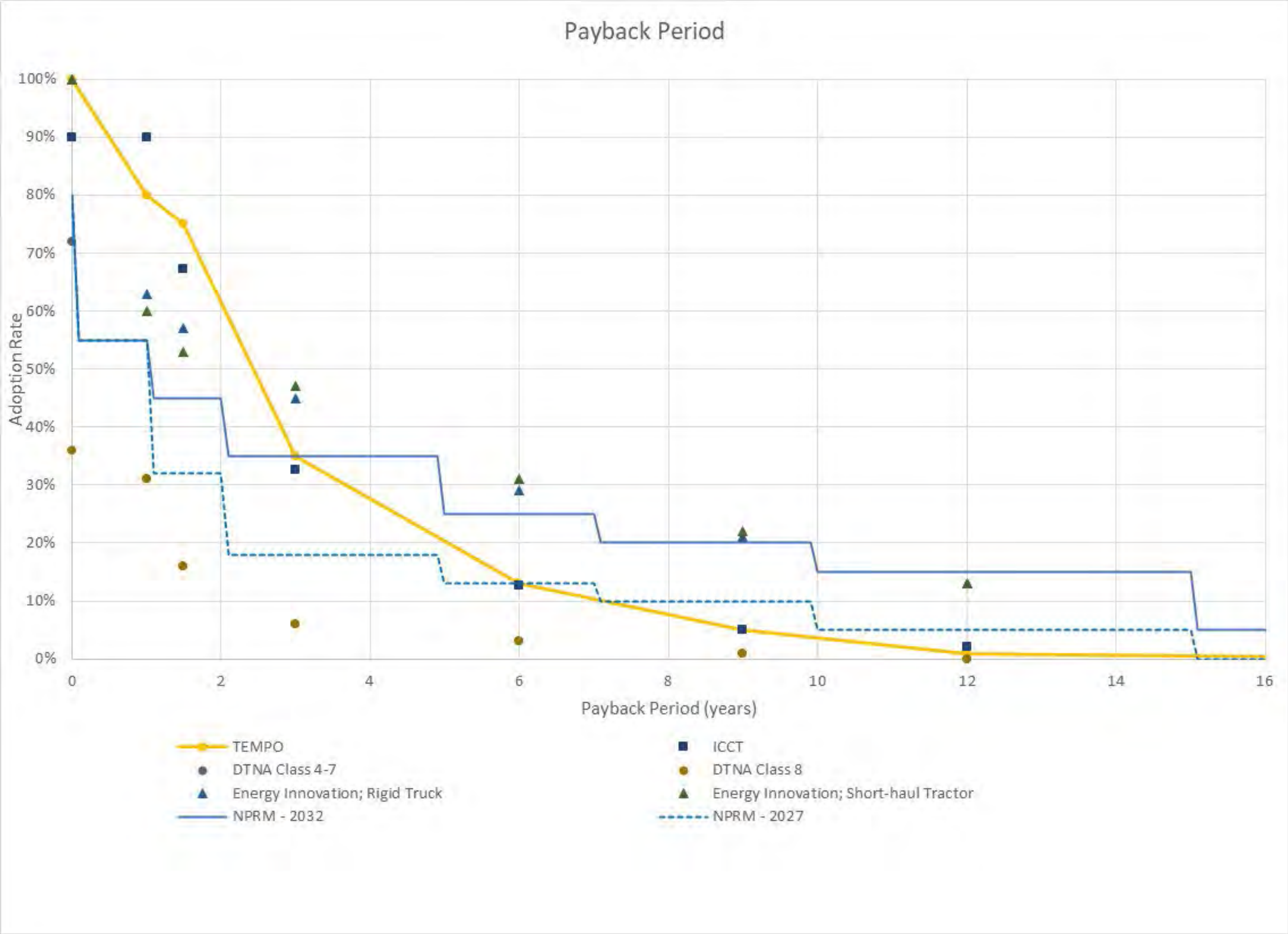

Figure 2-9 Payback Curve Data Provided in Comments

In the final rule, we used data from the NREL's TEMPO model as provided by EDF to inform our ZEV percentages in the technology packages in MY 2027, MY 2030, and MY 2032 in HD TRUCS (R_{TA}), using the same methodology we used in the proposal. We describe our reasons for doing so, and our adaptation of that model, in the following section.

2.7.1 Technology Adoption based on TEMPO

As noted in RTC Sections 2.4 and 3.12.2, commenters criticized EPA's use at proposal of the ACT Research payback equation. The critique from these commenters was both for lack of transparency – stating that the equation was proprietary and so did not appear in the DRIA making comment difficult without getting access – and one commenter obtained the equation and asserted that they found no substantive basis for it. As just noted, in one commenter's submitted comment, ACT Research itself reviewed the NPRM and stated that EPA had misapplied the equation by leaving out various factors, including a consideration of total cost of ownership in addition to payback period. Some commenters asserted that the total cost of ownership approach used in NREL's Transportation Energy & Mobility Pathway Options (TEMPO) Model (Muratori et al., 2021) was a better way to assess the shape of the payback relative to adoption rate. One of these commenters stated that the NREL model "overcomes key deficiencies of the ACT Research-based curve by being based on validated empirical data, subject to peer-review, and freely available to the public."[1217] One commenter also provided an alternate distribution of adoption rate based on payback period developed from their assessment of the inputs from a NREL study using the TEMPO Model.[1218] This commenter also suggested standards of significantly increased stringency using the TEMPO model.

The TEMPO model was one of those considered by EPA before proposal, as noted above. We evaluated it as a part of the T3CO model. At that time, EPA did not use it because the adoption distribution as a function of payback was not readily available. For the final rule, we further evaluated NREL's TEMPO model, including discussions with NREL.[1219, 1220] NREL describes TEMPO as "a transportation demand model that covers the entire U.S. transportation sector" including the medium- and heavy-duty market. Inputs to the model include vehicle cost and performance, fuel costs, charging and refueling availability, and travel behavior. The model receives this information and applies a technology adoption based on market segment, vehicle technology, scenario year, and vehicle class as a part of the outputs for TEMPO. The model uses a logit formulation to describe a relationship between purchaser adoption and aforementioned inputs, cost coefficients and financial horizon. The TEMPO model specifically evaluates HD ICE vehicles, BEVs, and FCEVs, which aligns with the technologies we are evaluating with the payback period curve. We agree with the assessment in comment that the approach developed by NREL for use in the TEMPO model is more transparent. We also found NREL's TEMPO model and approach to be robust.

A commenter provided in comments an adoption rate distribution as a function of payback years using inputs and outputs obtained from NREL's TEMPO model. Using the outputs from NREL, this commenter then calculated the adoption rates using the payback calculation methodology we used in the proposal.[1221] We evaluated the work conducted by this commenter in development of their suggested alternative payback curve derived from the TEMPO outputs.

We obtained input and output TEMPO data from NREL, similar to the dataset they provided to the commenter and analyzed it to obtain the relationship between the adoption rate and payback period. Our purpose was to assess the reasonableness of utilizing the TEMPO results for adoption rates and payback period relationships. As explained further below, our evaluation of the work conducted by the commenter was that we were able to reproduce similar adoption rates relative to payback periods as those provided by the commenter. Our assessment is that this indicates that the results are replicable, and validates the use of the TEMPO model outputs as explained below. Therefore, based on our assessment that NREL's TEMPO model is robust and the adoption rates to payback period relationship is reproducible, for the final rule, we are

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[1217] ICCT Comments to Docket. EPA-HQ-OAR-2022-0985-1553-A1, p. 2.

[1218] EDF Comments to Docket. EPA-HQ-OAR-2022-0985-1644-A1, p. 58-59.

[1219] Muratori, M, et.al. "Exploring the future energy-mobility nexus: The transportation energy & mobility pathway options (TEMPO) model." September 2021. Available online: https://www.sciencedirect.com/science/article/pii/S1361920921002650?via%3Dihub. Also see "The Transportation Energy and Mobility Pathway Options (TEMPO) Model Overview and Validation of V1.0." 2021. Available online: https://www.nrel.gov/docs/fy21osti/80819.pdf.

[1220] Miller, Neil. Memorandum to docket EPA-HQ-OAR-2022-0985. Summary of Stakeholder Meetings. March 2024.

[1221] We note TEMPO normally uses a total cost of ownership method to relate vehicle costs to adoption rates, however in publications and discussions, they state it is also a reasonable method to relate payback to adoption rates.

continuing to use the same payback period method we used in the proposal but have revised the adoption rates that correspond to the payback period bins based on data from NREL's TEMPO model instead of the use of the ACT Research-based model.

The dataset provided by NREL included primary inputs and outputs as shown in Table 2-81; these inputs and outputs are further disaggregated based on scenarios, class, market segment, fuel and technologies for years 2020 to 2050 as shown in Table 2-82. Based on discussions with the commenter, they only assessed the "central" scenario year and the relationship between adoption rate was determined for all years from 2020 to 2050, vehicle classes and market segments.[1222]

The TEMPO model uses a total cost of ownership (TCO) in assessing potential adoption rates of the technologies. We recognize that TCO is another common approach to address technology adoption rates, but we believe that showing data in the form of payback years is a more transparent way of showing an adoption rate. In the case of TCO, the financial horizon is an input into the calculation rather than an output of the model, thus one has to assume a time period in which to compare one cost of ownership analysis to another using the TCO method. In the case of payback calculation, the payback time can be determined based on when operational savings from a new technology is greater than the initial cost of investing in the technology. We feel this is an important distinction. The scatter in Figure 2-10 shows that while the payback may be the same, adoption rates may vary. This variation is not exclusive to the time horizon in which TCO reaches cost parity; however, it does impart some additional information in that not all fleets have the same considerations for adoption based on a payback time frame. A 4-year payback, for example, may yield 7-40% adoption rates based on Figure 2-10. The adoption rate scatter decreases as the payback period becomes shorter or negative, suggesting less variation in response to adoption for technologies that immediately payback. Similarly, there is less scatter in the adoption rates for technologies that pay back in more than six years, suggesting agreement in reduced adoption rates for longer payback. Therefore, having payback as an output provides additional information compared to using it as an input. Additional discussion of choice of payback as a metric can be found at Preamble Section II.F.1 and RTC Section 3.12. For the final rule analysis, we also evaluated TCO within the HD TRUCS tool. As shown in Chapter 2.12, the results of our payback analysis are complemented by the TCO results.

Thus, we need to determine the relationship between technology adoption rate determined in TEMPO and payback where the payback year is the year when the upfront cost is offset by operational savings. For EPA's analysis, incremental purchaser upfront cost was equal to the incremental technology cost of the ZEV compared to the comparable ICE vehicle cost (i.e. the incremental purchaser upfront vehicle cost) and the associated costs of the EVSE hardware and installation (for BEVs using depot charging) after accounting for IRA tax credits, sales tax, and FET. In NREL's TEMPO model, the dataset did not provide the upfront EVSE costs; instead, this EVSE cost is amortized and combined with the dollar per kWh electricity cost. Therefore, the cost of the EVSE is included in the operational cost. Thus, we calculated the vehicle cost delta in TEMPO by subtracting ICEV vehicle cost from ZEV vehicle cost. Operating cost in TEMPO is the sum of the annual maintenance cost, annual fuel costs and annual charging time costs where the annual maintenance cost is computed using the dollar per mile cost and annual VMT, and annual fuel cost is computed using the dollar per content of energy (diesel gallon equivalent, kWh, or kg H2). The payback period for each technology, class, year and market

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[1222] Memo to Docket. Evaluation of TEMPO Model. Docket EPA-HQ-OAR-2022-0985.

segment is then calculated using the upfront cost divided by the operational cost. The adoption rate was calculated using the vehicle sales of each technology divided by the total vehicle sales. Since each ZEV (EV-150, EV-300, EV-500 and FCEV)[1223] technology may a have different payback period, the ZEV level payback period was weighted by the sales percent of each ZEV technology and divided by the sum of ZEV sales percent. The result of our analysis of the TEMPO data is plotted along with the data from the commenter for payback period and adoption rates as shown in Figure 2-10 and shows reasonable agreement.

Table 2-81 Primary Inputs and Outputs for TEMPO

Inputs/Outputs	**Unit**	**Input/Output Disaggregation Level**
Vehicle Sales	‘000 Vehicles	Scenario, Year, Class, Market Segment, Technology
Vehicle Stock	‘000 Vehicles	Scenario, Year, Class, Market Segment, Technology
CO2 Emissions	MMT	Scenario, Year, Class, Market Segment, Technology, Fuel
Energy Consumption	TBtu	Scenario, Year, Class, Market Segment, Technology, Fuel
TCD	$/mile	Scenario, Year, Class, Market Segment, Technology
Vehicle Cost	$/Vehicle	Scenario, Year, Class, Technology
Vehicle Fuel Economy	Miles/DGE	Scenario, Year, Class, Technology
Fuel Costs	$/DGE, $/kWh, $/kgH2	Scenario, Year
Maintenance	$/mile	Class, Technology
Charge Speed	kW	Scenario, Year, Class, Market Segment, Technology
Charging Time	Hr/mile	Scenario, Year, Class, Market Segment, Technology
Charging Time cost	$/mile	Scenario, Year, Class, Market Segment, Technology
Financial Horizon	Years	Class
Discount Rate	Percent	
Cost Coefficient		Class, Market Segment
Annual VMT	Mile/year	Market Segment

[1223] EV-150, EV-300, and EV-500 here are referring to EVs with ranges of 150, 300, and 500 mile ranges, respectively.

Table 2-82 Primary TEMPO Input and Output Disaggregation

Parameter	**Disaggregation Level**
Scenario	Advanced Electricity Price
	Advanced Hydrogen Price
	Advanced Technology
	Central
	Conservative Electricity Price
	Conservative Hydrogen & Electricity Price
	Conservative Hydrogen Price
	Conservative Technology
Class	Light Medium (Class 3)
	Medium (Class 4-6)
	Heavy (Class 7-8)
	Bus
Market Segment	Bus
	0-99 Miles
	100-249 Miles
	250-499 Miles
	500+ Miles
	500-749 Miles
	750-999 Miles
	1000-1499 Miles
	1500-1999 Miles
	2000+ Miles
Fuel	Electricity
	Hydrogen
	Diesel
Technology	EV-150
	EV-300
	EV-500
	FCEV
	HEV
	ICEV

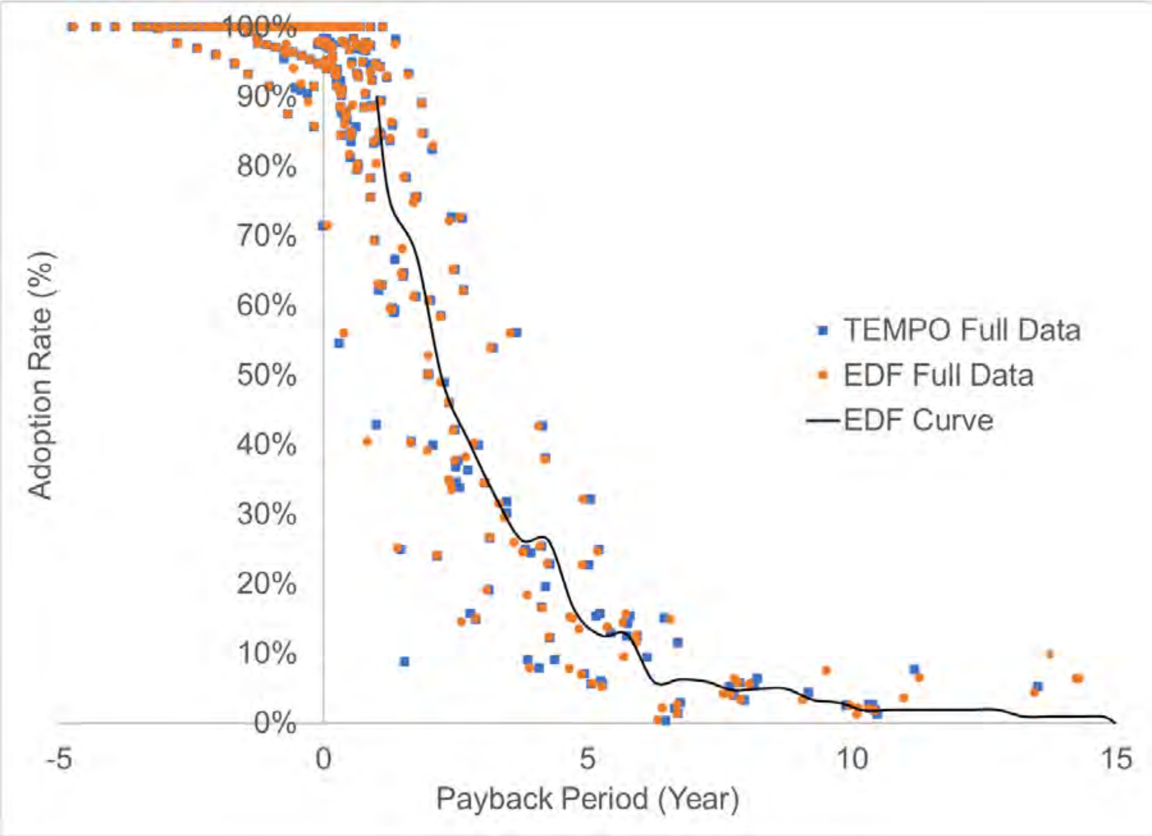

Figure 2-10 Adoption rate as a function of payback period for data received from NREL and the commenter (EDF).

The adoption rate curve was calculated by the commenter using the adoption rate data as shown in Figure 2-10 The commenter then averaged the adoption values within a half year period and smoothed the curve out in the longer payback periods to formulate the curve presented in another commenter's comment. For example, for payback period of 1 year, all values of adoption rates of technologies with a payback period between 0.75 to 1.25 years were averaged into a single value. Likewise, for a payback period of 6.5 years, all values of adoption rates within a payback period of between 6.25 to 6.75 years were averaged together. While there is significant data for payback periods before eight years using this approach, there is limited data for the payback periods longer than eight years. Table 2-83 tabulates the number of adoption rate data points available for each payback period. Therefore, for some payback periods longer than 6.25 years, the commenter used an approximate value. Figure 2-12 shows a comparison of the adoption rate curves developed by the commenter and EPA. As the figure shows, we were able to reproduce the commenter's results.

Table 2-83 Number of Data Points within each Payback Period Provided by the commenter (EDF)

Payback Period	Number of Data Points
<0	150
0-1	142
1-2	32
2-3	20
3-4	12
4-5	13
5-6	11
6-7	5
7-8	5
8-9	1
9-10	3
10-11	5
11-12	1
12-13	0
13-14	2
14-15	2
15+	2

To determine the adoption rates for each payback bin, we recognized that we need to average the data presented in Figure 2-10. We evaluated two methods to represent the adoption rates for each payback bin that is shown in Table 2-84. First, we recognize that there is scatter in adoption rate response to payback period as presented in Figure 2-10 and that EDF's half-year average curve captures the shape of this adoption rate response to payback period. Second, while there is more data for payback periods before one year, most of this data centers around a 95% adoption rate; however, for payback periods between 0 and 6 years there is less data and significantly more scatter. In some cases, as noted above, EDF used an approximation to fill in the data gaps or to replace a non-representative value. As a result of this scatter and lack of data in later years from more discrete averaging, we determined that it was reasonable to incorporate more years into the averaging before binning. In this case, we averaged over a one-year period. For example, for a payback period of 6 years, all values of adoption rates are averaged for payback periods of between 5.50 to 6.50 years. We found instead of averaging the half-year averaged data as presented by EDF, averaging over one-year shows similar results as the EDF curve, as shown in Figure 2-11.

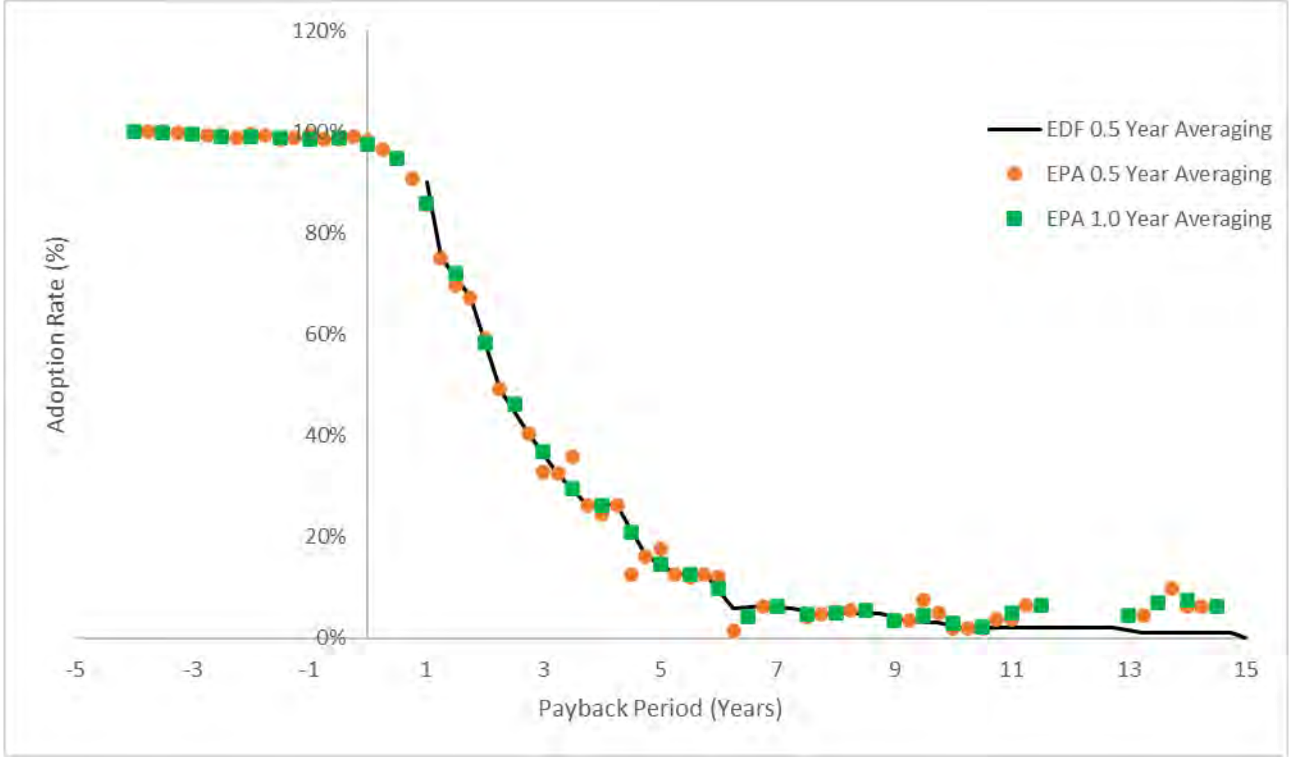

Figure 2-11 Adoption rate curve developed by the commenter (EDF) Compared to the Adoption rate curve produced by EPA, both using TEMPO data to show reproducibility between to datasets

Figure 2-12 shows the difference in adoption rates using the two different methods of averaging over 0.5 and 1 year averaging periods. While there are some slight differences between the two methods of averaging, the methods produced very similar results. Our assessment is that this indicates that the results are replicable, and validates the use of the TEMPO model in this modified form. For the final rule analysis, we used the one-year averaging method instead of the half-year method as presented by the commenter to avoid approximating data for the longer payback periods.

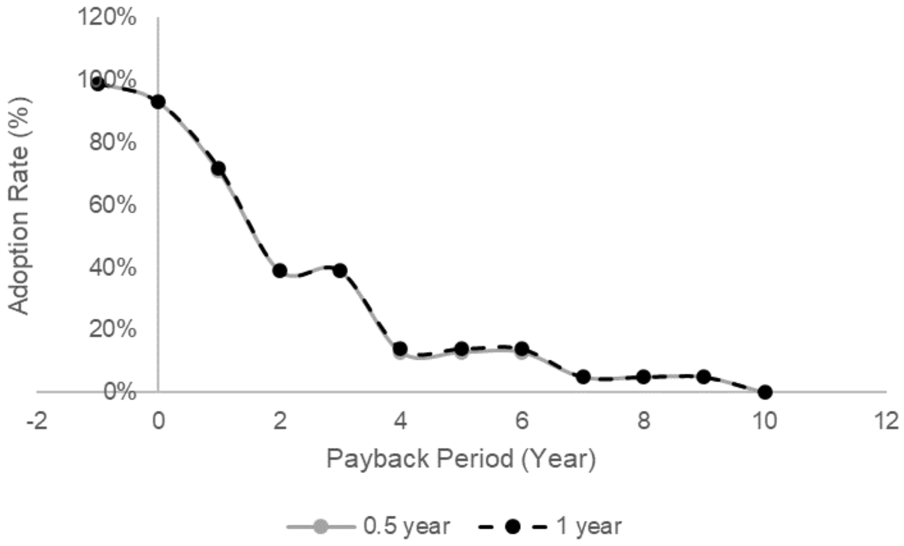

Figure 2-12 Adoption rate as a function of payback period for different averaging methods

For the final rule, we maintained the same payback period bins used for the NPRM for payback periods up to 10 years, as shown in Table 2-84. For the final rule analysis, we did not include payback periods longer than 10 years, as discussed in the next subsection. To determine the adoption rates for each payback bin for MY 2032, we averaged the data presented in Figure 2-11. For example, we averaged all of the adoption rate datapoints between the two and four years of payback, as shown in Figure 2-12, to determine the adoption rate for the 2-4 year payback bin.

Table 2-84 Payback Period Bins for the NPRM and Final Rule

NPRM	FRM
<0	<0
0-1	0-1
1-2	1-2
2-4	2-4
4-7	4-7
7-10	7-10
10-15	N/A

We note that this methodology is applicable to any technology, even though the data from the TEMPO model used to develop the methodology was focused on ICE vehicle, BEV, and FCEV technologies. We note again that the standards we have adopted in the final rule can be achieved by many combinations of technologies, including technology packages not utilizing any ZEV technologies. See Preamble Section II.F.4.

2.7.2 Payback Schedule for Final Rule

At proposal, we applied an additional constraint within HD TRUCS that limited the maximum penetration of the BEV and FCEV technologies to 80 percent for any given vehicle type. This limit was developed after consideration of the actual needs of the purchasers related to two primary areas of our analysis. First, this limit takes into account that we sized the batteries, power electronics, e-motors, and infrastructure for each vehicle type based on the 90th percentile of the average VMT. We utilize this technical assessment approach because we do not expect heavy-duty manufacturers to design ZEV models for the 100th percentile VMT daily use case for vehicle applications, as this could significantly increase the ZEV powertrain size, weight, and costs for a ZEV application for all users, when only a relatively small part of the market will need such specifications. Therefore, the ZEVs we analyzed and have used for the feasibility and cost projections for the proposal and final rule in this timeframe are likely not appropriate for 100 percent of the vehicle applications in the real-world. Our second consideration for including a limit for BEVs and FCEVs is that we recognize that there are a wide variety of real-world operations even for the same type of vehicle. For example, some owners may not have the ability to install charging infrastructure at their facility, or some vehicles may need to be operational 24 hours a day.

The TEMPO model, as shown in Chapter 2.7.1, would attribute 100% adoption to vehicles that have an immediate payback (payback less than or equal to 0 year). Commenters also provided ZEV adoption rate caps (or maximum rates of penetration in the adoption rate tables that were submitted). For example, DTNA suggested that Class 4-7 ZEVs with payback rates of <0 years would have an adoption rate of 73 percent, and Class 8 ZEVs with payback rates of <0 years would have an adoption rate of 36 percent, noting that these rates are consistent with CARB's 2019 initial market assessment for the ACT rule[1224] for vehicles. Energy Innovation's payback versus adoption rate curves by vehicle segment[1225] allowed for 100 percent adoption for vehicles with immediate payback. CALSTART stated that EPA's proposed cap of 80% and ACT Research's value of 86% with immediate payback were too constraining, and further describe applications that have the potential to reach 100%.[1226] ICCT recommended a cap of 90%.[1227]

After consideration of comments, including concerns raised by manufacturers, we re-evaluated the maximum penetration constraints in HD TRUCS for the final rule. The constraints discussed in the proposal, such as the methodology to size the batteries and the recognition of the variety of real-world applications of heavy-duty trucks, still apply to the final rule analysis. Furthermore, we are taking a phased-in approach to the constraints to recognize that the development of the ZEV market will take time to develop. We broadly considered the lead time necessary to increase heavy-duty battery production, as discussed in preamble Section II.D.2.ii.b, which shows a growth in the planned battery production capacity from now through 2031 and other issues like critical minerals, and for manufacturers to design, develop, and manufacture ZEVs (as discussed in preamble Section II.F.3). We also have generally accounted for the time required for infrastructure (as discussed in preamble Section II.F.3), including the potential distribution grid buildout through 2032 as informed by the DOE's TEIS and discussed in RIA Chapter 2.6.4. We see a similar trend in the growth of the infrastructure to support H2 refueling for FCEVs, as discussed in RIA Chapter 1.8.3.6.

In recognition of these considerations, for the final rule we applied more conservative maximum penetration constraints within HD TRUCS than at proposal. We limited the maximum penetration of the ZEV technologies in HD TRUCS for the final rule to 20 percent in MY 2027

[1224] Appendix E. Zero Emission Truck Market Assessment. CARB Advanced Clean Truck Regulations. October 22, 2019. Accessible at https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2019/act2019/appe.pdf

[1225] See Comments of Energy Innovation. Docket EPA-HQ-OAR-2022-0985-1604 at pages 9-12.

[1226] See Comments of CALSTART. Docket EPA-HQ-OAR-2022-0985-1656-A1 at p. 13.

[1227] See Comments of ICCT. Docket EPA-HQ-OAR-2022-0985-1553-A1, p. 7.

and 70 percent in MY 2032 for any given vehicle type, as shown in Figure 2-13. For payback bins with payback periods of 4 years or less, the MY 2030 adoption rates were established to reflect a 33 percent of the increase between the MY 2027 and MY 2032 adoption rates (see Equation 2-1). This ensures that the adoption rates in MY 2030 are lower than other reasonable approaches, such as a linear interpolation, allowing for more time for the electric charging and hydrogen refueling infrastructure to be better established.

Equation 2-1 MY 2030 Payback Schedule Calculation

$$AdoptRate_{MY30} = AdoptRate_{MY27} + [(AdoptRate_{MY32} - AdoptRate_{MY27}) * 33\%]$$

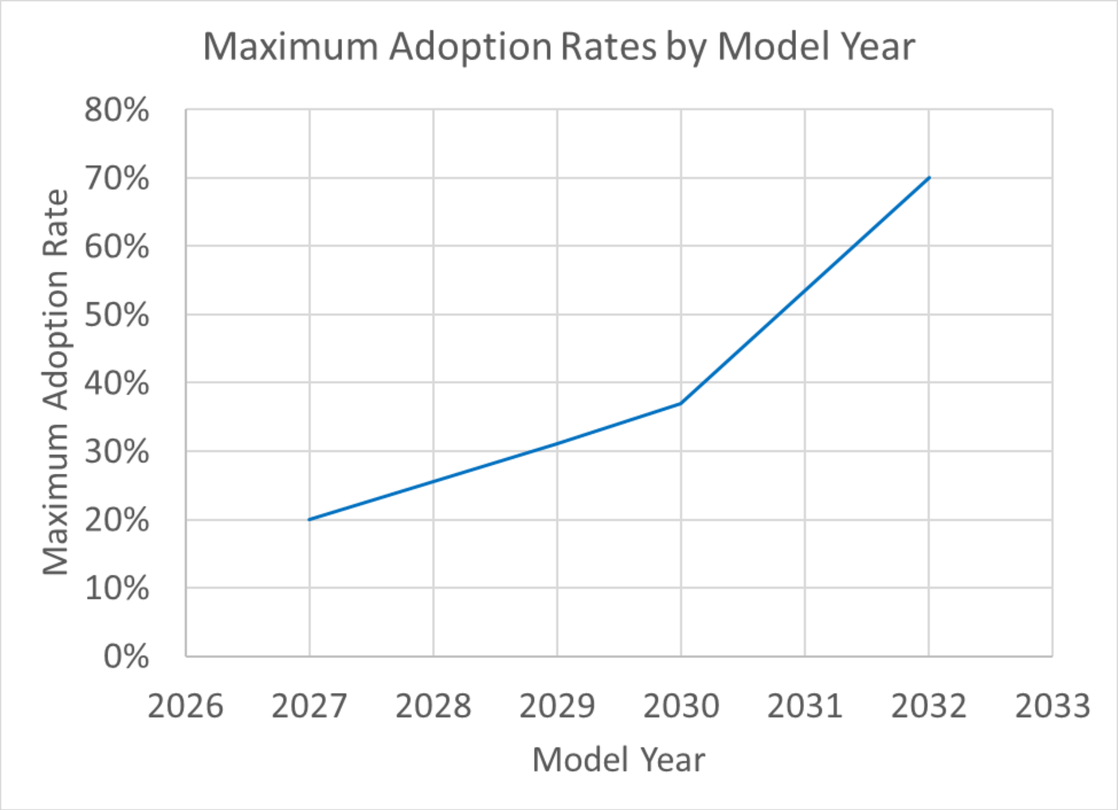

Figure 2-13 Maximum Adoption Rate Caps in Payback Schedules for Final Rule

We received comments suggesting that technology would not be adopted if the payback period was too long. For example, some commenters stated that an adoption period for payback exceeding 10 years was unrealistic. Another commenter believes it is not prudent to have a payback period longer than 10 years because of inherent risk of adopting new technology for first purchasers. Other commenters said that the financial horizon (or payback period) can be as long as 12 years depending on vehicle class and type, noting that municipalities may keep vehicles longer. While the TEMPO data provided by NREL showed adoption for time periods beyond 10 years, we recognize the available data in that timeframe is limited. Therefore, after consideration of comments, we did not project any adoption of technologies that had payback periods greater than 10 years in our analysis. The schedule also utilizes lower rates of technology acceptance than those used in the proposal for payback periods greater than four years.

The payback schedules used in HD TRUCS for the final rule are shown in Table 2-85. As discussed above in this section, the schedule shows that when the payback is immediate, in the final rule we conservatively project up to 20 percent of that type of vehicle could use BEV technology in MY 2027, for example, with diminishing adoption as the payback period increases to more than 4 years. After consideration of comments from some stakeholders, we also set the adoption rates to zero for payback bins that were greater than 10 years.

The comments raised by manufacturers were thus considered and addressed in our final rule's approach to HD TRUCS and the projected technology packages: by applying the MY 2027, MY 2030 and MY 2032 "cap" constraints, as discussed above, and through lower ZEV adoption in the technology packages for payback periods that are longer than 4 years (including setting adoption to zero for technologies with payback periods longer than 10 years) and higher ZEV adoption when payback is 4 years or sooner. The relationship between adoption and payback period that was created from TEMPO outputs differ from the ACT payback schedule used at proposal and reflects a more typical S-curve, where adoption starts slowly and then speeds up. (Note, the 70 percent constraint we imposed in MY 2032 and explained in this chapter limits the adoption of the shortest payback bins).

The schedule shown in Table 2-85 was used in HD TRUCS to evaluate the use of BEV or FCEV technologies for each of the 101 HD TRUCS vehicle types based on its payback period for MYs 2027, 2030 and 2032.

Table 2-85: Payback Schedule Used in the Final Rule HD TRUCS

Payback Bins	MY 2027	MY 2030	MY 2032
<0	20%	37%	70%
0-1	20%	37%	70%
1-2	20%	37%	70%
2-4	20%	26%	39%
4-7	14%	14%	14%
7-10	5%	5%	5%
> 10	0%	0%	0%

In Figure 2-14 the payback schedules we developed and used for the final rule analysis for MYs 2027 and 2032 are shown compared to the values shown previously in Figure 2-9.

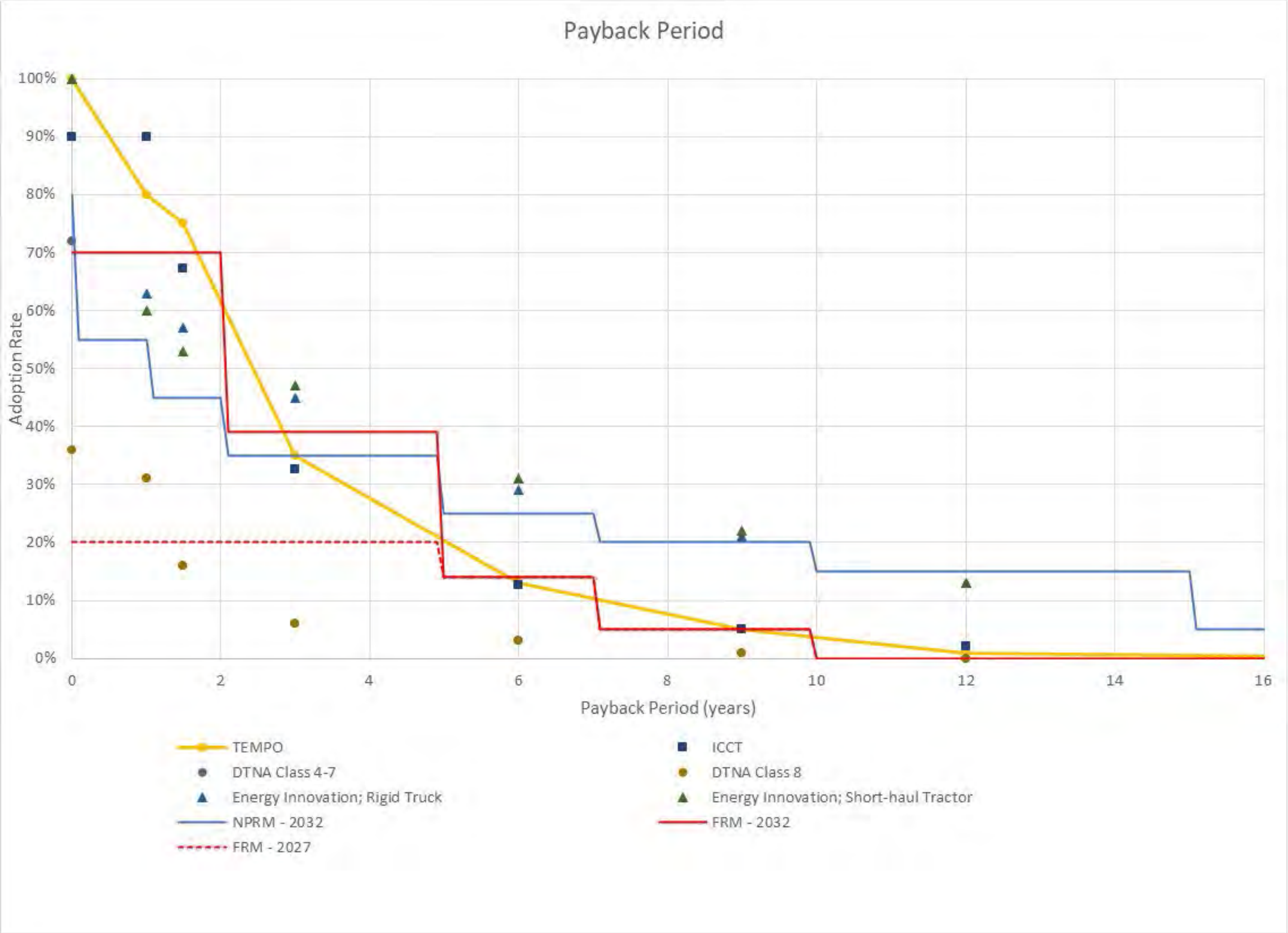

Figure 2-14 Adoption Rate to Payback Period Comparison for FRM

2.8 HD TRUCS Functionality

HD TRUCS is an extensive physics-based tool designed to project technology feasibility, payback, and adoption rates in future model years. In this rulemaking, EPA used HD TRUCS to evaluate inclusion of ZEV technologies in one potential compliance pathway. This chapter includes the methodology and formulas used in the tool, with main topics and calculations organized similarly to the structure of this chapter of the RIA. The ICE_Tech tab is covered in RIA Chapter2.3, the BEV_Tech tab in RIA Chapters 2.4 and 2.6, and the FCEV_Tech tab in RIA Chapter 2.5.

2.8.1 Baseline Energy and Fuel Consumption

EPA calculated the required energy consumption for vehicles using GEM with the physical parameters of an ICE vehicle. (See RIA Chapter2.2 for more information on the GEM runs.) We converted the GEM output of energy in kWh for each duty cycle to energy consumption per mile by dividing the energy consumption for each regulatory type by the distance of each GEM duty cycle (see Chapter 2.2.2.1.2).

Each of the energy consumption calculations was then weighted by the appropriate drive cycle weighting factor for their respective regulatory classes and summed to provide us with the weighted energy consumption of each regulatory class. GEM distance weighting and time weighting factors as well as average speed during non-idle cycles may be found in Chapter 2.2.2.1.2. Furthermore, GEM axle energy consumption includes air conditioning energy consumption; this value is subtracted out and considered separately for BEV and FCEV technologies.

The calculation for weighted energy consumption for tractors of each regulatory class is in Equation 2-2 and the vocational vehicle weighted energy consumption calculation is in Equation 2-3. Table 2-15 shows the results of the calculations.

Equation 2-2 Weighted Energy Consumption per Mile for Tractors

$$\left.\frac{kWh_{axle}}{mi}\right|_{tract} = \sum_{c=1}^{3} \frac{kWh_c * f_c}{d_c} - \left.\frac{kWh}{mi}\right|_{AC}$$

Where:

$\left.\frac{kWh_{axle}}{mi}\right|_{tract}$ = weighted energy consumption at the axle for tractors.

kWh_c = energy consumed during the appropriate test cycle, c.

f_c = weighting factor for the appropriate test cycle, c, as shown in Table 2-14.

d_c = the total driving distance for the indicated duty cycle, c, as shown in Table 2-13.

c = tractor drive cycles where 1 = ARB transient cycle, 2 = 55 MPH cruise or 3 = 65 MPH cruise cycles.

$\left.\frac{kWh}{mi}\right|_{AC}$ = weighted energy consumption of air conditioning (AC) load.

Equation 2-3 Weighted Energy Consumption per Mile for Vocational Vehicles

$$\left.\frac{kWh_{axle}}{mi}\right|_{voc} = \frac{1}{\bar{v}_{moving} * \left(1 - f'_{drive} - f'_{park}\right)} * \left(\left(1 - f'_{drive} - f'_{park}\right) * \sum_{c=1}^{3} \frac{kWh_c * f_c}{d_c} * \bar{v}_{moving} + f'_{drive} * kW'_{drive} + f'_{park} * kW'_{park}\right) - \left.\frac{kWh}{mi}\right|_{AC}$$

Where:

$\left.\frac{kWh_{axle}}{mi}\right|_{voc}$ = weighted energy consumption at the axle for vocational vehicles.

kWh_c = energy consumed during the appropriate test cycle, c.

f_c = weighting factor for the appropriate test cycle, c, shown in Table 2-14

d_c = the total driving distance for the indicated duty cycle, c, shown in Table 2-13.

$c =$ vocational drive cycles where 1 = ARB transient cycle, 2 = 55 MPH cruise or 3 = 65 MPH cruise cycles

drive-idle and parked-idle fractions

$\bar{v}_{moving}$ = mean composite weighted driven vehicle speed, excluding idle operation, as shown in Table 2-14, for Phase 2 vocational vehicles. For other vehicles, let $\bar{v}_{moving}$ = 1.

AC energy consumption at the axle is converted from AC load and using the appropriate weighting factors, shown in Equation 2-4.

Equation 2-4 Duty Cycle Weighted Average Air Conditioning Energy Requirement

$$\left.\frac{kWh}{mi}\right|_{AC} = kW_{AC} * \sum_{c=1}^{3} \frac{t_c * f_c}{d_c}$$

Where:

kW_{AC}= Air conditioning load; 1.0 for LHD and MHD, and 1.5 for all other vehicles

t_c = the total driving time in seconds for the respective cycles as shown in Table 2-13.

f_c = the weighting factors for the respective GEM duty cycles, shown in Table 2-14.

d_c = the distance in miles, shown in Table 2-13

.

$c =$ GEM drive cycles where 1 = ARB transient cycle, 2 = 55 MPH cruise or 3 = 65 MPH cruise cycles, shown in Table 2-13.

Regenerative braking plays a large role in energy consumption of electric and fuel cell vehicles, and we took this into account by calculating the distance-weighted percent of recovered energy[1228] from tractive energy for each regulatory class. To do this, we started with a model developed in-house for hybrid vehicles and adjusted the input parameters to prevent the battery capacity and state of charge from limiting the amount of recovered energy. We also limited braking capacity to 90 percent of total braking power to allow for some use of the traditional braking system. See Table 2-86 for input parameters.

[1228] Recovered energy is amount of energy that is gained while driving an electric vehicle. It is gained in the form of regenerative braking which is defined in footnote 928.

Table 2-86 Input Parameters for Hybrid Vehicle Model

Vehicle Parameters	**Input Values**
Mass (kg)	Table 2-10 and Table 2-11
CdA (m^2)	Table 2-10 and Table 2-11
Crr (kg/t)	Table 2-10 and Table 2-11
Battery Size (kwh)	200
Pmax Regen (kW)	500[1229]
Battery SoC Min (%)	10
Battery SoC Max (%)	90
Hybrid System Efficiency (%)	73
Axle Efficiency (%)	92
Accessory Power driven by wheels (kW)	1.5
Hybrid Braking Power (% of total braking power)	90

We then calculated the road load power required for each drive cycle via Equation 2-5 using positive values for tactive power and negative values for braking power.

Equation 2-5 Road Load Power

$$P_{road}|_c = \left(\frac{m_{veh} *\ g *\ Crr}{1000} + \frac{\rho_{air} * CdA * v_c^2}{2} + \ a_{veh} * m_{veh} + m_{veh} * g * \sin\left(atan\left(\frac{G}{100}\right)\right)\right) * \frac{v_c}{1000}$$

Where:

$P_{road}|_c$ = Road load power for each drive cycle, c

m_{veh} = mass of the vehicle (kg)

g = gravitational constant of 9.81 m/s^2

Crr = tire rolling resistance (kN/N)

CdA = drag area, m^2

ρ_{air} = density of air at a constant value of 1.17 (kg/m^3)

v_c = velocity of the vehicle at each specific point of the drive cycle, c

a_{veh} = acceleration of the vehicle at each specific point of the drive cycle

G = percent slope of the drive cycle

c = GEM drive cycles where 1 = ARB transient cycle, 2 = 55 MPH cruise or 3 = 65 MPH cruise cycles, shown in Table 2-13.

[1229] For the final rule we retained the use of 500 kW as the maximum regenerative power for all vehicle types in HD TRUCS, however, this was an error and we should have used the maximum motor power for each vehicle type in HD TRUCS. We have since performed checks on each regulatory sub-category using the motor power for each vehicle type in HD TRUCS as Pmax Regen and found that the change in Pmax Regen had no effect on regenerative braking.

We were then able to calculate the regenerative braking power in Equation 2-7 using only the negative values from hybrid available power in Equation 2-6.

Equation 2-6 Negative Road Load Power

$$P_{neg\_road}\big|_c = P_{road}|_c * P_{\%brake} * \eta_{hyb} * \eta_{axle} + P_{acc}$$

Where:

$P_{neg\_road}\big|_c$ = available hybrid power for the appropriate cycle (kW).

$P_{\%brake}$ = percent of braking power available to hybrid system, value is in Table 2-86.

η_{hyb} = hybrid system efficiency, shown in Table 2-86.

η_{axle} = axle efficiency, shown in Table 2-86.

P_{acc} = accessory power driven by the wheels, shown in Table 2-86.

$c =$ GEM drive cycles where 1 = ARB transient cycle, 2 = 55 MPH cruise or 3 = 65 MPH cruise cycles, shown in Table 2-13.

Equation 2-7 Regenerative Braking Power

$$P_{regen}\big|_c = P_{neg\_road}\big|_c * \eta_{hyb} * \eta_{axle}$$

Where:

$P_{regen}\big|_c$ = regenerative braking power for each cycle

$P_{neg\_rod}\big|_c$ = available hybrid power for the appropriate cycle (kW).

η_{hyb} = hybrid system efficiency, value is in Table 2-86.

η_{axle} = axle efficiency, value is in Table 2-86.

$c =$ GEM drive cycles where 1 = ARB transient cycle, 2 = 55 MPH cruise or 3 = 65 MPH cruise cycles, shown in Table 2-13.

Equation 2-8 Recovered Energy

$$kWh_{rec}|_c = \frac{1}{-36000}\sum\left(P_{regen}\big|_c\right)$$

Where:

$kWh_{rec}|_c$ = recovered energy of the appropriate cycle (kWh)

c = GEM drive cycles where 1 = ARB transient cycle, 2 = 55 MPH cruise or 3 = 65 MPH cruise cycles, shown in Table 2-13.

Equation 2-9 Tractive Energy

$$kWh_{tract}|_{cyc} = \frac{1}{36000}\sum(P_{tract}|_c)$$

Where:

$kWh_{tract}|_c$ = tractive energy of the appropriate cycle (kWh)

$P_{tract}|_c$ = tractive power of the appropriate cycle (kW)

c = GEM drive cycles where 1 = ARB transient cycle, 2 = 55 MPH cruise or 3 = 65 MPH cruise cycles, shown in Table 2-13.

The recovered energy percentage was calculated by dividing the recovered energy by the tractive energy, the final percent was then weighted by the appropriate distance weighting factor and summed to end up with a final percent of energy recovered during regenerative braking for each regulatory class based on the GEM duty cycles using Equation 2-10 the results may be found in Table 2-15.

Equation 2-10 Percent Regenerative Braking

$$\%_{regen} = 100 * \sum\left(\frac{kWh_{rec}}{kWh_{tract}} * f\right)_c$$

Where,

kWh_{rec}= recovery energy of the vehicle for cycle, c

kWh_{rec}= tractive energy of the vehicle for cycle, c

c = GEM drive cycles where 1 = ARB transient cycle, 2 = 55 MPH cruise or 3 = 65 MPH cruise cycles, shown in Table 2-13.

The percent regen was then multiplied against the energy per mile at the axle to end up with energy gain due to regenerative braking per mile using Equation 2-11. The results are in Table 2-16.

Equation 2-11 Energy Recovered from Regenerative Braking

$$\left.\frac{kWh_{regen}}{mi}\right|_{veh} = \%_{regen} * \frac{kWh_{axle}}{mi}$$

Where,

$\%_{regen}$ = Percent regenerative breaking

$\frac{kWh_{axle}}{mi}$ = weighted energy consumption per mile at the axle

The ZEV baseline per-mile energy consumed is described in Table 2-12. However, additional energies are required for both the HVAC unit as well as the conditioning of the battery; therefore, in this case, the ZEV vehicle level energy consumption is calculated as shown in Table 2-13. The per mile PTO ($\frac{kWh_{PTO}}{mi}$) and per mile temperature related energy consumption ($\frac{kWh_{Temp}}{mi}$) equations are described in Chapter 2.2.2.2.

Equation 2-12 ZEV Baseline Line Energy Consumption Per Mile

$$\left.\frac{kWh_{basline}}{mi}\right|_{veh} = \frac{kWh_{axle}}{mi} - \frac{kWh_{regen}}{mi} + \frac{kWh_{PTO}}{mi}$$

And,

Equation 2-13 ZEV Vehicle Level Energy Consumption Per Mile

$$\left.\frac{kWh_{Tot}}{mi}\right|_{veh} = \frac{kWh_{basline}}{mi} + \frac{kWh_{Temp}}{mi}$$

Where,

$\frac{kWh_{axle}}{mi}$ = weighted energy consumption at the axle

$\frac{kWh_{regen}}{mi}$ = regen energy consumption per mile

$\frac{kWh_{PTO}}{mi}$ = PTO energy consumption per mile

$\frac{kWh_{Temp}}{mi}$ = temperature related energy consumption per mile

2.8.2 Vehicle Miles Traveled

The annual miles driven for any particular vehicle changes with the age of the vehicle. We therefore used a decrease in operating VMT over time in our payback analysis. The annual operating VMT for each vehicle (AOR_{veh}) for vehicle age (VA_i) is calculated using Equation 2-14.

Equation 2-14 VMT for Vehicle Age i

$$AOR_{veh}(VA_i) = OR_{veh} t_{op_{day}} k_a$$

Where,

$t_{op_{day}}$ = number of operational days, 250 days with the exception of RVs where it is 8 days

OR_{veh} = 50th percentile range for a vehicle (mi/day)

$VA_i =$ Vehicle age at year i (where i = 0 is the first year of vehicle ownership and i = 9 is the tenth year of vehicle ownership)

$k_a =$ coefficient A

Here, change in coefficient A over time are shown in Table 2-4 for year 0 to 9. Cumulative VMT over time (COR_{veh}) is calculated using Equation 2-15.

Equation 2-15 Cumulative VMT over Year i

$$COR_{veh}(Y_i) = \sum_{i=0}^{9} AOR_{veh,i}$$

2.8.3 Power Take Off Loads

In addition to baseload of moving a vehicle, heavy-duty vehicles also perform additional functions such as lifting a garbage can or bucket. As explained in RIA Chapter 2.2.2.1.4, PTO fuel consumption is calculated using the percentage fuel consumption by auxiliary equipment type for various HD applications from the California Department of Tax and Fee Administration.[1230] The fuel consumption is converted into energy consumption in terms of kWh using the efficiency of diesel HD vehicles and associated PTO components, the energy content of diesel fuel, and the operational range and time of the PTO unit, as shown in Equation 2-16.

Equation 2-16 PTO Calculation

$$\left.\frac{kWh_{PTO}}{mi}\right|_{veh} = kWh_{gal\_Diesel}\frac{AOR_{veh}}{FE_{ICE}}(\%PTO)\left(\frac{1}{OR_{veh}t_{op-day}}\right)(FE_{ICE}) * \eta_{trans} * \eta_{hyd}$$

Where:

kWh_{gal_Diesel} = energy contet of a gallon of diesel fuel (40.5 kWh/gal[1231])[1232]

$AOR_{veh} =$ annual VMT for the vehicle (mi) for vehicle at age 0

$FE_{ICE} =$ GEM2 calculated fuel economy of the ICE vehicle (%), 35%

$\%PTO =$ percent fuel consumption from the PTO device

$OR_{veh} =$ 50th percentile range for a vehicle (mi)

$t_{op-day} =$ daily operating hours (hr)

$\eta_{trans} =$ Efficiency of the transmission (%), 95%

$\eta_{hyd} =$ Efficiency of the hydraulic pump (%), 85%

[1230] *See* Cal. Code Regs. tit. 18, § 1432, "Other Nontaxable Uses of Diesel Fuel in a Motor Vehicle," *available at* https://www.cdtfa.ca.gov/lawguides/vol3/dftr/dftr-reg1432.html. .

[1231] Alternative Fuels Data Center Fuel Properties Comparison. Accessed November 2023. Available online: https://afdc.energy.gov/files/u/publication/fuel_comparison_chart.pdf

[1232] Conversion of low sulfur diesel with energy content of 138,490 BTU/gal with conversion factor of 1 kWh per 3412 BTU.

2.8.4 ICE Vehicle Technology

2.8.4.1 ICE Vehicle Fuel Consumption

In the case of ICE vehicles, we calculated fuel consumption by converting the GEM output of grams of CO_2 into gallons of diesel for each regulatory class using Equation 2-17. See RIA Chapter 2.2.2.1.2 for the CO_2 output of each regulatory class and RIA Chapter 2.3.3 for fuel consumption values.

Equation 2-17 ICE Vehicle Fuel Consumption

$$MPG_{ICE} = \sum \left(\frac{g_{CO2}}{10180} * \frac{f_c}{d_c} \right)$$

Where:

MPG_{ICE} = mile per gallon of ICE vehicle

10,180 = conversion factor for grams of CO_2 into gallon of diesel consumed

f_c = the weighting factors for the respective GEM duty cycles, shown in Table 2-14.

d_c = the distance in miles, shown in Table 2-13.

2.8.4.2 Diesel Exhaust Fluid Consumption

DEF consumption (used in diesel vehicles) is a function of the DEF dosing rate where the NO_X reduction is estimated from the difference between estimated engine-out and tailpipe NO_X emissions, as described in Equation 2-18.

Equation 2-18 DEF Consumption

$$DEF = MPG_{ICE}(-73.679x + 0.0149)$$

Where

MPG_{ICE} = mile per gallon of ICE vehicle

x = the DEF dosing rate (5.18%).

2.8.4.3 ICE Powertrain System Cost

The cost of a ZEV powertrain system is calculated to determine the cost difference from the comparable ICE powertrain as described in Equation 2-19.

Equation 2-19 Cost of the ICE powertrain system

$$C_{ICE_{PT}} = \sum_i C_i$$

Where,

C_i = Cost of ICE powertrain component i for the following components

i = Engine cost as determined based on engine power (kW) including projected costs to meet the HD 2027 emission standards, gearbox, starter, torque converter clutch, final drive, accessories (including 12-volt battery and TPA), and generator.

2.8.5 BEV Technology

To better understand the technical feasibility and paybacks of BEV technologies, several calculations were performed. For physical parameters, the energy consumption, weight, and physical volume of battery packs for the 101 vehicle types as defined in the vehicle applications are sized in the 2_BEV_Tech worksheet in HD TRUCS. Other attributes including motor power, payload impact, and component costs associated with the BEVs are also incorporated into this section.

2.8.5.1 Temperature Effects on BEV

BEVs also have added energy requirements for heating and cooling of the vehicles as well as maintaining a constant temperature (conditioning) of the battery pack. The national average heating and cooling requirements are determined from the MOVES HD vehicle VMT distribution as a function of outside temperature, as well as the energy consumptions for HVAC and battery conditioning, detailed description can be found in Chapter 2.2.2.2. From MOVES, these values are broadly grouped into temperature ranges in Table 2-40 with average HVAC (Q_{bus}^{hvac}) in kW and battery conditioning ($\%BC$) as function size of the battery.

Table 2-87 Energy Consumption as a Function of Temperature Bands

Temperature Bins (°F)	% VMT Distribution	HVAC Power Consumption (kW)	Battery Conditioning (% of Battery)
<55	37%	5.06	1.9%
55-75	16%	-	-
>75	47.3%	2.01	3.0%

The power consumption for HVAC is rescaled for HD TRUCS using the surface area ratio for each vehicle (SAR_{veh}) as in Equation 2-20.

Equation 2-20 SAR for Each Vehicle ID to SA of a Class 8 Bus

$$SAR_{veh} = \frac{2 * (L * H + L * W + W * H)_{[veh]}}{2 * (L * H + L * W + W * H)_{[bus]}}$$

Where,

$L_{bus},\ H_{bus}, W_{bus}$ = length, height, and width of the bus, respectively

$L_{veh},\ H_{veh}, W_{veh}$ = length, height, and width of the vehicle, respectively

Table 2-88 shows the L_{veh}, H_{veh}, and W_{veh} different buses, ambulances, and for the remainder of the vehicles.

Table 2-88 HD Vehicle Dimensions

Vehicle Type	W_{veh} (ft)	H_{veh} (ft)	L_{veh} (ft)
Class 2b-3 School Bus Ambulance	7.5	6.3	12
Class 4-5 School Bus Ambulance	7.5	6.3	22
Class 6-7 School Bus Transit Bus	7.5	6.3	27
Class 8 School Bus	7.5	6.3	29
Class 8 Coach Bus	7.5	6.3	40
All Other vehicles	5.2	6.35	9.7

The HVAC energy consumption for any one particular vehicle ID is then calculated using Equation 2-21.

Equation 2-21 Energy Consumption from Heating or Cooling per mile

$$\left.\frac{kWh_{HVAC}}{mi}\right|_{veh} = \frac{1}{R_{size}}\left(SAR_{veh} * Q_{bus}^{hvac} * t_{op_{day}}\right)$$

Where,

$SAR =$ Surface area ratio of the vehicle compared to a Class 8 bus

Q_{bus}^{hvac} =Power requirement to heat or cool the inside of a Class 8 bus

$t_{op_{day}}$ = Daily operating time, 8 hrs

R_{size} = Vehicle 90th percentile VMT

Battery conditioning is expressed as a function of energy consumption, as shown in Equation 2-22:

Equation 2-22 Battery Conditioning per mile

$$\left.\frac{kWh_{BC}}{mi}\right|_{veh} = \%BC * \frac{kWh_{axle}}{mi}$$

$\frac{kWh_{axle}}{mi}$ = weighted energy consumption at the axle for the vehicle

$\%BC$ = percent battery conditioning, Table 2-87

2.8.5.2 BEV Energy Consumption Per Mile

The energy consumption of a vehicle can be considered a function of the per mile energy consumption, the daily VMT, and losses associated in converting the stored energy into mechanical energy used to move the vehicle. In the case of BEVs, these losses include the battery, DC/AC inverter, and e-motor efficiencies; therefore, the baseline energy consumption of an electric heavy-duty vehicle are calculated using Equation 2-23.

Equation 2-23 BEV Baseline Energy Consumption

$$\left.\frac{kWh_{basline}}{mi}\right|_{BEV} = \frac{1}{\eta_{ePT}} * \left.\frac{kWh_{basline}}{mi}\right|_{veh}$$

Where,

$\left.\frac{kWh_{basline}}{mi}\right|_{veh}$ = ZEV baseline vehicle level energy consumption per mile

η_{ePT} = efficiency of the electric powertrain system, Table 2-44.

The temperature related energy consumption consists of per mile energy consumption of the HVAC and battery conditioning, here the same equation can be used for heating or cooling, Equation 2-24.

Equation 2-24 BEV Temperature Energy Consumption per Mile

$$\left.\frac{kWh_{Temp}}{mi}\right|_{BEV} = \left(\frac{kWh_{HVAC}}{mi} + \frac{kWh_{BC}}{mi}\right)_{veh}$$

Where,

$\left.\frac{kWh_{HVAC}}{mi}\right|_{veh}$ = ZEV HVAC energy consumption per mile

$\left.\frac{kWh_{BC}}{mi}\right|_{veh}$ = ZEV battery conditioning energy consumption per mile

2.8.5.3 BEV Battery Pack Sizing

Battery packs are sized to meet the energy requirement for each of the 101 vehicle types as defined in Chapter 2.4.1.1 based on the vehicle class, duty cycle, and range requirements. The total energy consumption per mile of BEVs (Equation 2-25) is determined based on the baseline energy consumption and the temperature-dependent energy consumption. The temperature-dependent energy is determined by weighting the HVAC loads based on the heavy-duty vehicle miles traveled requiring heating, ventilation, or cooling using the MOVES VMT distribution in Table 2-87.

Equation 2-25 Total Energy Consumption Per Mile For BEV

$$\left.\frac{kWh_{Tot}}{mi}\right|_{BEV} = \%VMT_{<55F}\left(\frac{kWh_{temp}^{<55F}}{mi} + \frac{kWh_{baseline}}{mi}\right)_{BEV} + \%VMT_{55-75F}\left.\frac{kWh_{baseline}}{mi}\right|_{BEV} + \%VMT_{>75F}\left(\frac{kWh_{temp}^{>75\text{F}}}{mi} + \frac{kWh_{baseline}}{mi}\right)_{BEV}$$

Where,

$\%VMT_{<55F}$ = percent of VMT at temperature < 55 °F

$\%VMT_{55-75F}$ = percent of VMT at temperature 55-75 °F

$\%VMT_{>75F}$ = percent of VMT at temperature > 75 °F

$\frac{kWh_{temp}^{<55F}}{mi}$= ZEV temperature related energy consumption per mile at temperature < 55 °F

$\frac{kWh_{temp}^{>75F}}{mi}$= ZEV temperature related energy consumption per mile at temperature > 75 °F

$\left.\frac{kWh_{baseline}}{mi}\right|_{BEV}$ = Baseline energy consumption per mile of the BEV

The pack capacity in terms of kWh is calculated using Equation 2-26.

Equation 2-26 Battery Pack Sizing

$$\left.kWh_{pack}\right|_{BEV} = \left.\frac{kWh_{Tot}}{mi}\right|_{BEV}\left(\frac{1}{\eta_{DOD}}\right)(1 + \eta_{DET}) * R_{size}$$

Where,

$\left.\frac{kWh_{Tot}}{mi}\right|_{BEV}$ = vehicle level energy consumption for each BEV

η_{DOD} = depth of discharge (90%)

η_{DET} = battery capacity increase to account for deterioration over battery life (ranging between 0 to 15% depending on the vehicle type)

R_{size} = Sizing VMT

We adjusted Equation 2-25 to account for the energy efficiency of the BEV's electrical system, a daily maximum level of battery discharge, and the deterioration of battery capacity over time as shown in Equation 2-26. The pack size is calculated by the required range for the vehicle, R_{size}. This range is set at the sizing VMT, as described in Chapter 2.2.1. The maximum level of discharge, η_{DOD}, is equal to 90%.

For the final rule analysis, we applied a deterioration adjustment factor (η_{DET}) to the sizing of the battery as determined by the number of cycles the battery goes through over the course of a 10-year period instead of using the constant factor we used for the proposal analysis. A deterioration adjustment factor is applied such that the total number of cycles over the first 10 years of operation is less than 2,000 cycles. The total number of cycles is determined by first calculating the annual throughput energy and the total possible energy throughput for a given pack size for a given year, and the cycle number for each year is equal to the possible energy throughput divided by the actual annual throughput energy and the cumulative total cycle is the addition of each cycle over the 10 year period as show in Equation 2-27 through Equation 2-30.

Equation 2-27 Total number of battery cycles for vehicle age 0 to age 9

$$Cycle_{tot} = \sum_{i=0}^{9} Cycle_{y,i}$$

Where,

Equation 2-28 Battery single cycle

$$Cycle_{y,i} = \frac{Wh_{actual}}{Wh_{possible}}$$

And,

Equation 2-29 Actual daily energy use

$$Wh_{actual} = AOR_{veh,i} * \left.\frac{kWh_{Tot}}{mi}\right|_{BEV}$$

And,

Equation 2-30 Daily possible energy use

$$Wh_{possible} = R_{size} * t_{op_{day}} * \left.\frac{kWh_{Tot}}{mi}\right|_{BEV}\left(\frac{1}{\eta_{DOD}}\right)$$

$Cycle_{tot}$ = Total number of cumulative cycles

$Cycle_{y,i}$ = The number of cycles for vehicle age i where i = 0 to 9

Wh_{actual} = Actual throughput energy for vehicle age i where i = 0 to 9

$Wh_{possible}$ = Total possible throughput energy for a year

$AOR_{veh,i}$= Average operating range for a vehicle at vehicle age i (where i = 0 to 9)

In the case where the total cumulative cycles are less than 2,000, the deterioration parameter (η_{DET}) in Equation 2-26 is 0%. If the number of total cumulative cycles is greater than 2,000 cycles without a deterioration adjustment, the deterioration parameter is determined through iterations of η_{DET} values until the total number of cycles is less than 2,000 cycles. The η_{DET} for some vehicles in the final rule analysis is to 15%.

Using HD TRUCS, we also evaluated the payload impact of a BEV. The physical pack weight and volume are calculated from the kWh_{pack} and the pack level specific energy is 198 Wh/kg and energy density 396 Wh/L for MY 2027–2032. Furthermore, weight of the motor and gearbox are included to complete the BEV driveline system.

The weight of the pack (m_{pack}) is calculated using Equation 2-31.

Equation 2-31 Weight of the Battery Pack

$$m_{pack}\Big|_{BEV} = kWh_{pack}\Big|_{BEV} * E_{pack}$$

Where,

$kWh_{pack}\Big|_{BEV}$ = battery pack energy for each

E_{pack} = battery pack level specific energy

The weight of the motor (m_{motor}) is calculated using Equation 2-32 Motor Mass.

Equation 2-32 Motor Mass

$$\boldsymbol{m_{motor} = C_{\frac{kg}{kw}} * P_{motor}|_{veh}}$$

Where,

$C_{\frac{kg}{kw}}$ = Conversion factor from ANL BEAN (kg/kW)

$P_{motor}|_{veh}$ = Power of the motor for each vehicle (kW) (motor power is calculated in Equation 2-38)

The weight of the BEV powertrain system is calculated using Equation 2-33.

Equation 2-33 Weight of BEV Powertrain

$$m_{BEV\_PT}\Big|_{BEV} = m_{pack} + m_{motor} + m_{gearbox}$$

Where,

m_{pack} = weight of the battery pack

m_{motor} = weight of the e-motor

$m_{gearbox}$ = weight of the gearbox

Using the weight of the BEV driveline and the weight of the ICE powertrain components as calculated in RIA Chapter 2.3.1, we calculated the payload impact (%PL) using Equation 2-34.

Equation 2-34 Payload Impact

$$\%PL|_{veh} = \frac{m_{BEV\_PT} - m_{ICE}}{m_{PL}} * 100$$

Where,

m_{BEV_PT} = weight of the BEV powertrain

m_{ICE} = weight of the ICE powertrain system

m_{PL} = the Standard Payload as described in 40 CFR 1037.801, which is less than the maximum payload of a vehicle

The volume of the pack (V_{pack}) is calculated using Equation 2-35.

Equation 2-35 Pack Volume

$$V_{pack} = kWh_{pack} * \rho_{pack}$$

Where,

kWh_{pack} = energy of the battery pack

ρ_{pack} = pack level energy density

2.8.5.4 E-Motor Sizing

The e-motor in a BEV is used to convert electric energy into mechanical energy. To determine the power requirement of the e-motor that required in the BEVs, the power requirements for four performance metrics were calculated; these performance metrics are the peak power requirement of the ARB transient cycle, 0–30 MPH vehicle acceleration times, 0–60 MPH vehicle acceleration times, and constant cruise at 6 percent grade as described in RIA Chapter 2.4.1.2and below.

Power requirements for the transient cycle were calculated using the road load power as described in Equation 2-5; for motor sizing, the power requirement is determined to be the absolute peak power requirement.

Power requirements to meet the 0–30 MPH and 0–60 MPH acceleration time targets were calculated using Equation 2-36. The target times associated with each vehicle class are shown in Table 2-45.

Equation 2-36 Power Required for Vehicle Acceleration

$$P_{acc} = \left(\frac{v_{class} * (m_{veh} + m_{rot})}{t_{acc}|_{class}} + \left(\frac{m_{veh} * g * Crr}{1000} + \frac{\rho_{air} * v_{class}^2}{2} \right) \right) * \frac{v_{class}}{1000}$$

Where:

P_{acc} = Power required to accelerate to specific speed in kW

v_{class} = Final velocity of the vehicle in the specific weight class in m/s

$t_{acc}|_{class}$ = Time to accelerate to the final speed for the specific weight class in seconds

m_{veh} = mass of the vehicle (kg)

g = gravitational constant of 32.2 m/s^2

Crr = tire rolling resistance (kg/ton)

ρ_{air} = density of air at a constant value of 1.17 (kg/m^3)

Power requirements to maintain a constant cruise speed at 6 percent grade were calculated by applying a grade factor to the road load power in Equation 2-5 and can be seen in Equation 2-37.[1233] The vehicle speed for each class of vehicle was taken from ANL and can be seen in Table 2-45.[1234]

Equation 2-37 Power Required for 6% Slope

$$P_{road}|_{veh} = \left(\frac{m_{veh} * \ g * \cos\tan^{-1}\theta * \ Crr}{1000} + \frac{\rho_{air} * CdA * v_{class}^2}{2} + \ a_{veh} * m_{veh} * \sin\tan^{-1}\theta\right) * \frac{v_{class} * 0.44704}{1000}$$

Here:

m_{veh} = mass of the vehicle (kg)

g = gravitational constant of 32.2 m/s^2

θ = grade of 6%

v_{class} = velocity by vehicle weight class as listed in Table 2-45.

Crr = tire rolling resistance in (kg/ton)

ρ_{air} = density of air at a constant value of 1.17 (kg/m^3)

a_{veh} = acceleration of the vehicle at each specific point of the duty cycle

The maximum value of the power required to perform the ARB transient cycle, accelerate 0–30 MPH, 0–60 MPH, and of maintaining a specific speed on a 6 percent grade was used for the power requirement of the electric motor for each vehicle that is not a day cab or heavy haul truck as shown in Equation 2-38. For a day cab, the power requirement is set at 400 kW and 450 kW for heavy haul trucks., as described in RIA Chapter 2.4.1.2.

Equation 2-38 Power of Electric Motor

$$P_{motor}|_{veh} = MAX\left(P_{road_{ARB}}, P_{acc_{0-30}}, P_{acc_{0-60}}, P_{road_{6\%}}\right)$$

[1233] Islam, Ehsan Sabri, Ram Vijayagopal, Aymeric Rousseau. “A Comprehensive Simulation Study to Evaluate Future Vehicle Energy and Cost Reduction Potential”, *Report to the U.S. Department of Energy, Contract ANL/ESD-22/6*, October 2022. Available online: https://anl.app.box.com/s/an4nx0v2xpudxtpsnkhd5peimzu4j1hk/file/1406494585829.

[1234] Argonne National Laboratory. VTO HFTO Analysis Reports – 2021. “ANL – ESD-2110 Report – BEAN Tool – Heavy Duty Vehicle Techno-Economic Analysis.xlsx”. Available online: https://anl.app.box.com/s/an4nx0v2xpudxtpsnkhd5peimzu4j1hk/folder/177858439896.

Where:

P_{motor} = Power of electric motor in kW for each vehicle

η_{motor} = Electric motor efficiency, as defined in RIA Chapter 2.4.1.1.3.

$P_{road_{ARB}}$ = peak power requirement for ARB transient cycle

$P_{acc_{0-30}}$ = peak power requirement for acceleration from 0-30 MPH

$P_{acc_{0-60}}$ = peak power requirement for acceleration from 0-60 MPH

$P_{road_{6\%}}$ = peak power requirement for maintaining a constant speed at 6 percent grade

2.8.5.5 BEV Powertrain System Cost

The cost of BEV powertrain systems is calculated to determine the cost difference from the comparable ICE powertrain as described in Equation 2-39.

Equation 2-39 Cost of the BEV powertrain system

$$C_{BEV_{PT}} = \sum_{i} C_i$$

Where,

C_i = Cost of BEV powertrain component i

Here component i includes the battery pack (C_{pack}), e-motor (C_{motor}), power converter (C_{PConn}), on-board charger ($C_{OnCharger}$), gearbox ($C_{gearbox}$), final drive ($C_{finaldrive}$) and accessories (including the auxiliary converter and TPA) (C_{acc}) costs. The individual component costs are described in RIA Chapter 2.4.3. Furthermore, C_{pack} and C_{motor} are determined using Equation 2-40 and Equation 2-41. The cost of the battery pack is determined from the pack size as sized in RIA Chapter 2.4.1.1.3.

Equation 2-40 Cost of the Battery Pack

$$C_{pack} = kWh_{pack} * \left(\frac{\$}{kWh}\right)_{IRA} = kWh_{pack} * \left(\frac{\$}{kWh} - IRA_{battery}/RPE\right)$$

Where,

$\left(\frac{\$}{kWh}\right)_{IRA}$ = An effective per kilowatt-hr DMC of the battery. When this is multiplied by RPE, the indirect costs are calculated based on the actual DMC as discussed in RIA Chapter2.4.3.1.

$\frac{\$}{kWh}$ = Per kilowatt-hr DMC of the battery as shown in Table 2-48.

$IRA_{battery}$ = IRA total battery credits from Section 13502 as shown in Table 2-49.

$RPE =$ Retail Price Equivalent, 1.42

Likewise, the cost of the motor is determined using the size of the motor as sized in RIA Chapter 2.8.5.4.

Equation 2-41 Cost of the E-Motor

$$C_{motor} = kW_{motor} * \frac{\$}{kW}$$

Where,

$kW_{motor} =$ E-motor power

$\frac{\$}{kW} =$ Per kilowatt cost of the electric motor.

For a breakdown of the e-drive component costs for all 101 vehicle types, see Tables 2-57 through 2-59.

2.8.6 FCEV Technology

Several calculations were performed to understand the payback periods of FCEV technologies. For physical parameters, fuel cell system power output, the hydrogen consumption, hydrogen fuel tank size, and physical volume of battery packs for the 101 vehicle types as defined in the vehicle applications are sized in the 2_FCEV_Tech worksheet in HD TRUCS. Other attributes including motor power and component costs associated with FCEVs are also incorporated into this section.

2.8.6.1 Fuel Cell System Power Requirement

The power demand for a HD vehicle is calculated using either the continuous power at constant cruise at 75 MPH or the 90th percentile power for the ARB transient cycle. Equation 2-42 shows that the fuel cell power demand is determined to be the maximum of the two cycles, plus an additional 50% is added to the system sizing to accommodate occasional performance scenarios where the vehicle requires more power plus the operation of the system’s balance of plant, using Equation 2-42. A portion of this size increase represents the addition of cells, which can also add fuel cell stack durability.

Equation 2-42 Power of Fuel Cell Stack

$$P_{FC}|_{veh} = MAX\left(\mathrm{P}_{ARB}^{90th}, P_{75}\right) * \eta_{FCS}$$

Where,

P_{ARB}^{90th} = 90th percentile ARB transient cycle power

P_{75} = Power at 75 MPH cruise

η_{FCS} = Fuel cell system oversizing, as described in RIA Chapter 2.5.1.1.2

2.8.6.2 E-Motor Sizing

The e-motors for FCEVs are sized to accommodate peak power needs the same way as BEVs, as described in RIA Chapter 2.8.5.4.

2.8.6.3 FCEV Battery Pack Sizing

Battery packs are sized to provide 10 minutes of additional power to the HD vehicle when requirements are not met by the fuel cell stack alone as shown in Equation 2-43.

Equation 2-43 FCEV Battery Pack Sizing

$$kWh_{pack}^{FCEV}\Big|_{veh} = (P_{motor} - P_{FC}) * t_{discharge}\left(\frac{1}{\eta_{DOD}}\right)$$

Where,

P_{motor} = Motor power

P_{FC} = Fuel Cell power

$t_{discharge}$ = Battery discharge time, here it is assumed to be 10 minutes or 0.167 hour

η_{DOD} = Depth of Discharge (60%)

2.8.6.4 Temperature Effects on FCEVs

While FCEVs can use waste heat from the fuel cell, like vehicles with internal combustion engines, FCEVs have energy requirements for cooling of the vehicles as well as maintaining a constant temperature (conditioning) of the battery pack. The considerations for energy required to cool the interior cabin of the vehicle are similar to those of BEVs as described in RIA Chapter 2.8.5.1, where the HVAC (Q_{bus}^{hvac}) in kW and battery conditioning ($\%BC$) are shown in Table 2-89. The per-mile energy consumption of HVAC and battery conditioning for FCEVs are calculated using Equation 2-45.

Table 2-89 Energy Consumption as a Function of Temperature Bands

Temperature Bins (°F)	% VMT Distribution	HVAC Power Consumption (kW)	Battery Conditioning (% of Battery)
<55	37%	-	1.9%
55-75	16%	-	-
>75	47.3%	2.01	3.0%

2.8.6.5 FCEV Energy Consumption Per Mile

Like ICE vehicles, the energy required of a FCEV is stored in the form of fuel that is converted into mechanical energy by a powertrain system. In the case of a FCEV, the stored energy is in the form of hydrogen fuel. RIA Chapter 2.5.1.2describes how the daily energy consumption of a HD FCEV is considered, which is similar to that of a BEV; briefly these include the per-mile energy consumption, daily VMT, and losses associated with fuel cell stack, DC/AC inverter, gearbox, and e-motor efficiencies. The total energy consumption of a FCEV is calculated using Equation 2-44:

Equation 2-44 FCEV Total Energy Consumption Per Mile

$$\left.\frac{kWh_{Tot}}{mi}\right|_{FCEV} = \frac{1}{\eta_{FCEV}} * \left(\frac{kWh_{basline}}{mi} + \frac{kWh_{Temp}}{mi}\right)$$

And,

$$\eta_{FCEV} = \eta_{FC} * \eta_{ePT}$$

Where,

η_{FCEV} = efficiency of the fuel cell powertrain, as shown in Table 2-66.

η_{FC} = efficiency of the fuel cell system, as described in RIA Chapter 2.5.1.2.1

η_{ePT} = Electric powertrain system efficiency, Table 2-44.

$\frac{kWh_{basline}}{mi}$ = baseline per mile energy consumption at the axle, Equation 2-12

The temperature related energy consumption consists of per mile energy consumption of the HVAC and battery conditioning, here the equation is be used for cooling only for HVAC and heating and cooling for battery conditioning, see RIA Chapters 2.8.5.1 and Equation 2-45.

Equation 2-45 FCEV Temperature Energy Consumption per Mile

$$\left.\frac{kWh_{Temp}}{mi}\right|_{FCEV} = \frac{1}{\eta_{FCEV}} * \left(\frac{kWh_{HVAC}}{mi} + \frac{kWh_{BC}}{mi}\right)_{veh}$$

Where,

$\left.\frac{kWh_{HVAC}}{mi}\right|_{veh}$ = ZEV HVAC energy consumption per mile, for heating this value is 0

$\left.\frac{kWh_{BC}}{mi}\right|_{veh}$ = ZEV battery conditioning energy consumption per mile

η_{FCEV} = efficiency of the FCEV powertrain

2.8.6.6 FCEV Hydrogen Storage and Use

The total energy consumption per mile of FCEVs (Equation 2-46) is determined based on the baseline energy consumption and the temperature-dependent energy consumption. The temperature-dependent energy is determined by weighting the HVAC loads based on the heavy-duty vehicle miles traveled requiring heating, ventilation, or cooling using the MOVES VMT distribution in Table 2-87.

Equation 2-46 Total Energy Consumption Per Mile For FCEV

$$\left.\frac{kWh_{Tot}}{mi}\right|_{FCEV} = \%VMT_{55-75F} \left.\frac{kWh_{baseline}}{mi}\right|_{FCEV} + \%VMT_{>75F} \left(\frac{kWh_{temp}^{>75F}}{mi} + \frac{kWh_{baseline}}{mi}\right)_{FCEV}$$

Where,

$\%VMT_{55-75F}$ = percent of VMT at temperature 55-75 °F

$\%VMT_{>75F}$ = percent of VMT at temperature > 75 °F

$\frac{kWh_{temp}^{>75F}}{mi}$= ZEV temperature related energy consumption per mile at temperature > 75 °F

$\left.\frac{kWh_{baseline}}{mi}\right|_{FCEV}$ = Baseline energy consumption per mile of the FCEV

The stored energy requirement ($kWh_{S\_H2}|_{veh}$), in the form of hydrogen fuel, is calculated from the total energy consumption per mile of the FCEV using Equation 2-44 and the daily sizing VMT (R_{size}), as shown in Equation 2-47.

Equation 2-47 Maximum Daily Energy Consumption of a FCEV

$$kWh_{S\_H2}\big|_{veh} = R_{size}\left(\left.\frac{kWh_{Tot}}{mi}\right|_{FCEV}\right)$$

Where,

$\left.\frac{kWh_{Tot}}{mi}\right|_{FCEV}$ = total energy consumption per mile of FCEV

R_{size}= Sizing range of the vehicle

The energy in kWh is converted into amount of hydrogen required, or stored hydrogen, using the energy content for each kg of hydrogen using Equation 2-48.

Equation 2-48 Required Hydrogen Storage Weight

$$m_{S\_H2}\big|_{veh} = kWh_{S\_H2}\left(\frac{1g\ H_2}{33.33\ kWh}\right)\left(\frac{1}{\eta_{H2}}\right)\left(\frac{1}{1-\eta_{deplete}}\right)$$

Where,

kWh_{S_H2} = Daily maximum energy consumption of a FCEV

η_{H2} =is the fraction of usable hydrogen (0.95)

$\eta_{deplete}$ = oversizing to avoid complete depletion of usable hydrogen (0.10)

We differentiate the operating energy requirement ($kWh_{Op\_H2}|_{veh}$) from the sizing energy requirement using daily operating VMT, as shown in Equation 2-49.

Equation 2-49 Daily Operational Energy Consumption of a FCEV

$$kWh_{Op\_H2}\Big|_{veh} = DOR_{veh}\left(\frac{kWh_{Tot}}{mi}\Big|_{FCEV}\right)$$

Where,

DOR_{veh} = daily operational range or VMT, Equation 2-14

$\frac{kWh_{Tot}}{mi}\Big|_{FCEV}$ = total energy consumption per mile for an FCEV, Equation 2-44

The energy in kWh is converted into amount of hydrogen required, or stored hydrogen, using the energy content for each kg of hydrogen using Equation 2-50.

Equation 2-50 Required Hydrogen Weight for Operating the FCEV

$$m_{Op\_H2}\Big|_{veh} = kWh_{Op\_H2}\left(\frac{1g\ H_2}{33.33\ kWh}\right)\left(\frac{1}{\eta_{H2}}\right)\left(\frac{1}{1-\eta_{deplete}}\right)$$

Where,

kWh_{Op_H2} = Daily operating energy consumption of a FCEV

η_{H2} = is the fraction of usable hydrogen (0.95)

$\eta_{deplete}$ = oversizing to avoid complete depletion of usable hydrogen (0.10)

2.8.6.7 FCEV Powertrain System Cost

The cost of FCEV powertrain systems is calculated to determine the cost difference from the comparable ICE powertrain as described in Equation 2-51.

Equation 2-51 Cost of the FCEV powertrain system

$$C_{FCEV_{PT}} = \sum_{j} C_j$$

Where,

C_j = Cost of FCEV powertrain component j

Here component j includes the cost of fuel cell system (C_{FC}), hydrogen tank (C_{H2Tank}), battery pack (C_{pack}), e-motor (C_{motor}), power electronics (C_{PElec}), gearbox ($C_{gearbox}$), differential (C_{diff}) and accessories (C_{acc}). The individual component costs are described in Chapters 2.4.3 and 2.5.2. Most component costs are calculated the same way as BEVs, while C_{FC} and C_{H2Tank} are determined using Equation 2-52 and Equation 2-53.

Equation 2-52 Cost of the Fuel Cell System

$$C_{FC} = kW_{FC} * \frac{\$}{kW}$$

Where,

kW_{FC} = Fuel cell stack power$\frac{\$}{kW}$ = Per kilowatt cost of the fuel cell

The cost of the hydrogen tank is determined using the mass of the stored hydrogen (m_{H2}),

Equation 2-53 Cost of Hydrogen Tank

$$C_{H2Tank} = m_{S\_H2} * \frac{\$}{kg\ H2}$$

Where,

m_{S_H2} = weight of stored hydrogen,

kg$\frac{\$}{kg\ H2}$ = Per kg hydrogen-stored cost of the hydrogen tank

2.8.7 Charging Infrastructure

In the final rule analysis, we project BEVs either charge at depots or en-route at public charging stops depending on vehicle type (see discussion in RIA Chapter 2.6). For BEVs using depot charging, we assign an upfront per-vehicle cost associated with hardware and installation of depot charging infrastructure to each of the vehicle types. For BEVs using public charging, the upfront capital EVSE cost is assumed to be $0; hardware and installation costs for public charging equipment are instead passed onto customers through the cost to charge (see Chapter 2.4.4.2).

2.8.7.1 Depot Charging Costs

2.8.7.1.1 Charging Time

We start by estimating in Equation 2-54 how many hours[1235] it would take to charge a vehicle sufficiently to cover its expected daily electricity consumption with each of four EVSE types: Level 2─19.2 kW, DCFC─50 kW, DCFC─150 kW, DCFC─350 kW.

That is, for each charging type:

Equation 2-54 Hours to Charge by EVSE Type

$$t_c = kWh_{BEV} * \frac{1}{\eta_c} * \frac{1}{kW_c} * \eta_{DOD}$$

Where,

t_c = hours to charge for each EVSE type

c = charging (or EVSE) type

kWh_{BEV} = Total energy based on the depth of discharge and the battery size (corresponding to sizing VMT)

[1235] Charging rate may vary based on the state of charge of the battery, e.g., by slowing down when the battery is nearly full. We have made the simplifying assumption that the charging rate is uniform for this purpose.

η_c = charging efficiency of EVSE type c (89.3%)[1236]

kW_c = power level for each EVSE type c (19.2, 50, 150, 350 kW)

η_{DOD} = depth of discharge (90%)

2.8.7.1.2 EVSE Sharing

In the NPRM analysis, we projected that each vehicle using Level 2 charging had a dedicated EVSE port while up to two vehicles using DCFC could share a port if there was sufficient dwell time at the depot for both vehicles to charge. We have modified our approach in the FRM after consideration of comments that this approach was too conservative and due to the availability of more refined depot dwell times (discussed in RIA Chapter 2.6.2.1.4). For the final rule analysis, we allow up to two vocational vehicles and up to four tractors - to share an EVSE port. This is implemented as follows. We first check how many vehicles could share an EVSE port of a given power level and meet their charging needs within the assumed depot dwell time. Vehicles are assumed to have a depot dwell time (t_d) as shown in Table 2-78 and explained in RIA Chapter 2.6.2.1.4. This value divided by the charge time of the same vehicle type as shown in Equation 2-55. The result is the potential number of vehicles that could share an EVSE port (S_c). S_c is rounded down to the nearest whole number.

Equation 2-55 Number of vehicles shared per EVSE port

$$S_c = \frac{t_d}{t_c}$$

Where,

S_c = potential number of vehicles that could share an EVSE port rounded down to the nearest integer

t_c = hours to recharge for each EVSE type

t_d = dwell time for each vehicle

The potential number of vehicles that could share an EVSE port within the allotted depot dwell time is then compared to the cap or maximum allowed number of vehicles sharing an EVSE port (S_M) for that vehicle type. The actual sharing per EVSE type (S_{EVSE}) is assumed to be the lower of the two values, as shown in Equation 2-56.

Equation 2-56 Actual number of vehicles sharing an EVSE port

$$S_{EVSE} = MIN(S_c, S_M)$$

Here, S_M is two for vocational vehicles and four for tractors. Note that if the dwell time is less than the charging time using a given EVSE type (i.e. if $S_C < 1$), we do not consider that EVSE type viable for the vehicle in our analysis.

[1236] We adjust the estimated electricity consumption upward to account for charging losses from the wall to the battery. While these losses may vary by charging type and other factors, as a simplifying assumption, we assign the same losses for all charging types. The charging efficiency of 89.3 percent is the product of the AC/DC converter efficiency of 94% and a battery charge and discharge efficiency of 95% from the MOVES model.

2.8.7.1.3 Per Vehicle EVSE Cost

Lastly, the per vehicle EVSE cost depends on the cost of the EVSE and the number of vehicles sharing the EVSE port. In some cases, a higher power EVSE that is shared by two vehicles, for example, is a lower cost option than a lower power EVSE that is not shared. The per vehicle EVSE cost (PV_{EVSE}) is calculated using Equation 2-57.

Equation 2-57 Per vehicle EVSE cost

$$PV_{EVSE} = \frac{C_{EVSE}}{S_{EVSE}}$$

Where, PV_{EVSE} = Per vehicle EVSE cost

C_{EVSE} = cost of EVSE type

S_{EVSE} = number of vehicles sharing an EVSE port

The per vehicle EVSE cost is compared between the different EVSE types and we use the EVSE type with the lowest per vehicle cost as the EVSE type assigned for that vehicle in HD TRUCS. Below is an example of this determination.

For a tractor with a 400 kWh battery, the resulting charging time estimates (rounded to the nearest hour) for each of the four charging types are shown in Table 2-90.

Table 2-90 Example Charging Times (for 400 kWh)

Level 2 ─19.2kW	DCFC─50 kW	DCFC─150 kW	DCFC─350 kW
24 hours	9 hours	3 hours	1 hour

If the depot dwell time for this vehicle type is 10 hours, then the potential number of vehicles that can share an EVSE port is shown in Table 2-91.

Table 2-91 Number of vehicles that can share an EVSE port

Level 2 ─19.2kW	DCFC─50 kW	DCFC─150 kW	DCFC─350 kW
NA	1	3	4

Accordingly, the per-vehicle infrastructure costs for each of the viable charging options are shown in Table 2-92.

Table 2-92 Example per-vehicle EVSE Costs in 2022$

Level 2 ─19.2kW	DCFC─50 kW	DCFC─150 kW	DCFC─350 kW
NA	$52,014	$42,418	$47,704

The lowest cost option is for a 150 kW DCFC port shared between three vehicles at about $42K per vehicle so we would assign that EVSE type and cost for the vehicle category in this example.

2.8.7.2 EVSE Port Counts at Depots

We estimate the number of new EVSE ports needed to support the MY 2027 through MY 2032 depot-charged BEVs in the modeled potential compliance pathway's technology packages. For each vehicle type, we calculate the number of new BEV sales each model year as follows:

Equation 2-58 New BEV sales by model year

$$SA_{BEV,MY} = HS_{MY} * B_{MY}$$

Where, $SA_{BEV,MY}$ = number of new BEV sales for each vehicle type for the specified model year

$HS_{MY} =$ new vehicle sales for the entire heavy-duty fleet for the specified model year as estimated in MOVES[1237]

$B_{MY} =$ BEV sales share for the specified model year, equal to the BEV adoption rate for that vehicle type multiplied by the percent of total HD sales for that vehicle type[1238,1239]

For each depot-based BEV type, we then calculate the number of new EVSE ports needed each model year as follows:

Equation 2-59 EVSE port counts

$$P_{EVSE,MY} = \frac{SA_{BEV,MY}}{S_{EVSE}}$$

Where, $P_{EVSE,MY}$ = number of EVSE ports needed for the specified model year for each depot-based BEV type[1240]

S_{EVSE} = number of vehicles sharing an EVSE port for that vehicle type

As described in Chapter 2.8.7.1.3, we assign an EVSE type to each depot-charged BEV. As a final step, we sum the port counts by EVSE type across all depot-charged BEVs for each model year between 2027 and 2032. Resulting EVSE port counts are presented in Chapter 2.10.3.

2.8.7.3 Public Charging

For the FRM, we project that sleeper cabs, some day cab tractors, and any BEV coach buses will use public charging. As described in RIA Chapter 2.6.3, we modeled our public charging

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[12371237] Sales numbers are from MOVES4.R3. More details on MOVES4.R3 can be found in RIA Chapter 4.

[1238] For heavy heavy-duty vocational vehicles, we scaled the adoption rates down in MYs 2027 and 2028 because the Phase 3 standards for these vehicles do not begin until MY 2029. These adoption rates were scaled to match the reference case ZEV adoption shown in RIA Chapter 4.2.2.

[1239] For day cab tractors, since our technology assessment for MYs 2027–2029 is based solely on depot-charged BEVs (vehicle numbers 30, 31, 83, and 101), we scaled sales of only the depot-charged BEVs (in equal proportion) to the levels consistent with our technology packages for MYs 2028 and 2029. Similar to the heavy heavy-duty vocational vehicles, the day cab tractors were scaled to match the reference case in MY 2027 since the Phase 3 standards for these vehicles do not begin until MY 2028. Beginning in MY 2030, our technology assessment includes BEVs and FCEVs utilizing public infrastructure. Consequently, our projections of sales of depot-charged BEVs and associated EVSE decrease in MY 2030 from the MY 2029 levels as ZEV tractors designed to rely on public infrastructure gain market share.

[1240] We round up the number of EVSE ports to a whole number.

assumptions after a recent ICCT analysis, which assumed that a mix of 1 MW and 150 kW DCFC ports would be utilized. Although megawatt EVSE have the capability of 1 MW charging, BEV batteries may not be able to accept the full power level. In order to ensure that our public charging assumptions are feasible, in HD TRUCS we constrain the charging power to a c-rate of 2 (or 2C).[1241] In our analysis, we calculate the amount of time it takes to charge up to their daily operational demand (50th percentile VMT) with charging power levels at either 2C or 1 megawatt, whichever is the lower power level.[1242] We have calculated this estimate using year 0 of operation (when the vehicle is new); however, since operating miles generally decline over time as, described in RIA Chapter 2.2.1, the charge time for operating VMT would also be expected to decline over time. Equation 2-60 shows how the power level for 2C is calculated for each battery size.

Equation 2-60 Power at 2C charge rate

$$P_{2C} = \frac{2 * kWh_{pack}\big|_{BEV}}{1hr}$$

Where,

P_{2C} = charging power at 2C in kW

$kWh_{pack}\big|_{BEV}$ = size of the battery pack in kWh

If P_{2C} is less than 1 MW, then the P_{2C} power value is used, however, if $P_{2C}$is greater than 1 MW, 1 MW power is used as charging power.

The daily energy consumption for the BEV is determined using Equation 2-61,

Equation 2-61 Daily Energy Consumption

$$kWh_{day} = \left(\frac{kWh_{Tot}}{mi}\bigg|_{BEV}\right) * \frac{AOR_{veh}(Y_i)}{t_{OP_{day}}}$$

Here,

$kWh\ _{day}$ = daily energy consumption

$\frac{kWh_{Tot}}{mi}\Big|_{BEV}$ = operating energy of the BEV

$AOR_{veh}(Y_i)$ = Annual operating VMT for each vehicle for vehicle age i where i = year 0

$t_{OP_{day}}$ = number of operating days, 250 days

Time for megawatt charging is calculated using Equation 2-62.

[1241] For the same battery size (in kWh), 1C = Fully charged in 1 hour, 2C = Fully charge in 30 min. For example, to charge a 150 kWh battery using a c-rate of 1, the charging power is 150 kW and the charging time is 1 hr; whereas to charge it to the same 150 kWh using a c-rate of 2, the charging power is 300 kW and the charging time is 30 min.

[1242] This calculation uses a uniform charging rate; however, charging rates may vary based on the state of charge of the battery.

Equation 2-62 Time for Mega-watt Charging

$$t_{MW} = \frac{kWh_{day}}{P_{2C}} * 60$$

Using the same parameters, we also calculated the time required to charge the battery to enable the vehicle to travel the 90th percentile daily VMT, assuming that the vehicle has started the day charged to travel the daily operating VMT. Equation 2-63 shows how we determined the additional daily energy consumption required for a BEV to go from 50th percentile daily VMT to 90th percentile daily VMT.

Equation 2-63 Additional Energy Consumption to Achieve 90th Percentile Daily VMT from 50th Percentile Daily VMT

$$kWh_{90th-50th} = (R_{size} - OR_{veh}) * \left(\left.\frac{kWh_{Tot}}{mi}\right|_{BEV}\right)$$

Where,

R_{size} = Vehicle 90th percentile VMT

OR_{veh} = 50th percentile range for a vehicle (mi/day)

$\left.\frac{kWh_{Tot}}{mi}\right|_{BEV}$ = Operating energy of the BEV

Time for megawatt (or 2C) charging to go from 50th percentile daily VMT to 90th percentile daily VMT is calculated using Equation 2-64.

Equation 2-64 Time to Mega-watt Charge from 50th Percentile Daily VMT to 90th Percentile Daily VMT

$$t_{90th-50th} = \frac{kWh_{90th-50th}}{P_{2C}} * 60$$

2.8.8 Payback

We calculate the payback period (PBP) by subtracting cumulative operational savings from upfront costs until the cumulative savings are greater than the upfront costs; the year when cumulative savings are greater than the upfront costs is the year that is considered the payback year as shown in Equation 2-65.

Equation 2-65 Payback period for each vehicle

$$PBP_{veh}(Y) = \text{Upfront costs delta} - \text{ Cumulative operational savings} \leq 0$$

Where the upfront costs delta is described in Equation 2-66,

Equation 2-66 Upfront cost delta between ICE and ZEV

$$\text{Upfront costs delta} = \text{ Upfront costs ZEV} - \text{ Upfront costs ICE}$$

In addition to upfront technology costs as described in RIA Chapters 2.7.4.3, 2.7.5.5 and 2.7.6, we also incorporated state sales tax and Federal Excise tax into the total upfront cost as shown in Equation 2-67 and Equation 2-68.

Equation 2-67 Upfront costs for ICE or FCEV

$$\text{Upfront costs ICE and FCEV} = C_{PT} * RPE * (1 + FET + ST)$$

or,

Equation 2-68 Upfront costs for BEV

$$\text{Upfront costs BEV} = C_{PT} * RPE * (1 + FET + ST) + PV_{EVSE}$$

Where,

C_{PT} = Powertrain technology costs

RPE = Retail Price Equivalent, 1.42

FET = Federal Excise Tax, 12% for all Class 8 vehicles and all tractors and 0% for all other vehicles

ST = State sales tax, 5.02%

PV_{EVSE} = Per vehicle cost of the EVSE unit for depot charging BEV vehicles

The annual operating cost is calculated the same way for all technologies in Equation 2-69,

Equation 2-69 Annual operating cost

$$\text{Annual Operating Cost } (OY) = \text{AFC} + \text{AMR} + \text{AIC} + \text{ZF}$$

Where,

OY = Operating year, which starts in with the first year of operation and is calculated through each of the first 10 years)

AFC = Annual Fuel cost for diesel, electricity and hydrogen fuels (RIA Chapter 2.7.8.1) AMR = Annual Maintenance and repair cost (RIA Chapter 2.7.8.2)

AIC = Annual Powertrain Insurance cost (RIA Chapter 2.7.8.3)

ZF = $100 Annual ZEV registration fee (only applies to ZEV vehicles)

The cumulative operating cost for a vehicle in that model year (MY) is calculated by summing the annual operating cost and the cumulative operational savings as the delta between the annual ICE operational cost and the annual ZEV operating cost using Equation 2-70,

Equation 2-70 Cumulative operational savings

$$\begin{aligned}&\text{Cumulative operational savings } (MY) \\ &\quad = \sum_{OY=MY}^{MY+1} [(\text{Annual ICE Operating Cost of } MY)_{CY} \\ &\quad - (\text{Annual ZEV Operating Cost of } MY)_{CY}]\end{aligned}$$

Where,

MY = Model Year for 2027 to 2032

OY = Operation year, where OY = MY for the first year of operation and increases to year 10 (the maximum payback period in our analysis, see RIA Chapter 2.7) according to Table 2-93,

Table 2-93 Operation years for each model year (MY)

	Operational Year (i)									
	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
MY2027	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036
MY2028	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037
MY2029	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038
MY2030	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039
MY2031	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040
MY2032	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041

2.8.8.1 Operational Fuel Consumption Cost

We calculate fuel costs for diesel, charging, and hydrogen using the total energy per mile consumption of the vehicle as described in RIA Chapters 2.8.4.1, 2.8.5.2 and 2.8.5.3, and 2.8.6.4, respectively. In the case of ICE vehicles, the GEM fuel economy (FE) values are reported in miles per gallon instead of kWh per mile. For HD TRUCS computed per-mile energy consumption, the values are reported in kWh/mi. Equation 2-71 describes the annual diesel fuel consumption cost.

Equation 2-71 Annual Diesel Fuel Consumption Cost

$$AFP_{diesel}(OY_i) = \left(\frac{AOR_{veh}}{FE_{ICE}} + \frac{AOR_{veh}}{FE_{ICE}}(1 + \%PTO)\right) * Pr_{diesel}(OY_i)$$

Where,

AOR_{veh} = annual operating VMT (RIA Chapter 2.8.2)

$Pr_{diesel}(OY_i)$ = Price of diesel fuel, \$/gal, for operating year (OY) where i can be 1 – 10 according to Table 2-93.

$\%PTO$ = Percent PTO use

The annual charging cost for a BEV is calculated using the total per-mile energy consumption, the operating range and price of charging as shown in Equation 2-72 and described in RIA Chapter 2.4.4.2.

Equation 2-72 Annual Electricity Fuel Consumption Cost

$$AFPr_{elec}(Y_i) = AOR_{veh} * \frac{kWh_{BEV}}{mi} * \frac{1}{\eta_{ACDC}} * \frac{1}{\eta_{Batt}} * Pr_{elec}(Y_i)$$

Where,

AOR_{veh} = annual operating VMT (RIA Chapter 2.8.2)

$\frac{kWh_{BEV}}{mi}$ = the total per mile energy consumption for a BEV

$\frac{1}{\eta_{ACDC}}$ = converter efficiency, 94%

$\frac{1}{\eta_{Batt}}$ = battery efficiency, 95%

$Pr_{elec}(Y_i) =$ Price of charging, \$/kWh, for operating year (OY) where i can be 1 – 10 according to Table 2-93.

The annual hydrogen consumption price on average during operation of the vehicle is calculated using the operational energy consumption, the operating VMT, and the price of hydrogen as shown in Equation 2-73 and described in RIA Chapter 2.5.3.1:

Equation 2-73 Annual Hydrogen Consumption Cost

$$AFPr_{elec}(Y_i) = AOR_{veh}\left(\frac{kWh_{FCEV}}{mi}\right) * Pr_{H2}(OY_i)$$

Where,

AOR_{veh} annual operating VMT (RIA Chapter 2.8.2)

$\frac{kWh_{FCEV}}{mi}$ = the total per mile energy consumption for a FCEV, RIA Chapter 2.8.6.4

$Pr_{H2}(OY_i) =$ Price of hydrogen, \$/kg, for operating year (OY) where i can be 1 – 10 according to Table 2-93.

2.8.8.2 Maintenance and Repair Cost

Maintenance and repair costs are calculated for ICE vehicles, BEVs, and FCEVs. The costs of maintenance and repair for ICE vehicles is calculated annually using Equation 2-74:

Equation 2-74 Annual Maintenance and Repair of ICE Cost

$$AMR_{ICE}(Y_i) = AOR_{veh}(Y_i) * (k_a OY_i + k_b)$$

Where,

$OY_i =$ operating year i where i is between 1 and 10

$k_a =$ coefficients a, 0.03

$k_b =$ coefficients b, 0.11

AOR_{veh} = annual operating VMT (RIA Chapter 2.8.2)

Here, coefficients a and b are as described in RIA Chapter 2.3.4.2. These coefficients are derived from equations found in the 2022 BEAN tool.[1243,1244]

The maintenance and repair costs of BEVs and FCEVs are scaled from the maintenance and repair costs of ICE vehicles for the same vehicle type as in Equation 2-75 and Equation 2-76. Please see RIA Chapters 2.4.4.1and 2.5.3.2for more details on the BEV and FCEV scaling factors, which have been revised for the final rule analysis.

Equation 2-75 Annual Maintenance and Repair of BEV Cost

$$AMR_{BEV}(OY_i) = \beta_{BEV}(OY_i) * AMR_{ICE}(OY_i)$$

Equation 2-76 Annual Maintenance and Repair of FCEV Cost

$$\overline{MR}_{FCEV} AMR_{FCEV}(OY_i) = \beta_{FCEV}(OY_i) * AMR_{ICE}(OY_i)$$

Where,

(β) can be found in Table 2-94.

Table 2-94 Maintenance and repair scaling factor for BEV and FCEV

Operating Year	$\boldsymbol{\beta_{BEV}}$	$\boldsymbol{\beta_{FCEV}}$
2027	0.88	1
2028	0.846	1
2029	0.812	1
2030	0.778	1
2031	0.744	0.95
2032	0.71	0.9
2033	0.71	0.85
2034	0.71	0.8
2035	0.71	0.75
2036	0.71	0.75
2037	0.71	0.75
2038	0.71	0.75
2039	0.71	0.75
2040	0.71	0.75
2041	0.71	0.75

2.8.8.3 Insurance Cost

Annual insurance cost (AIC) of the technology is determined using the upfront technology RPE and an insurance rate (IR) of 3% using Equation 2-77,

Equation 2-77 Annual insurance cost

$$\mathrm{AIC} = C_{PT} * RPE * (1 + IR)$$

Where,

[1243] See "Coef A" and "Coef B" in the "TCO Assumptions" tab.

[1244] Argonne National Laboratory. VTO HFTO Analysis Reports – 2022. "ANL – ESD-2206 Report – BEAN Tool – MD HD Vehicle Techno-Economic Analysis.xlsm". Available online: https://anl.app.box.com/s/an4nx0v2xpudxtpsnkhd5peimzu4j1hk/folder/242640145714.

C_{PT} = Powertrain technology costs

RPE = Retail Price Equivalent, 1.42

IR = Insurance Rate, 3%

In the heavy-duty sector, technology adoption rates often follow an S-shape. See RIA Chapter 2.7 above. As discussed there, the adoption rates are initially slow, followed by a rapid adoption period, then leveling off as the market saturates.[1245] Studies have long used payback period to inform new technology adoption rates.[1246]

The payback schedule in Table 2-95 for MY 2027 was used to assign the percentage of BEVs to each of the 101 HD TRUCS vehicle types based on its payback period for MY 2027. For MY 2030 and MY 2032, the payback schedule was applied to both BEVs and select FCEVs. The discussion on how we determined this schedule based on the TEMPO model is in Chapter 2.7.

Table 2-95 Payback Schedule in HD TRUCS

Payback Bins	MY 2027	MY 2030	MY 2032
<0	20%	37%	70%
0-1	20%	37%	70%
1-2	20%	37%	70%
2-4	20%	26%	39%
4-7	14%	14%	14%
7-10	5%	5%	5%
> 10	0%	0%	0%

2.8.8.4 Percentage of ZEVs in the Technology Packages

The percentage of ZEVs for each vehicle type is then weighted using the MY 2021 sales volume from MOVES (see RIA 2.2.3) and 2021 sales volume adjusted maximum for that vehicle type as shown in Equation 2-78.

Equation 2-78 Sales-Weighted Vehicle Percentage

$$R'_{TA}|_{veh} = R_{TA}|_{veh} * S_{veh}$$

Here,

$R_{TA}|_{veh}$ = Vehicle-level adoption %

S_{veh} = Sales percent of the vehicle

The ZEV adoption values are aggregated into different levels for various calculations. For example, aggregation is done for both MOVES sourcetypeID and regclassID as well as

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[1245] See also a similar discussion in the preamble to EPA's Phase 2 HD rule. U.S. Environmental Protection Agency. 81 FR at 73558 (Oct 25, 2016).

[1246] Packey, Daniel. National Renewable Energy Laboratory. "Market Penetration of New Technologies." February 1993. Available at: https://www.nrel.gov/docs/legosti/old/4860.pdf.

regulatory classes. Generally, the aggregated technical adoption values are calculated using Equation 2-79.

Equation 2-79 Aggregated Technical Adoption

$$R'_{TA}|_{agg} = \frac{(R'_{TA})_{agg}}{S_{agg}}$$

Here,

$R'_{TA}|_{agg}$ = The aggregated adjusted technical adoption rate where the aggregation can be on any level

S_{agg} = Aggregated sales value that is aggregated to the same level as $(R'_{TA})_{agg}$

2.8.8.5 Battery Demand

We used HD TRUCS and MOVES to estimate the total annual HD vehicle battery demand for BEVs and FCEVs in MYs 2027 and 2032. For both BEVs and FCEVs, we multiplied sales-weighted averages of battery sizes for each MOVES SourceTypeID and RegClass ID combination by MOVES' projected sales for those vehicle types. The battery size is calculated from the multiplication of the battery size of the vehicle (as described in RIA Chapter 2.8.5.3 for BEVs and RIA Chapter 2.8.6.3 for FCEVs) and the sales weighted vehicle adoption rates (Equation 2-78), shown in Equation 2-80.

Equation 2-80 Sales Weighted Battery Size for each MOVES SourceType ID and RegClass ID

$$kWh_{MOVES\_ID} = \frac{\sum kWh_{pack} * R'_{TA}|_{veh}}{\sum R'_{TA}|_{veh}}$$

Here,

kWh_{MOVES_ID} = Sales weighted battery size for each MOVES SourceType ID and RegClassID for each MY

kWh_{pack}= Battery pack size for BEV, Equation 2-26, or FCEV, Equation 2-43

$R'_{TA}|_{veh}$ =sales weighted vehicle adoption rates, Equation 2-78.

To determine the total battery demand in the analysis, the sales weighted battery size for each MOVES SourceType ID and RegClass ID is multiplied by the sales value for that MOVES SourceType ID and RegClass ID as shown in Equation 2-81.

Equation 2-81 Annual Battery Demand for each MY in GWh

$$GWh_{MY} = \frac{1}{10^6} \sum S_{MOVES\_ID} * kWh_{MOVES\_ID}$$

S_{MOVES_ID} = vehicle sales for each MOVES Source TypeID and RegClassID vehicle for each MY.

2.9 HD TRUCS Analysis Results

HD TRUCS is a flexible tool that was used to analyze both the operational characteristics and costs of ZEV technologies that we used to estimate heavy-duty ZEV technologies feasibility and payback period.[1247] Then we translated the payback period, which is the number of years it takes to offset any incremental cost increase of a ZEV over a comparable ICE vehicle, into projected potential technology adoption of BEV or FCEV technologies.

2.9.1 HD TRUCS Technology Analysis

As discussed in RIA Chapter2.1, HD TRUCS evaluates the design features needed to meet the power and energy demands of various HD vehicle types, in this rule, when using ZEV technologies. Since BEV technology (and, likewise, FCEV technology) may be more suitable for some applications compared to others, to assess the technical suitability of ZEVs for specific vehicle applications, we created 101 representative vehicles in HD TRUCS that cover the full range of weight classes within the scope of the final standards (Class 2b through 8 vocational vehicles and tractors). The representative vehicles cover many aspects of work performed by the industry. This work was translated into total energy and power demands per vehicle type based on everyday use of HD vehicles, ranging from moving goods and people to mixing cement. We then identified the technical properties required for a BEV or FCEV to meet the operational needs of a comparable ICE HD vehicle.

Since batteries can add weight and require space for packaging, we evaluated the battery mass and physical volume impacts of BEV technology. Similarly, we determined the H2 storage tank volume required for packaging on FCEVs. If the performance needs of a ZEV resulted in a battery that was too large or heavy, then we did not include the ZEV for that application in our modeled potential compliance pathway's technology package because of the potential impact on payload and, thus, potential work accomplished relative to a comparable ICE vehicle. However, we also show multiple additional example potential compliance pathways (in Chapter 2.11) that illustrate it is possible to comply with the final standards without ZEVs (e.g., relative to the reference case), which further supports our conclusion that the final standards can be met—and can be achieved through a number of compliance strategies— even if certain ZEVs have payload impacts.

2.9.1.1 BEV Payload Weight Impact

In the case of HD vehicles, battery mass may impact the overall payload available for use. The payload mass impact is the difference in weight between an ICE powertrain and a BEV powertrain. The ICE powertrain mass includes weight of the engine including the aftertreatment system, transmission, fuel, and DEF (see RIA Chapter 2.3.2). The BEV powertrain mass includes weight of battery, the motor, and the gearbox. The BEV battery weight is converted from the battery size (in terms of kWh) and the pack-level specific energy of the battery as discussed in RIA Chapter 2.4.2.1. The BEV motor mass is discussed in Chapter 2.4.1.2. The BEV gearbox weights are mapped to the BEAN gearbox weight from the "Autonomie Out

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[1247] We also show multiple additional example potential compliance pathways (in RIA Chapter 2.11) that illustrate it is possible to comply with the final standards without the use of ZEVs, which further supports our conclusion that the final standards can be met and can be achieved through a number of compliance strategies.

Import" tab to the appropriate medium heavy-duty and heavy heavy-duty vehicles in HD TRUCS by calculating MY 2027 values using linear interpolation of the average of the high- and low-tech scenarios for 2025 and 2030.[1248] Table 2-96 shows the weight differences calculated in HD TRUCS of a BEV powertrain compared to its ICE counterpart. Negative values in the Weight Difference column indicate that the BEV vehicle weighs less than the ICE vehicle.

Table 2-96 Weight Difference between BEV and ICE Vehicles in HD TRUCS

Vehicle ID	**ICE Powertrain (lbs)**	**BEV Powertrain (lbs)**	**Weight Difference (BEV-ICE) (lbs)**
01V_Amb_Cl4-5_MP	1738	1593	-145
02V_Amb_Cl2b-3_MP	1019	1518	499
03V_Amb_Cl4-5_U	1738	1502	-236
04V_Amb_Cl2b-3_U	1019	1425	406
05T_Box_Cl8_MP	3021	3322	301
06T_Box_Cl8_R	3021	3411	390
07T_Box_Cl6-7_MP	1937	2237	300
08T_Box_Cl6-7_R	1937	2401	464
09T_Box_Cl8_U	3021	3237	216
10T_Box_Cl6-7_U	1937	2169	232
11T_Box_Cl2b-3_U	1019	1375	356
12T_Box_Cl2b-3_R	1019	1575	556
13T_Box_Cl2b-3_MP	1019	1471	452
14T_Box_Cl4-5_U	1738	1375	-363
15T_Box_Cl4-5_R	1738	1575	-163
16T_Box_Cl4-5_MP	1738	1471	-267
17B_Coach_Cl8_R	5076	8405	3329
19C_Mix_Cl8_MP	3979	5370	1391
20T_Dump_Cl8_U	3021	3754	733
21T_Dump_Cl8_MP	3021	3795	774
22T_Dump_Cl6-7_MP	1937	3444	1507
23T_Dump_Cl8_U	3021	3754	733
24T_Dump_Cl6-7_U	1937	3246	1309
25T_Fire_Cl8_MP	3021	3954	933
26T_Fire_Cl8_U	3021	3961	940
27T_Flat_Cl6-7_MP	1937	2232	295
28T_Flat_Cl6-7_R	1937	2396	459
29T_Flat_Cl6-7_U	1937	2087	150
30Tractor_DC_Cl8	3979	4730	751
31Tractor_DC_Cl7	3979	4065	86
32Tractor_SC_Cl8	3979	11568	7589
33Tractor_DC_Cl8	3979	6643	2664
34T_Ref_Cl8_MP	3885	4498	613

[1248] Argonne National Laboratory. VTO HFTO Analysis Reports – 2022. "ANL – ESD-2206 Report – BEAN Tool – MD HD Vehicle Techno-Economic Analysis.xlsm". Available online: https://anl.app.box.com/s/an4nx0v2xpudxtpsnkhd5peimzu4j1hk/folder/242640145714.

Vehicle ID	**ICE Powertrain (lbs)**	**BEV Powertrain (lbs)**	**Weight Difference (BEV-ICE) (lbs)**
35T_Ref_Cl6-7_MP	1937	3582	1645
36T_Ref_Cl8_U	3885	4498	613
37T_Ref_Cl6-7_U	1937	3539	1602
38RV_Cl8_R	1937	6772	4835
39RV_Cl6-7_R	1308	7029	5721
40RV_Cl4-5_R	1164	4508	3344
42RV_Cl8_MP	1937	6772	4835
43RV_Cl6-7_MP	1308	6473	5165
44RV_Cl4-5_MP	1164	4154	2990
46B_School_Cl8_MP	2665	3459	794
47B_School_Cl6-7_MP	2665	2141	-524
48B_School_Cl4-5_MP	1182	1593	411
49B_School_Cl2b-3_MP	1182	1518	336
50B_School_Cl8_U	2665	3303	638
51B_School_Cl6-7_U	2665	2141	-524
52B_School_Cl4-5_U	1182	1502	320
53B_School_Cl2b-3_U	1182	1425	243
54Tractor_SC_Cl8	3979	13691	9712
55B_Shuttle_Cl2b-3_MP	1261	2089	828
56B_Shuttle_Cl4-5_U	1738	2024	286
57B_Shuttle_Cl2b-3_U	1261	1947	686
58B_Shuttle_Cl6-7_MP	2665	3291	626
59B_Shuttle_Cl6-7_U	2665	3078	413
60S_Plow_Cl6-7_MP	1937	2577	640
61S_Plow_Cl8_MP	3021	4997	1976
62S_Plow_Cl6-7_U	1937	2437	500
63S_Plow_Cl8_U	3021	4923	1902
64V_Step_Cl6-7_MP	1308	2241	933
65V_Step_Cl4-5_MP	1738	1471	-267
66V_Step_Cl2b-3_MP	1019	1471	452
67V_Step_Cl6-7_U	1308	2096	788
68V_Step_Cl4-5_U	1308	1375	67
69V_Step_Cl2b-3_U	1019	1375	356
70S_Sweep_Cl6-7_U	2665	2384	-281
71T_Tanker_Cl8_R	3021	3608	587
72T_Tanker_Cl8_MP	3021	3552	531
73T_Tanker_Cl8_U	3021	3537	516
74T_Tow_Cl8_R	3021	5206	2185
75T_Tow_Cl6-7_R	1937	3704	1767
76T_Tow_Cl8_U	3021	5060	2039
77T_Tow_Cl6-7_U	1937	3259	1322
78Tractor_SC_Cl8	3979	10019	6040
80Tractor_DC_Cl8	3979	7948	3969
81Tractor_DC_Cl7	3979	6445	2466
82Tractor_DC_Cl8	3979	7944	3965
83Tractor_DC_Cl7	3979	5644	1665

Vehicle ID	ICE Powertrain (lbs)	BEV Powertrain (lbs)	Weight Difference (BEV-ICE) (lbs)
84Tractor_DC_Cl8	3979	4750	771
85B_Transit_Cl8_MP	2684	5749	3065
86B_Transit_Cl6-7_MP	1742	4504	2762
87B_Transit_Cl8_U	2684	5749	3065
88B_Transit_Cl6-7_U	1742	4156	2414
89T_Utility_Cl8_MP	3021	3441	420
90T_Utility_Cl8_R	3021	3513	492
91T_Utility_Cl6-7_MP	1937	2411	474
92T_Utility_Cl6-7_R	1937	2564	627
93T_Utility_Cl4-5_MP	1738	1597	-141
94T_Utility_Cl2b-3_MP	1709	1529	-180
95T_Utility_Cl4-5_R	1738	1689	-49
96T_Utility_Cl2b-3_R	1709	1689	-20
97T_Utility_Cl8_U	3021	3392	371
98T_Utility_Cl6-7_U	1937	2292	355
99T_Utility_Cl4-5_U	1738	1521	-217
100T_Utility_Cl2b-3_U	1709	1442	-267
101Tractor_DC_Cl8	2284	3893	1609

In the NPRM version of HD TRUCS, we calculated the payload impact[1249] based on the standard payload used to demonstrate compliance with Phase 2 (see 40 CFR 1037.801), and we used a 30% payload threshold to exclude a BEV from consideration. Based on consideration of the comments received, for the final rule we are not using a 30 percent payload reduction as a metric for determining BEV suitability. Instead, we assess specific applications in HD TRUCS on an individual basis and determine the suitability of each application for BEVs based on the payload difference between comparable ICE vehicles and BEVs. This change was made for two reasons: (1) the Phase 2 payloads do not reflect the full payload that is available for most vehicles; and (2) we received persuasive comment on the effect of payload on individual vehicle applications and have concluded that it is more appropriate to assess each of these applications, and the included HD TRUCS vehicles, on a case-by-case basis. The applications mentioned in comments that require additional specific assessment of payload impact are the concrete mixer, dump truck, tanker, coach buses, and tractor applications.

Several manufacturers and associations raised issues concerning ability of cement pumpers and mixers to achieve emission standards predicated on electrification. Before discussing specifics, EPA notes that two issues are presented: whether application of these technologies should be considered for these vehicles in setting the emission standard for the subcategory of which they are a part (HHD vocational vehicle), and whether we should consider application of these technologies in determining whether to set new optional custom chassis standards for concrete mixers and for mixed-use vehicles. Our disposition of these issues is that it is appropriate to include consideration of these technologies and performance of cement mixers in

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[1249] In the NPRM, the impact on payload calculated as the delta between the weight of the BEV powertrain components and the weight of the ICE powertrain components divided by the payload used to determine compliance with the HD GHG Phase 1 and Phase 2 vehicle CO_2 emission standards, which is less than the maximum payload capacity of the vehicle.

developing the potential compliance pathway's technology packages for HHD vocational vehicle standards, but that we are not going to revise or set new Phase 3 optional custom chassis standards for concrete mixers and for mixed-use vehicles, for the reasons explained in this section.

Certain commenters maintained that energy used by concrete mixers and pumpers is significantly higher than what is represented in GEM and suggested that the load and energy inputs for these vehicles in HD TRUCS is unrepresentative such that these vehicles in fact would need more energy, larger batteries, and incur higher costs than EPA projected at proposal. These comments are persuasive. For the final rule, EPA obtained data based on information provided by one commenter which show significantly larger power demands (and hence battery sizes) than EPA considered at proposal. As a result, EPA determined that EPA's optional custom chassis standards for Concrete Mixers/Pumpers and Mixed-Use Vehicles will remain unchanged from the Phase 2 MY 2027+ CO_2 emission standards.

There were other comments, however, that some electrified concrete mixers and pumpers presently exist, at least as prototypes in Europe. This suggests that these vehicles – represented in HD TRUCS as vehicle 19C_Mix_C18_MP – could be considered for utilization of ZEV technologies in the HD TRUCS analysis for the HHD vocational vehicle subcategory. To that end, EPA investigates if there are payload constraints that would make such inclusion inappropriate.[1250] The HD TRUCS concrete mixer has a BEV powertrain weighing 1391 pounds more than the comparable ICE powertrain. Although this is 9.3% of the Phase 2 payload (15,000 pounds used in HD TRUCS), a mixer user desiring a full load would see an impact of 3.5% as the full payload is 40,000 pounds.[1251] Since a cubic yard of concrete weighs about 4,000 pounds, the mixer maximum load (by volume) would reduce from 10 cubic yards to 9.65 cubic yards. This minor payload impact would not be a limiting factor for adoption rates of 39% at 2032, and therefore we are continuing to include this vehicle in the HD TRUCS analysis, and correspondingly the technology packages used in the modeled potential compliance pathway for HHD vocational vehicles.[1252]

Many of the BEV powertrains weigh more than their ICE comparator with a significant contribution coming from the battery size. Battery chemistry impacts the battery pack specific energy and battery technology continues to evolve suggesting that battery pack weight may decrease and payload increase. To assess the sensitivity of payload to higher specific energy, EPA reviewed two additional scenarios 1) use of NiMn batteries (HD TRUCS uses a value that represents a 50/50 mix of NiMn and LFP to align with battery cost assumptions) and 2) possible NiMn battery pack specific energy improvements through 2030. Per ANL/DOE, NiMn pack specific energy in 2027 is 226 Wh/kg and the same pack in 2030 is 248 Wh/kg. If NiMn battery chemistry with the specific energy increasing to 226 Wh/kg is applied to concrete mixer

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[1250] Landgraf, Michael. Memorandum to Docket EPA-HQ-OAR-2022-0985. "HD GHG Phase 3 Rule BEV Payload Analysis" February 26, 2024.

[1251] Gerges, Rafik. "How Full Can Concrete Trucks be when Driving on Slabs-on-Grade?". Structure Magazine. January 2017. Available online: https://www.structuremag.org/?p=10927#:~:text=A%20typical%20fully%20loaded%20truck,of%20concrete%20adds%204%2C000%20pounds.

[1252] According to the CARB Large Entity Fleet Report, 54% of vocational vehicles do not weigh out in operation. CARB. Large Entity Fleet Reporting. Page 22. Available online: https://ww2.arb.ca.gov/sites/default/files/2022-02/Large_Entity_Reporting_Aggregated_Data_ADA.pdf.

19C_Mix_C18_MP, the payload loss is 2.0 percent. If battery improvements over time are realized as ANL predicts, the NiMn battery specific energy increases to 248 Wh/kg and the payload reduction drops to 1.1 percent. This battery pack specific energy sensitivity was evaluated for most applications that have a payload reduction due to BEV powertrain weight.

We also received comments about the potential for payload weight impacts on dump trucks. HD TRUCS has five dump truck vehicles; 20T_Dump_Cl8_U, 21T_Dump_Cl8_MP, 22T_Dump_Cl6-7_MP, 23T_Dump_Cl8_U, and 24T_Dump_Cl6-7_U. The Class 8 dump trucks have an HD TRUCS GEM payload of 15,000 pounds and a corresponding loss due to the BEV powertrain of 4.9 to 5.2 percent. Since the maximum payload can be 30,000 lbs (Example: 10 cubic yards of rock or sand at 3,000 lbs/yd) the payload impact is 2.6 percent such that the payload weight impact would not be an impediment towards achieving the adoption rates in the modeled potential compliance pathway. Additionally, the battery specific energy improvements of chemistry (226 Wh/kg) and chemistry plus improvements at 2030 (248 Wh/kg) take the payload loss to 1.3 percent and then 0.4 percent. We therefore are retaining these vehicles in the HD TRUCS analysis, and correspondingly in the technology packages used in the modeled potential compliance pathway. Indeed, the 10 cubic yard volume assumption is conservative as dump bodies (for public roads) can reach 34.6 cubic yards.[1253] Vehicles 22T_Dump_Cl6-7_MP and 24T_Dump_Cl6-7_U are Class 6-7. Applying the Class 8 ratio of peak load to GEM load (with the rationale that a dump truck would deliver a full load and return empty such that GEM load is logically ½ of maximum load) gives a maximum payload of 22,400 lbs as these Class 6-7 dump trucks have a GEM payload of 11,200 lb. The Class 6-7 dump trucks have a maximum payload degradation of 6.7 percent and 5.8 percent. Applying the aforementioned specific energy improvements of 226 Wh/kg results in payload loss of 5.0 and 4.0 percent instead of 6.7 and 5.8 percent. The 248 Wh/kg battery specification drops the payload loss to 4.0 and 3.2 percent. While not negligible, the payload reduction is small enough that there are no payload constraints which would disqualify these vehicles from being retained in HD TRUCS or the corresponding technology packages for Class 6-7 vocational vehicles (note, the projected adoption rates in our HD TRUCS analysis for the two Class 6-7 vocational vehicles is 5 percent and 14 percent in 2027 and 2032).

The tanker trucks, 71T_Tanker_Cl8_R, 72T_Tanker_Cl8_MP, and 73T_Tanker_Cl8_U, have a weight impact from their BEV powertrain of 516 to 587 pounds which is a small percentage (3.4 percent to 3.9 percent) of their GEM payload weight. Increasing the payload to a more realistic 30,000 pounds[1254] gives a payload loss of 1.7 to 2.0 percent. This small weight disadvantage supports our assumed 2032 adoption rates (14 to 70 percent) are supported by the specific energy opportunities. Applying the specific energy improvement of 226 Wh/kg results in payload loss of 215 pounds (0.7 percent), and if NiMn battery pack specific energy continues to improve as projected by ANL/DOE, there will be no payload loss for vehicles produced in MY 2030.

We have carefully examined whether there are payload constraints for each of the tractors in our analysis and have concluded that it is appropriate for most of them to remain in our HD

[1253] Municibid. “How to Calculate Dump Truck Capacity”. Last updated June 14, 2023. Available online: https://blog.municibid.com/calculate-dump-truck-capacity/

[1254] Clean Management Environmental Group. “Tankers”. Accessed February 20, 2024. Available online: https://cleanmanagement.com/service/tankers/.

TRUCS analysis and the corresponding technology packages for our modeled potential compliance pathway. Our explanation follows.

A tractor typically weighs up to 25,000 pounds and an empty 53 foot box trailer can add another 10,000 pounds, leaving 45,000 pounds of cargo capacity for a Class 8 tractor-trailer maxed out at 80,000 lbs GCWR.[1255] Applying the HD TRUCS payload impact to this Class 8 maximum payload of 45,000 lbs shows six vehicles (HD TRUCS Tractors 30Tractor_DC_Cl8, 33Tractor_DC_Cl8, 80Tractor_DC_Cl8_HH, 82Tractor_DC_Cl8, 84Tractor_DC_Cl8, and 101Tractor_DC_Cl8) have less than a 9 percent payload loss. In fact, 80Tractor_DC_Cl8_HH is a heavy-haul tractor, so its payload can be higher and the percent of payload loss even less. Class 8 BEV are allowed to operate at a GCWR of 82,000 pounds thus adding 2,000 pounds of payload.[1256] This allowance drives tractors like 30Tractor_DC_Cl8, 84Tractor_DC_Cl8, and 101Tractor_DC_Cl8 to have no payload loss while the worst-case payload loss of 3965 pounds (82Tractor_DC_Cl8) is cut in half. When the battery specific energy improvements are applied (taking specific energy to 248 Wh/kg) the worst two of these tractors lose just over 2500 pounds which is 5.6%. When the 2,000 pound payload allowance is then applied, 4 of these tractors have no payload loss and two have a payload reduction of just over 500 pounds or 1.1 percent.

Class 8 tractors 32Tractor_SC_Cl8 and 78Tractor_SC_Cl8 have larger payload impacts (assuming 45,000 lbs payload): 16.9 percent and 13.4 percent respectively. With a battery specific energy increase to 248 Wh/kg, the payload loss drops to 12.0 and 9.3 percent. When the 2,000-pound payload allowance is applied the loss is 7.6 and 4.8 percent. In considering whether these payload losses should justify exclusion of these vehicles from the tractor technology package, we evaluated typical cargo types in relation to payload capacity.[1257] Some tractors consistently haul heavy loads (assumed here as 90-100 percent of maximum load) while others haul different product with each trip and must be capable of maximum or nearly maximum load for those occasions when the product requires high payload capacity. EPA’s review of Federal Highway Administration data, and more specifically, commodity data per the 2002 Vehicle Inventory and Use Survey (VIUS), show that 15 of 43 commodities covered had average loads at or within 10 percent of maximum load.[1258] Twenty four percent of the total tractor ton-miles reflect delivery of this group of commodities. Using this same approach, 14 commodities had average loads at 80 percent to 90 percent of maximum and accounted for 20 percent of ton-miles. Also 6 commodities had average loads that were 70 percent to 80 percent of maximum and accounted for 35 percent of ton miles. Some commodities may always or occasionally need maximum load capability, in which case a BEV may not be a suitable application. Other commodities such as Meat, Fish and Seafood, Precision Instruments, Machinery, Tobacco, Alcohol, Pharmaceuticals, Milled Grain, Textiles, Furniture, Mail, Other Foodstuffs will have consistent loads that are 10 percent to 30 percent below maximum. There is no payload capacity

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[1255] Hawley, Dustin. “How Much Does a Semi Truck Weigh”. J.D. Power February 04, 2021. Available Online: https://www.jdpower.com/cars/shopping-guides/how-much-does-a-semi-truck-weigh#:~:text=The%20unladen%20weight%20of%20a,weight%20of%20about%2035%2C000%20pounds.

[1256] See Consolidated Appropriations Act of 2019, at § 2, div. G, title 4, Pub. L. 116-6, 133 Stat. 13, 474 (Feb. 15, 2019) (codified at 23 U.S.C. § 127(s)).

[1257] Landgraf, Michael. Memorandum to docket EPA-HQ-OAR-2022-0985. “HD GHG Phase 3 Rule BEV Payload Analysis”. February 26, 2024.

[1258] Federal Highway Administration (FHWA) Office of Operations (HOP). “Research, Development, and Application of Methods to Update Freight Analysis Framework Out-of-Scope Commodity Flow Data and Truck Payload Factors”. Available online: https://ops.fhwa.dot.gov/publications/fhwahop20011/chap12.htm.

loss associated with carriage of these commodities by Class 8 BEV tractors. We consequently are not excluding these tractors from the tractor technology packages, and, moreover, we see these data as supporting the modest adoption rates in our technology package for long haul tractors. Put another way, our modeled compliance pathway projects most of these vehicles remain ICE vehicles during the time frame of the Phase 3 rule which can accommodate those commodities for which maximum loads are needed, and (as shown by the VMT data) BEVs remain a viable alternative for other commodities.

BEV 54Tractor_SC_Cl8, a Class 8 sleeper cab has the highest payload impact of all the tractors at 9,712 pounds which is 22 percent of the 45,000-pound maximum payload. Due to the higher payload impact, we are not considering this tractor as part of the tractor technology package for the modeled potential compliance pathway.

Class 7 tractor 31Tractor_DC_Cl6-7 has no payload loss due to its BEV powertrain weight. BEV Class 7 tractors (81Tractor_DC_Cl7 and 83Tractor_DC_Cl7) are at a payload loss of 6.7 and 9.9 percent. Turning again to VIUS data, a significant distribution exists across commodities aligned with Class 7 tractor use. While some users will need maximum payload (taken here as the 25,000 lbs GEM weight) other Class 7 tractors are suitable for commodities not requiring maximum load. Examples are Animal Feed, Pulp, Electronic and Electrical Equipment, Plastics and Rubber, and Fertilizers. These have average loads that range from 23 percent to 55 percent lower than the 25,000 lbs GEM payload. The ability of these commodities to use BEV Class 7 tractors confirms that the HD TRUCS analysis projected adoptions rates are viable. With a pack specific energy of 248 Wh/kg, the payload loss reduces to 2.5 percent and 5.1 percent. This value of payload loss supports the projected adoption rates.

Coach and Transit buses (17B_Coach_Cl8_R, 85B_Transit_Cl8_MP, 86B_Transit_Cl6-7_MP, 87B_Transit_Cl8_U, 88B_Transit_Cl6-7_U) see a payload impact of 20.4 to 24.7 percent. Payload loss with the 248 Wh/kg battery pack drops to 11.6 to 17.2 percent.

The remaining trucks with a 10-20 percent reduction in payload are 35T_Ref_Cl6-7_MP, 37T_Ref_Cl6-7_U, 55B_Shuttle_Cl2b-3_MP, 57B_Shuttle_Cl2b-3_U, 61S_Plow_Cl8_MP, 63S_Plow_Cl8_U, 74T_Tow_Cl8_R, 75T_Tow_Cl6-7_R, 76T_Tow_Cl8_U, 77T_Tow_Cl6-7_U. The range in payload loss is 11.8 percent (77T_Tow_Cl6-7_U) to 15.8 percent (75T_Tow_Cl6-7_R). The payload loss for these trucks with the higher (248 Wh/kg) battery pack is 6.6 to 9.8 percent. Of the 101 vehicle types in HD TRUCS, 15 have no payload loss and 54 have a 0 to 10 percent payload loss (some of which were in areas of specific interest and discussed above).

As proposed, we are not setting new optional custom chassis standards for motor homes after consideration of the projected impact of applying such technologies, including the weight of batteries in BEVs in the MYs 2027-2032. The HD TRUCS evaluation of RVs demonstrates that it is unlikely that ZEV technology will pay back for RVs that typically travel low annual miles (as they are modeled in HD TRUCS) and are expected to travel long distances in a day over a small number of annual operational days. Consistent with the concrete mixer in HD TRUCS, we are reflecting the adoption rate (which are 0 percent for RVs) in the corresponding vocational vehicle standards.

2.9.1.2 BEV and FCEV Payload Volume Impact

Like battery weight, the physical volume required to package a battery pack can also be challenging to integrate onto a HD vehicle. The pack-level energy density (370 Wh/L) is used to convert the battery size in terms of kWh into the volume of the battery. For the proposal, we had calculated the width of the physical battery using the volume, wheelbase, and 110% of the frame rail height. If the battery width was less than 8.5 feet, we projected that the battery would package on each vehicle. We received comments on this approach and realized there were aspects we had not considered in our analysis, including space for tires and the width of each frame rail. Based on consideration of comments received, we updated our approach to factor battery volume into our analysis for BEVs. Comments and our responses for battery volume are available in Section 3.10.3 of the RTC.

For the final rule we have taken an approach where we compare the volume of each battery with comparable current BEVs in the market today and base our analysis on this information. In our analysis, we found that of the 101 vehicles that we are considering as BEVs, 3 vehicles had batteries that were greater than 15% larger than a comparable battery in a current BEV and 5 vehicles (including the 3 with batteries greater than 15% increase in battery size) had batteries that were 10% larger than comparable current BEVs.[1259] Of the vehicles that had a 10% greater battery size than current BEVs, one is a coach bus being considered as a fuel cell vehicle (see the following discussion in this subsection), two are sleeper cab tractors (32Tractor_SC_Cl8, 54Tractor_SC_Cl8, one is a shuttle bus (56B_Shuttle_Cl4-5_U), and one is a transit bus (86B_Transit_Cl6-7_MP).

The shuttle bus (56B_Shuttle_Cl4-5_U) has a battery size of 158 kWh in HD TRUCS and a comparable BEV has a battery size of 141 kWh. We considered this difference negligible and that shuttle buses should not be limited by battery volume in our analysis.

The transit bus (86B_Transit_Cl6-7_MP) has a battery size of 373 kWh in HD TRUCS and a comparable BEV has a battery size of 320 kWh. Even though this represents a 16 percent larger battery for this vehicle type in HD TRUCS, we did not consider the difference to limit the battery volume in our analysis. We made this determination based on comparisons to class 8 transit buses which are a similarly sized vehicle, but with much larger batteries, going up to 738 kWh.

The tractor 32Tractor_SC_Cl8 battery size in HD TRUCS is 973 kWh and the current comparable BEV has a battery size of 850 kWh. Even though the capacity of the battery of this vehicle is about 14 percent larger than the current comparable BEV, the battery volume of 2.46 cubic meters is about 18 percent smaller than the battery in the comparable BEV of 3.0 cubic meters.[1260] Since the physical size of the battery for 32Tractor_SC_Cl8 is smaller than the comparable current BEV, this vehicle is not limited by battery volume in our analysis.

The last vehicle with a battery larger than a comparable current BEV is 54Tractor_SC_Cl8, which has a battery size of 1,164 kWh in HD TRUCS and the comparable current BEV has a battery size of 850 kWh, an increase of 37% in battery size. The comparable current BEV in this instance is the Tesla Semi which has a battery volume of 3 cubic meters which is larger than the

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[1259] Miller, Neil. See Memorandum to docket EPA-HQ-OAR-2022_0985. BEV Battery Packaging Analysis. March 3, 2024.

[1260] Battery Design. 2022 Tesla Semi Specifications. Available online: https://www.batterydesign.net/2022-tesla-semi-specifications/.

battery volume calculated in HD TRUCS for this vehicle which has 2.94 cubic meters.[1261] The wheelbase of vehicle 54 in HD TRUCS is 143 inches while a typical tractor has a wheelbase between 245 and 265 inches and the Tesla Semi is cited with a wheelbase of 156 inches.[1262,1263] By allowing the wheelbase of vehicle 54 to increase from 143 inches, the battery volume of 2.94 cubic meters would be able to package on a sleeper cab semi with the same wheelbase as a Tesla Semi and therefore battery volume will not be a constraint for this vehicle. That said, we have determined that this vehicle would not be included within the technology package to support the potential compliance pathway due to our current assessment of potential near-term weight impact of the battery (see previous subsection).

Since hydrogen tanks take up considerable space, even at pressures up to 700 bar (just over 10,000 psi), we also assessed FCEV hydrogen tank packaging for tractors and specifically Class 8 sleeper cab tractors like vehicle 79Tractor_SC_Cl8. Due to having few HD FCEV vehicles in production, we relied on the FEV study to provide guidance on how HD FCEV may store and package hydrogen.[1264] FEV's analysis showed that six tanks, each with 12.8 kg of hydrogen (10.7 kg useable) at 700 bar, could fit on a wheelbase of 265 inches with a sleeper cab. In HD trucks, we set the FCEV sleeper cab tractor sizing VMT at 420 miles, the same as the operational VMT. The 43.6 kg of hydrogen needed for this range (according to HD TRUCS) is well below what FEV identified as feasible with their packaging study. See RTC Section 5.3 and RIA Chapter 1.7.3 for additional detail.

Several stakeholders raised significant concerns related to the ability of motorcoaches (referred to as coach buses in 40 CFR 1037.105(h) and in HD TRUCS) to perform their mission (transporting people and their luggage) using battery electric technology. Furthermore, commenters raised concerns regarding the infrastructure needs for electrified motorcoaches because these vehicles would need to rely on public enroute charging.

As described in Chapter 2.2.1.2, there are some existing BEV coach buses; however, these buses include less underfloor storage volume than comparable coach buses in the market today. As mentioned above, HD TRUCS includes both a BEV and FCEV coach bus. EPA contracted FEV to conduct an analysis of the packaging feasibility of a FCEV powertrain on a coach bus.[1265] FEV found that a FCEV powertrain would require the loss of 2-4 seats and 30% of the luggage volume. The capacity loss was driven by the space needed for the hydrogen tanks, fuel cell with BOP, and batteries. FEV did not conduct analysis of a BEV coach bus as the BEV powertrain size and weight (and capacity loss) were greater than the FCEV.

Due to our consideration of the potential concerns raised in comment and through our analyses, EPA's optional custom chassis standards for Coach Buses will remain unchanged from the Phase 2 MY 2027 CO_2 emission standards. Consistent with the concrete mixers and RVs in HD TRUCS, we are reflecting the adoption rate in the corresponding primary vocational

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[1261] Battery Design. 2022 Tesla Semi Specifications. Available online: https://www.batterydesign.net/2022-tesla-semi-specifications/.

[1262] Carabin Shaw. Facts About 18 Wheelers. Available online: https://www.carabinshaw.com/facts-about-18-wheelers.html.

[1263] Dimensions. Tesla Semi. Available online: https://www.dimensions.com/element/tesla-semi

[1264] FEV Consulting. "Heavy Duty Commercial Vehicles Class 4 to 8: Technology and Cost Evaluation for Electrified Powertrains—Final Report". Prepared for EPA. March 2024.

[1265] FEV Consulting. "Heavy Duty Commercial Vehicles Class 4 to 8: Technology and Cost Evaluation for Electrified Powertrains—Final Report". Prepared for EPA. March 2024.

standards; however, we limited the adoption rate of each coach bus to 14 percent in MY 2030 and 2032, due to potential impact on seat space and luggage capacity for ZEV coach buses.

2.9.1.3 Other Constraints

One commenter stated that utility vehicles may periodically have higher performance demands than typical daily operation, in particular, due to the need for their extensive use after weather events cause power outages. We agree and have consequently increased the sizing VMT of utility vehicles with a regional application (see Chapter 2.2.1.2) and limited the ZEV adoption rates of the regional utility HD TRUCS vehicle types in our HD TRUCS analysis and corresponding technology packages. Specifically, in HD TRUCS, vehicles 90T_Utility_Cl8_R, 92T_Utility_Cl6-7_R, 95T_Utility_Cl4-5_R, and 96T_Utility_Cl2b-3_R were assigned zero adoption in MY 2027 and capped at 14 percent ZEV adoption in MY 2030 and 2032. We chose to use the regional utility vehicles because they have higher daily VMT than the urban and multipurpose vocational vehicles and are therefore the most likely candidates for extensive use. While there is not a regulatory subcategory that applies exclusively to utility vehicles, this has the effect of lowering the overall utilization of ZEV technologies in our analysis for LHD and MHD vocational vehicles.

2.9.2 Payback

As explained in Chapter 2.8 above**,** after assessing the suitability of the technology and costs associated with ZEVs, EPA performed a payback calculation on each of the 101 HD TRUCS vehicles for the BEV technology and FCEV technology that we were considering for the technology packages for each use case for each MY in the MY 2027–2032 timeframe. The payback period was calculated by determining the number of years that it will take for the annual operational savings of a ZEV to offset the incremental upfront purchase price of a BEV or FCEV. For the NPRM, the upfront costs included the RPE multiplier of 1.42 discussed in RIA Chapter 3, accounted for the IRA section 13502 battery tax credit and IRA section 13403 vehicle tax credit as described in Chapters 2.4.3.1and 2.4.3.5, respectively, and included the charging infrastructure costs for depot-charged BEVs. The operating costs in the NPRM included the diesel, hydrogen, or charging costs, DEF costs, along with the maintenance and repair costs. The payback calculation in the NPRM was performed using a 10-year average of operational costs and compared to the incremental upfront cost of ICE vehicle and ZEV.

As explained in Chapter 2.8.8, in the final rule analysis, EPA made several changes when calculating the payback period for each of the 101 vehicles. Upfront cost includes the component technology costs and the associated battery tax credits and vehicle tax credits, the EVSE for depot-charged BEVs and an updated approach to accounting for associated EVSE tax credits, and now also accounts for the state sales tax and (as applicable) the Federal Excise tax. Operational costs in the final rule include the fuel costs and maintenance and repair costs considered in the NPRM (with updates to phase in the M&R scaling factor), along with the addition of the annual insurance cost and an annual ZEV registration fee. Lastly, the operational costs were determined on an annual basis for the final rule, instead of using a 10-year average.

The addition of State Sales Tax and Federal Excise Tax to upfront costs are simple additions to the technology costs. The reason for the last change in payback calculation method is because of the changes to how operational costs are computed in the analysis. As described in Chapter 2.2.1.2, operational VMT changes with the age of the vehicle based on the sourceType ID provided in MOVES. This change in VMT yields changing operational fuel costs as described in Chapters 2.3.4.3, 2.4.4.2 and 2.5.3.1, as well as changing M&R costs as described in Chapters 2.3.4.2, 2.4.4.1, and 2.5.3.2. In this modification, total fuel costs not only change with annual VMT but with the fuel price for that particular calendar year as well. Likewise, the M&R scaling factor also changed with the calendar year. Therefore, it became more appropriate to account for annual operating costs and to subtract those costs from the initial upfront costs. So, payback period in the final rule analysis is the number of years when the cumulative operating cost savings from purchasing a ZEV is equal to the initial upfront cost delta when compared to the comparable ICE vehicle. As in the NPRM, payback period typically occurs during some fractional part of a year. EPA defined the payback period as the first year where the cumulative operational cost savings for the purchase of a ZEV is greater than the initial additional upfront cost delta of the ZEV.

The payback results are shown in Table 2-97 and Table 2-98 for BEVs for MY 2027, MY 2030 and MY 2032, and in Table 2-100 for FCEVs for MY 2030 and MY 2032. The upfront costs include the incremental RPE cost difference between a ZEV powertrain (PT) and an ICE powertrain, plus the EVSE RPE, minus the applicable IRA vehicle tax credit. As discussed above and in RIA Chapter 2.2.1.1.3, for the final rule version of HD TRUCS, we have assessed each year of operation using the appropriate changes that occur over time for inputs such as VMT, maintenance and repair, and fuel costs; however, we are continuing to show a 10-year average operational costs value in tables such as those below, as a single value point of comparison. Appendix A includes each year of a 10-year schedule for VMT. Note that not all of the BEVs shown in these tables are included in the technology packages to support the final rule standards. We have only included BEVs that pay back in 10 years or less in our technology packages.

Table 2-97 Results of the BEV Payback Analysis for MY 2027[1266] (2022$)

Vehicle ID	ICE PT RPE + Sales Tax and FET ($/unit)	BEV PT RPE + Sales Tax and FET ($/unit)	EVSE RPE ($/unit)	IRA Vehicle Tax Credit ($/unit)	Average Annual ICE Operating ($/year)	Average Annual BEV Operating ($/year)	BEV Payback (years)
01V_Amb_Cl4-5_MP	45669	40544	13932	0	5885	3832	5
02V_Amb_Cl2b-3_MP	43602	39412	6966	0	8080	4887	2
03V_Amb_Cl4-5_U	45669	39245	13932	0	7049	4101	3
04V_Amb_Cl2b-3_U	43602	38074	13932	0	7091	4045	3
05T_Box_Cl8_MP	96937	77955	26007	0	15697	9296	2
06T_Box_Cl8_R	96937	79380	52014	0	14328	9313	7
07T_Box_Cl6-7_MP	48973	51018	13932	1947	8237	5099	5
08T_Box_Cl6-7_R	48973	53367	13932	4184	7963	5240	6
09T_Box_Cl8_U	85684	76608	52014	0	17657	9128	5
10T_Box_Cl6-7_U	48973	50044	13932	1020	8515	4847	4
11T_Box_Cl2b-3_U	42894	37433	6966	0	9949	5363	1
12T_Box_Cl2b-3_R	42894	40286	13932	0	9128	5728	4
13T_Box_Cl2b-3_MP	42894	38796	6966	0	9434	5537	1
14T_Box_Cl4-5_U	43040	37433	13932	0	6831	3862	3
15T_Box_Cl4-5_R	43040	40286	13932	0	6304	4126	6

[1266] Since our assessment of publicly-charged BEVs begins in MY 2030, there is no payback year listed for MY 2027 in Table 2-97 for those vehicles.

Vehicle ID	ICE PT RPE + Sales Tax and FET ($/unit)	BEV PT RPE + Sales Tax and FET ($/unit)	EVSE RPE ($/unit)	IRA Vehicle Tax Credit ($/unit)	Average Annual ICE Operating ($/year)	Average Annual BEV Operating ($/year)	BEV Payback (years)
16T_Box_Cl4-5_MP	43040	38796	6966	0	6500	3988	2
17B_Coach_Cl8_R	76281	157812	0	40000	31328	26704	NA
19C_Mix_Cl8_MP	85684	110590	52014	21283	35181	17068	3
20T_Dump_Cl8_U	96937	84845	52014	0	13093	6750	7
21T_Dump_Cl8_MP	96937	85493	26007	0	11489	6802	4
22T_Dump_Cl6-7_MP	48698	68212	26007	18581	12150	7187	6
23T_Dump_Cl8_U	85684	84845	52014	0	12804	6750	9
24T_Dump_Cl6-7_U	48698	65386	52014	15891	12907	6935	9
25T_Fire_Cl8_MP	96937	88024	52014	0	12376	7004	8
26T_Fire_Cl8_U	85684	88136	52014	2095	13905	7013	8
27T_Flat_Cl6-7_MP	48698	50871	13932	2070	8229	5095	5
28T_Flat_Cl6-7_R	48698	53220	26007	4306	8106	5319	10
29T_Flat_Cl6-7_U	48698	48804	13932	101	8686	4898	4
30Tractor_DC_Cl8	102128	106686	42148	3895	19331	13388	8
31Tractor_DC_Cl7	80312	91530	31611	9587	17384	11941	6
32Tractor_SC_Cl8	105942	214205	0	40000	72143	60467	NA
33Tractor_DC_Cl8	81291	135847	0	40000	39247	31864	NA
34T_Ref_Cl8_MP	80656	95977	52014	13093	19825	9158	5
35T_Ref_Cl6-7_MP	48698	70184	52014	20459	23648	12579	5
36T_Ref_Cl8_U	80656	95977	52014	13093	19825	9158	5
37T_Ref_Cl6-7_U	48698	69574	52014	19878	25333	12479	5
38RV_Cl8_R	56701	131782	13932	40000	3450	4545	>15*
39RV_Cl6-7_R	48821	119775	13932	40000	3416	4622	>15*
40RV_Cl4-5_R	42131	82238	13932	38190	2806	3344	>15*
42RV_Cl8_MP	56701	131782	13932	40000	3450	4545	>15*
43RV_Cl6-7_MP	48821	111830	13932	40000	3453	4348	>15*
44RV_Cl4-5_MP	42131	77170	13932	33364	2867	3170	>15*
46B_School_Cl8_MP	56701	78984	26007	19042	10885	7546	9
47B_School_Cl6-7_MP	48821	49863	13932	992	10646	5884	4
48B_School_Cl4-5_MP	42131	40544	6966	0	7730	4840	3
49B_School_Cl2b-3_MP	44153	39612	6966	0	7788	4730	1
50B_School_Cl8_U	56701	76489	13932	16910	12485	7306	4
51B_School_Cl6-7_U	48821	49863	13932	992	10646	5884	4
52B_School_Cl4-5_U	42131	39245	6966	0	8138	4701	2
53B_School_Cl2b-3_U	44153	38274	6966	0	8196	4586	1
54Tractor_SC_Cl8	105942	248045	0	40000	72143	68463	NA
55B_Shuttle_Cl2b-3_MP	44153	47777	13932	3451	17267	9938	3
56B_Shuttle_Cl4-5_U	42131	46711	13932	4361	18210	9787	2
57B_Shuttle_Cl2b-3_U	44153	45740	13932	1511	18267	9618	2
58B_Shuttle_Cl6-7_MP	48821	66312	26007	16655	21236	12509	4
59B_Shuttle_Cl6-7_U	48821	63275	52014	13763	22555	12031	6
60S_Plow_Cl6-7_MP	48698	55818	13932	6780	9024	5356	4
61S_Plow_Cl8_MP	96937	104658	52014	6598	12444	7717	12*
62S_Plow_Cl6-7_U	48698	53811	26007	4869	9561	5178	6
63S_Plow_Cl8_U	85684	103476	52014	15204	13929	7637	9
64V_Step_Cl6-7_MP	48594	50965	13932	2258	11839	6968	4
65V_Step_Cl4-5_MP	42131	38796	6966	0	6474	3988	2
66V_Step_Cl2b-3_MP	43602	38729	6966	0	9265	5434	1
67V_Step_Cl6-7_U	48594	48882	13932	274	12537	6698	3

Vehicle ID	ICE PT RPE + Sales Tax and FET ($/unit)	BEV PT RPE + Sales Tax and FET ($/unit)	EVSE RPE ($/unit)	IRA Vehicle Tax Credit ($/unit)	Average Annual ICE Operating ($/year)	Average Annual BEV Operating ($/year)	BEV Payback (years)
68V_Step_Cl4-5_U	42131	37433	13932	0	6805	3862	4
69V_Step_Cl2b-3_U	43602	37366	13932	0	9770	5262	2
70S_Sweep_Cl6-7_U	48698	53055	13932	4149	12183	6280	3
71T_Tanker_Cl8_R	96937	82514	52014	0	13090	8197	8
72T_Tanker_Cl8_MP	85684	81629	26007	0	13812	8105	4
73T_Tanker_Cl8_U	85684	81384	52014	0	15880	8080	6
74T_Tow_Cl8_R	99968	107988	52014	6854	15798	10236	10
75T_Tow_Cl6-7_R	48698	71929	52014	22121	11928	7494	14*
76T_Tow_Cl8_U	85684	105650	52014	17062	19275	10032	6
77T_Tow_Cl6-7_U	48698	65566	52014	16062	12887	6930	9
78Tractor_SC_Cl8	105942	189518	0	40000	52307	49346	NA
80Tractor_DC_Cl8	107145	156714	47704	40000	26905	18970	8
81Tractor_DC_Cl7	80312	129470	0	40000	36123	31698	NA
82Tractor_DC_Cl8	105943	158615	0	40000	39872	36204	NA
83Tractor_DC_Cl7	80312	116699	42148	31095	21064	14828	8
84Tractor_DC_Cl8	99430	106496	0	6039	23224	20762	NA
85B_Transit_Cl8_MP	76281	115477	63222	33496	33123	17183	5
86B_Transit_Cl6-7_MP	48821	83670	52014	33183	14894	9518	10
87B_Transit_Cl8_U	75366	115477	63222	34277	33100	17183	5
88B_Transit_Cl6-7_U	48821	78684	52014	28435	15791	9078	8
89T_Utility_Cl8_MP	96937	79855	26007	0	8493	5134	3
90T_Utility_Cl8_R	96937	81001	52014	0	7971	5210	15*
91T_Utility_Cl6-7_MP	48698	53438	13932	4514	10814	6212	4
92T_Utility_Cl6-7_R	48698	55633	26007	6603	10635	6456	7
93T_Utility_Cl4-5_MP	45669	40604	13932	0	8800	4998	3
94T_Utility_Cl2b-3_MP	43602	39557	13932	0	4676	2904	6
95T_Utility_Cl4-5_R	45669	41920	13932	0	8337	5056	4
96T_Utility_Cl2b-3_R	43602	41854	13932	0	8278	5054	4
97T_Utility_Cl8_U	85684	79078	52014	0	9275	5083	12*
98T_Utility_Cl6-7_U	48698	51733	13932	2890	11477	6023	3
99T_Utility_Cl4-5_U	45669	39512	13932	0	9303	4877	2
100T_Utility_Cl2b-3_U	43602	38317	13932	0	4906	2821	5
101Tractor_DC_Cl8	99430	92831	31611	0	12952	9053	7

Note: We did not include BEVs in our technology package for those vehicle types with a payback period of longer than 10 years; these vehicle types are marked with an * in the table. Vehicles indicated with a "NA" are considered to be publicly-charged BEVs that are not included in the technology packages prior to MY 2030.

Table 2-98 Results of the BEV Payback Analysis for MY 2030 (2022$)

Vehicle ID	ICE PT RPE + Sales Tax and FET ($/unit)	BEV PT RPE + Sales Tax and FET ($/unit)	EVSE RPE ($/unit)	IRA Vehicle Tax Credit ($/unit)	Average Annual ICE Operating ($/year)	Average Annual BEV Operating ($/year)	BEV Payback (years)
01V_Amb_Cl4-5_MP	45212	32934	13932	0	5896	3537	1
02V_Amb_Cl2b-3_MP	43166	32086	6966	0	8105	4565	0

Vehicle ID	ICE PT RPE + Sales Tax and FET ($/unit)	BEV PT RPE + Sales Tax and FET ($/unit)	EVSE RPE ($/unit)	IRA Vehicle Tax Credit ($/unit)	Average Annual ICE Operating ($/year)	Average Annual BEV Operating ($/year)	BEV Payback (years)
03V_Amb_Cl4-5_U	45212	31969	13932	0	7069	3804	1
04V_Amb_Cl2b-3_U	43166	31092	13932	0	7112	3756	1
05T_Box_Cl8_MP	95967	62284	26007	0	15759	8708	0
06T_Box_Cl8_R	95967	63342	52014	0	14378	8713	4
07T_Box_Cl6-7_MP	48483	41026	13932	0	8265	4714	2
08T_Box_Cl6-7_R	48483	42770	13932	0	7989	4835	3
09T_Box_Cl8_U	84828	61283	52014	0	17743	8550	4
10T_Box_Cl6-7_U	48483	40303	13932	0	8547	4474	2
11T_Box_Cl2b-3_U	42465	30624	6966	0	9986	5036	0
12T_Box_Cl2b-3_R	42465	32742	13932	0	9157	5376	2
13T_Box_Cl2b-3_MP	42465	31636	6966	0	9466	5198	0
14T_Box_Cl4-5_U	42609	30624	13932	0	6850	3582	1
15T_Box_Cl4-5_R	42609	32742	13932	0	6318	3822	2
16T_Box_Cl4-5_MP	42609	31636	6966	0	6516	3697	0
17B_Coach_Cl8_R	75518	121231	0	39065	31495	25342	2
19C_Mix_Cl8_MP	84828	86514	52014	1442	35420	16129	3
20T_Dump_Cl8_U	95967	67399	52014	0	13145	6188	4
21T_Dump_Cl8_MP	95967	67881	26007	0	11527	6235	0
22T_Dump_Cl6-7_MP	48211	53776	26007	5299	12206	6631	5
23T_Dump_Cl8_U	84828	67399	52014	0	12860	6188	5
24T_Dump_Cl6-7_U	48211	51678	52014	3301	12970	6403	8
25T_Fire_Cl8_MP	95967	69760	52014	0	12422	6418	5
26T_Fire_Cl8_U	84828	69843	52014	0	13970	6426	5
27T_Flat_Cl6-7_MP	48211	40901	13932	0	8258	4710	2
28T_Flat_Cl6-7_R	48211	42645	26007	0	8133	4914	7

Vehicle ID	ICE PT RPE + Sales Tax and FET ($/unit)	BEV PT RPE + Sales Tax and FET ($/unit)	EVSE RPE ($/unit)	IRA Vehicle Tax Credit ($/unit)	Average Annual ICE Operating ($/year)	Average Annual BEV Operating ($/year)	BEV Payback (years)
29T_Flat_Cl6-7_U	48211	39365	13932	0	8718	4530	2
30Tractor_DC_Cl8	101106	85108	42148	0	19409	12555	4
31Tractor_DC_Cl7	79508	72789	31611	0	17455	11198	4
32Tractor_SC_Cl8	104883	164610	0	40000	72536	58080	2
33Tractor_DC_Cl8	80478	106435	0	22182	39459	30528	1
34T_Ref_Cl8_MP	79850	75471	52014	0	19942	8472	4
35T_Ref_Cl6-7_MP	48211	55240	52014	6693	23791	11886	5
36T_Ref_Cl8_U	79850	75471	52014	0	19942	8472	4
37T_Ref_Cl6-7_U	48211	54787	52014	6262	25492	11792	4
38RV_Cl8_R	56134	101904	13932	39113	3448	3752	>15*
39RV_Cl6-7_R	48333	92089	13932	40000	3415	3803	>15*
40RV_Cl4-5_R	41709	63891	13932	21121	2802	2795	>15*
42RV_Cl8_MP	56134	101904	13932	39113	3448	3752	>15*
43RV_Cl6-7_MP	48333	86189	13932	36047	3452	3588	>15*
44RV_Cl4-5_MP	41709	60128	13932	17538	2864	2658	>15*
46B_School_Cl8_MP	56134	62703	26007	5613	10931	6994	7
47B_School_Cl6-7_MP	48333	40180	13932	0	10690	5486	2
48B_School_Cl4-5_MP	41709	32934	6966	0	7753	4517	0
49B_School_Cl2b-3_MP	43711	32258	6966	0	7810	4415	0
50B_School_Cl8_U	56134	60850	13932	4030	12546	6773	3
51B_School_Cl6-7_U	48333	40180	13932	0	10690	5486	2
52B_School_Cl4-5_U	41709	31969	6966	0	8164	4389	0
53B_School_Cl2b-3_U	43711	31264	6966	0	8221	4283	0
54Tractor_SC_Cl8	104883	189736	0	40000	72536	65783	8
55B_Shuttle_Cl2b-3_MP	43711	38320	13932	0	17339	9413	2
56B_Shuttle_Cl4-5_U	41709	37513	13932	0	18291	9272	2

Vehicle ID	ICE PT RPE + Sales Tax and FET ($/unit)	BEV PT RPE + Sales Tax and FET ($/unit)	EVSE RPE ($/unit)	IRA Vehicle Tax Credit ($/unit)	Average Annual ICE Operating ($/year)	Average Annual BEV Operating ($/year)	BEV Payback (years)
57B_Shuttle_Cl2b-3_U	43711	36807	13932	0	18349	9112	1
58B_Shuttle_Cl6-7_MP	48333	52393	26007	3866	21342	11824	3
59B_Shuttle_Cl6-7_U	48333	50138	52014	1719	22673	11375	5
60S_Plow_Cl6-7_MP	48211	44574	13932	0	9059	4933	3
61S_Plow_Cl8_MP	95967	82110	52014	0	12488	7012	7
62S_Plow_Cl6-7_U	48211	43083	26007	0	9601	4771	5
63S_Plow_Cl8_U	84828	81233	52014	0	13993	6940	7
64V_Step_Cl6-7_MP	48108	40959	13932	0	11890	6529	2
65V_Step_Cl4-5_MP	41709	31636	6966	0	6490	3697	0
66V_Step_Cl2b-3_MP	43166	31578	6966	0	9295	5096	0
67V_Step_Cl6-7_U	48108	39411	13932	0	12594	6277	1
68V_Step_Cl4-5_U	41709	30624	13932	0	6825	3582	1
69V_Step_Cl2b-3_U	43166	30567	13932	0	9805	4936	1
70S_Sweep_Cl6-7_U	48211	42522	13932	0	12243	5850	2
71T_Tanker_Cl8_R	95967	65669	52014	0	13136	7613	4
72T_Tanker_Cl8_MP	84828	65011	26007	0	13871	7529	2
73T_Tanker_Cl8_U	84828	64830	52014	0	15958	7505	4
74T_Tow_Cl8_R	98968	84583	52014	0	15861	9449	6
75T_Tow_Cl6-7_R	48211	56536	52014	7927	11982	6908	11*
76T_Tow_Cl8_U	84828	82847	52014	0	19378	9262	5
77T_Tow_Cl6-7_U	48211	51811	52014	3428	12950	6397	8
78Tractor_SC_Cl8	104883	146280	0	35376	52579	47390	3
80Tractor_DC_Cl8	106074	121967	47704	13581	27046	17727	6
81Tractor_DC_Cl7	79508	100959	0	18330	36306	30385	2
82Tractor_DC_Cl8	104883	123843	0	16202	40077	34692	2

Vehicle ID	ICE PT RPE + Sales Tax and FET ($/unit)	BEV PT RPE + Sales Tax and FET ($/unit)	EVSE RPE ($/unit)	IRA Vehicle Tax Credit ($/unit)	Average Annual ICE Operating ($/year)	Average Annual BEV Operating ($/year)	BEV Payback (years)
83Tractor_DC_Cl7	79508	91477	42148	10228	21157	13857	6
84Tractor_DC_Cl8	98436	84838	0	0	23328	19861	0
85B_Transit_Cl8_MP	75518	89798	63222	12204	33319	16163	4
86B_Transit_Cl6-7_MP	48333	65281	52014	16138	14962	8800	9
87B_Transit_Cl8_U	74613	89798	63222	12977	33296	16163	4
88B_Transit_Cl6-7_U	48333	61579	52014	12613	15867	8401	8
89T_Utility_Cl8_MP	95967	63695	26007	0	8510	4643	0
90T_Utility_Cl8_R	95967	64545	52014	0	7982	4710	7
91T_Utility_Cl6-7_MP	48211	42806	13932	0	10862	5781	2
92T_Utility_Cl6-7_R	48211	44436	26007	0	10681	6006	5
93T_Utility_Cl4-5_MP	45212	32979	13932	0	8830	4667	1
94T_Utility_Cl2b-3_MP	43166	32193	13932	0	4683	2642	2
95T_Utility_Cl4-5_R	45212	33956	13932	0	8364	4713	1
96T_Utility_Cl2b-3_R	43166	33898	13932	0	8305	4711	2
97T_Utility_Cl8_U	84828	63118	52014	0	9304	4598	7
98T_Utility_Cl6-7_U	48211	41540	13932	0	11531	5607	2
99T_Utility_Cl4-5_U	45212	32167	13932	0	9338	4555	1
100T_Utility_Cl2b-3_U	43166	31273	13932	0	4915	2570	1
101Tractor_DC_Cl8	98436	74692	31611	0	12992	8414	2
Note: We did not include BEVs in our technology package for those vehicle types with a payback period of longer than 10 years; these vehicle types are marked with an * in the table.							

Table 2-99 Results of the BEV Payback Analysis for MY 2032 (2022$)

Vehicle ID	ICE PT RPE + Sales Tax and FET ($/unit)	BEV PT RPE + Sales Tax and FET ($/unit)	EVSE RPE ($/unit)	IRA Vehicle Tax Credit ($/unit)	Average Annual ICE Operating ($/year)	Average Annual BEV Operating ($/year)	BEV Payback (years)
01V_Amb_Cl4-5_MP	44755	33541	13932	0	5905	3539	2
02V_Amb_Cl2b-3_MP	42730	32603	6966	0	8126	4558	0

Vehicle ID	ICE PT RPE + Sales Tax and FET ($/unit)	BEV PT RPE + Sales Tax and FET ($/unit)	EVSE RPE ($/unit)	IRA Vehicle Tax Credit ($/unit)	Average Annual ICE Operating ($/year)	Average Annual BEV Operating ($/year)	BEV Payback (years)
03V_Amb_Cl4-5_U	44755	32462	13932	0	7085	3802	1
04V_Amb_Cl2b-3_U	42730	31492	13932	0	7129	3750	1
05T_Box_Cl8_MP	94998	64303	26007	0	15815	8724	0
06T_Box_Cl8_R	94998	65485	52014	0	14423	8733	4
07T_Box_Cl6-7_MP	47993	42164	13932	0	8290	4727	3
08T_Box_Cl6-7_R	47993	44113	13932	0	8012	4854	4
09T_Box_Cl8_U	83971	63184	52014	0	17821	8564	4
10T_Box_Cl6-7_U	47993	41355	13932	0	8574	4485	2
11T_Box_Cl2b-3_U	42036	30959	6966	0	10019	5020	0
12T_Box_Cl2b-3_R	42036	33326	13932	0	9183	5367	2
13T_Box_Cl2b-3_MP	42036	32090	6966	0	9494	5186	0
14T_Box_Cl4-5_U	42179	30959	13932	0	6867	3576	1
15T_Box_Cl4-5_R	42179	33326	13932	0	6330	3822	3
16T_Box_Cl4-5_MP	42179	32090	6966	0	6530	3694	0
17B_Coach_Cl8_R	74755	130647	0	40000	31648	25500	4
19C_Mix_Cl8_MP	83971	91384	52014	6335	35636	16192	3
20T_Dump_Cl8_U	94998	70020	52014	0	13191	6233	4
21T_Dump_Cl8_MP	94998	70558	26007	0	11559	6281	1
22T_Dump_Cl6-7_MP	47724	56436	26007	8296	12256	6680	5
23T_Dump_Cl8_U	83971	70020	52014	0	12909	6233	6
24T_Dump_Cl6-7_U	47724	54091	52014	6062	13027	6445	8
25T_Fire_Cl8_MP	94998	72658	52014	0	12462	6470	5
26T_Fire_Cl8_U	83971	72751	52014	0	14029	6478	6
27T_Flat_Cl6-7_MP	47724	42046	13932	0	8282	4724	3
28T_Flat_Cl6-7_R	47724	43995	26007	0	8157	4933	7
29T_Flat_Cl6-7_U	47724	40330	13932	0	8747	4539	2
30Tractor_DC_Cl8	100085	88389	42148	0	19480	12587	5
31Tractor_DC_Cl7	78705	76044	31611	0	17520	11232	5
32Tractor_SC_Cl8	103824	177685	0	40000	72892	58203	3
33Tractor_DC_Cl8	79665	112659	0	28195	39654	30578	1
34T_Ref_Cl8_MP	79043	79300	52014	220	20047	8540	5
35T_Ref_Cl6-7_MP	47724	58073	52014	9854	23919	11916	5
36T_Ref_Cl8_U	79043	79300	52014	220	20047	8540	5
37T_Ref_Cl6-7_U	47724	57566	52014	9372	25634	11820	4
38RV_Cl8_R	55567	109046	13932	40000	3444	3930	>15*
39RV_Cl6-7_R	47845	99220	13932	40000	3412	4002	>15*
40RV_Cl4-5_R	41288	68140	13932	25568	2798	2912	>15*
42RV_Cl8_MP	55567	109046	13932	40000	3444	3930	>15*
43RV_Cl6-7_MP	47845	92626	13932	40000	3449	3767	>15*
44RV_Cl4-5_MP	41288	63934	13932	21564	2860	2762	>15*
46B_School_Cl8_MP	55567	65231	26007	8258	10974	7032	7
47B_School_Cl6-7_MP	47845	41203	13932	0	10730	5491	2
48B_School_Cl4-5_MP	41288	33541	6966	0	7772	4513	0
49B_School_Cl2b-3_MP	43270	32764	6966	0	7829	4409	0
50B_School_Cl8_U	55567	63161	13932	6489	12602	6806	3
51B_School_Cl6-7_U	47845	41203	13932	0	10730	5491	2
52B_School_Cl4-5_U	41288	32462	6966	0	8188	4382	0
53B_School_Cl2b-3_U	43270	31653	6966	0	8244	4274	0
54Tractor_SC_Cl8	103824	205768	0	40000	72892	65968	10

Vehicle ID	ICE PT RPE + Sales Tax and FET ($/unit)	BEV PT RPE + Sales Tax and FET ($/unit)	EVSE RPE ($/unit)	IRA Vehicle Tax Credit ($/unit)	Average Annual ICE Operating ($/year)	Average Annual BEV Operating ($/year)	BEV Payback (years)
55B_Shuttle_Cl2b-3_MP	43270	39539	13932	0	17405	9398	2
56B_Shuttle_Cl4-5_U	41288	38658	13932	0	18366	9255	2
57B_Shuttle_Cl2b-3_U	43270	37849	13932	0	18423	9092	1
58B_Shuttle_Cl6-7_MP	47845	54853	26007	6673	21439	11838	3
59B_Shuttle_Cl6-7_U	47845	52333	52014	4274	22782	11383	5
60S_Plow_Cl6-7_MP	47724	46151	13932	0	9091	4958	3
61S_Plow_Cl8_MP	94998	86462	52014	0	12527	7100	8
62S_Plow_Cl6-7_U	47724	44485	26007	0	9638	4792	5
63S_Plow_Cl8_U	83971	85481	52014	1291	14049	7025	8
64V_Step_Cl6-7_MP	47622	42126	13932	0	11935	6534	2
65V_Step_Cl4-5_MP	41288	32090	6966	0	6504	3694	0
66V_Step_Cl2b-3_MP	42730	32036	6966	0	9323	5083	0
67V_Step_Cl6-7_U	47622	40397	13932	0	12645	6277	2
68V_Step_Cl4-5_U	41288	30959	13932	0	6841	3576	2
69V_Step_Cl2b-3_U	42730	30905	13932	0	9837	4920	1
70S_Sweep_Cl6-7_U	47724	43858	13932	0	12296	5863	2
71T_Tanker_Cl8_R	94998	68086	52014	0	13176	7646	5
72T_Tanker_Cl8_MP	83971	67351	26007	0	13923	7560	2
73T_Tanker_Cl8_U	83971	67148	52014	0	16028	7536	4
74T_Tow_Cl8_R	97968	89226	52014	0	15917	9532	7
75T_Tow_Cl6-7_R	47724	59521	52014	11233	12030	6965	11*
76T_Tow_Cl8_U	83971	87285	52014	2833	19470	9340	5
77T_Tow_Cl6-7_U	47724	54240	52014	6205	13007	6440	8
78Tractor_SC_Cl8	103824	157198	0	40000	52826	47508	4
80Tractor_DC_Cl8	105003	129967	47704	21334	27173	17865	6
81Tractor_DC_Cl7	78705	107528	0	24630	36475	30443	2
82Tractor_DC_Cl8	103824	131444	0	23603	40266	34770	2
83Tractor_DC_Cl7	78705	96930	42148	15574	21242	13935	6
84Tractor_DC_Cl8	97441	88260	0	0	23423	19883	0
85B_Transit_Cl8_MP	74755	95515	63222	17741	33499	16239	4
86B_Transit_Cl6-7_MP	47845	69258	52014	20389	15023	8876	9
87B_Transit_Cl8_U	73859	95515	63222	18506	33476	16239	4
88B_Transit_Cl6-7_U	47845	65120	52014	16449	15937	8465	8
89T_Utility_Cl8_MP	94998	65880	26007	0	8523	4685	0
90T_Utility_Cl8_R	94998	66830	52014	0	7991	4754	8
91T_Utility_Cl6-7_MP	47724	44176	13932	0	10904	5796	3
92T_Utility_Cl6-7_R	47724	45997	26007	0	10722	6026	5
93T_Utility_Cl4-5_MP	44755	33591	13932	0	8857	4662	1
94T_Utility_Cl2b-3_MP	42730	32723	13932	0	4688	2647	2
95T_Utility_Cl4-5_R	44755	34683	13932	0	8387	4712	2
96T_Utility_Cl2b-3_R	42730	34629	13932	0	8329	4710	2
97T_Utility_Cl8_U	83971	65235	52014	0	9330	4637	7
98T_Utility_Cl6-7_U	47724	42761	13932	0	11579	5618	2
99T_Utility_Cl4-5_U	44755	32684	13932	0	9368	4548	1
100T_Utility_Cl2b-3_U	42730	31694	13932	0	4923	2572	2
101Tractor_DC_Cl8	97441	76919	31611	0	13027	8439	3

Note: We did not include BEVs in our technology package for those vehicle types with a payback period of longer than 10 years; these vehicle types are marked with an * in the table.

Table 2-100 Results of the FCEV Payback Analysis for MY 2030 (2022$)

Vehicle ID	ICE PT RPE + Sales Tax and FET ($/unit)	FCEV PT RPE + Sales Tax and FET ($/unit)	IRA Vehicle Tax Credit ($/unit)	Average Annual ICE Operating ($/year)	Average Annual FCEV Operating ($/year)	FCEV Payback (years)
18B_Coach_Cl8_MP	75518	140378	40000	31495	27011	8
41Tractor_DC_Cl7	79508	134151	40000	36306	33348	8
45Tractor_DC_Cl8	104883	176819	40000	40077	38405	>15*
79Tractor_SC_Cl8	104883	180139	40000	72536	69973	12
Note: We did not include FCEVs in our technology package for those vehicle types with a payback period of longer than 10 years; these vehicle types are marked with an * in the table.						

Table 2-101 Results of the FCEV Payback Analysis for MY 2032 (2022$)

Vehicle ID	ICE PT RPE + Sales Tax and FET ($/unit)	FCEV PT RPE + Sales Tax and FET ($/unit)	IRA Vehicle Tax Credit ($/unit)	Average Annual ICE Operating ($/year)	Average Annual FCEV Operating ($/year)	FCEV Payback (years)
18B_Coach_Cl8_MP	74755	132431	40000	31648	25161	4
41Tractor_DC_Cl7	78705	127555	40000	36475	30961	4
45Tractor_DC_Cl8	103824	168261	40000	40266	35618	7
79Tractor_SC_Cl8	103824	170436	40000	72892	64953	6

2.9.3 HD TRUCS Results

The technology packages for our modeled potential compliance pathway includes vehicles with ICE powertrains and vehicles with ZEV powertrains. In our analysis, the ICE vehicles include a suite of technologies that represent a vehicle that meets the previous MY 2027 Phase 2 CO_2 emission standards. These technologies exist today and continue to evolve to improve the efficiency of the engine, transmission, drivetrain, aerodynamics, and tire rolling resistance in HD vehicles and therefore reduce their CO_2 emissions. In addition, the heavy-duty industry continues to develop CO_2-reducing technologies such as hybrid powertrains and H2-ICE powered vehicles, also discussed in preamble Section II.F.4. These further technology improvements are not part of the modeled potential compliance pathway's technology packages on which the final rule is predicated but are available to any manufacturer determining its own compliance pathway.

After the technology assessment, as described in preamble Section II.D.4 and the preceding sections of this RIA Chapter 2, and the payback analysis, as just described, EPA determined the technology mix of ICE vehicle and ZEV technologies for the technology package for each regulatory subcategory. We first determined the ZEVs that are appropriate for each of the 101 vehicle types for MYs 2027, MY 2030, and 2032 based on their technical feasibility and payback, as shown in Table 2-97 through Table 2-101. Table 2-102 shows the total vehicle sales fraction, the regulatory subcategory grouping and the ZEV adoption rate percentages that correspond to the payback years for MY 2027, MY2030, and MY 2032.

Table 2-102 ZEV Percentages by HD TRUCS Vehicle Type

Vehicle ID*	Sales %	Regulatory Group[a]	MY 2027 ZEV Percentage	MY 2030 ZEV Percentage	MY 2032 ZEV Percentage
01V_Amb_Cl4-5_MP	1.69%	LHD	14%	37%	70%
02V_Amb_Cl2b-3_MP	1.69%	LHD	20%	37%	70%
03V_Amb_Cl4-5_U	1.69%	LHD	20%	37%	70%
04V_Amb_Cl2b-3_U	1.69%	LHD	20%	37%	70%
05T_Box_Cl8_MP	0.34%	HHD	20%	37%	70%
06T_Box_Cl8_R	0.29%	HHD	14%	26%	39%
07T_Box_Cl6-7_MP	0.77%	MHD	14%	37%	39%
08T_Box_Cl6-7_R	0.58%	MHD	14%	26%	39%
09T_Box_Cl8_U	0.34%	HHD	14%	26%	39%
10T_Box_Cl6-7_U	0.77%	MHD	20%	37%	70%
11T_Box_Cl2b-3_U	1.69%	LHD	20%	37%	70%
12T_Box_Cl2b-3_R	1.69%	LHD	20%	37%	70%
13T_Box_Cl2b-3_MP	1.69%	LHD	20%	37%	70%
14T_Box_Cl4-5_U	1.69%	LHD	20%	37%	70%
15T_Box_Cl4-5_R	1.69%	LHD	14%	37%	39%
16T_Box_Cl4-5_MP	1.69%	LHD	20%	37%	70%
17B_Coach_Cl8_R	0.21%	HHD/Coach Bus	0%	14%	14%
18B_Coach_Cl8_MP	0.21%	HHD/Coach Bus	0%	5%	14%
19C_Mix_Cl8_MP	0.34%	HHD/Concrete Mixer	20%	26%	39%
20T_Dump_Cl8_U	0.54%	HHD	14%	26%	39%
21T_Dump_Cl8_MP	0.54%	HHD	20%	37%	70%
22T_Dump_Cl6-7_MP	1.45%	MHD	14%	14%	14%
23T_Dump_Cl8_U	0.54%	HHD	5%	14%	14%
24T_Dump_Cl6-7_U	1.45%	MHD	5%	5%	5%
25T_Fire_Cl8_MP	0.34%	HHD	5%	14%	14%
26T_Fire_Cl8_U	0.34%	HHD	5%	14%	14%
27T_Flat_Cl6-7_MP	0.77%	MHD	14%	37%	39%
28T_Flat_Cl6-7_R	0.77%	MHD	5%	14%	14%
29T_Flat_Cl6-7_U	0.77%	MHD	20%	37%	70%
30Tractor_DC_Cl8	3.33%	DC	5%	26%	14%
31Tractor_DC_Cl7	1.70%	DC	14%	26%	14%
32Tractor_SC_Cl8	2.70%	SC	0%	37%	39%
33Tractor_DC_Cl8	1.51%	DC	0%	37%	70%
34T_Ref_Cl8_MP	0.21%	HHD/Refuse Hauler	14%	26%	14%
35T_Ref_Cl6-7_MP	0.04%	MHD/Refuse Hauler	14%	14%	14%
36T_Ref_Cl8_U	0.21%	HHD/Refuse Hauler	14%	26%	14%
37T_Ref_Cl6-7_U	0.04%	MHD/Refuse Hauler	14%	26%	39%
38RV_Cl8_R	0.38%	HHD	0%	0%	0%
39RV_Cl6-7_R	0.66%	MHD	0%	0%	0%
40RV_Cl4-5_R	1.40%	LHD	0%	0%	0%
41Tractor_DC_Cl7	1.04%	DC	0%	5%	39%
42RV_Cl8_MP	0.38%	HHD	0%	0%	0%

Vehicle ID*	Sales %	Regulatory Group[a]	MY 2027 ZEV Percentage	MY 2030 ZEV Percentage	MY 2032 ZEV Percentage
43RV_Cl6-7_MP	0.66%	MHD	0%	0%	0%
44RV_Cl4-5_MP	1.40%	LHD	0%	0%	0%
45Tractor_DC_Cl8	1.51%	DC	0%	0%	14%
46B_School_Cl8_MP	0.15%	HHD/School Bus	5%	14%	14%
47B_School_Cl6-7_MP	1.98%	MHD/School Bus	20%	37%	70%
48B_School_Cl4-5_MP	0.07%	LHD/School Bus	20%	37%	70%
49B_School_Cl2b-3_MP	0.07%	LHD/School Bus	20%	37%	70%
50B_School_Cl8_U	0.15%	HHD/School Bus	20%	26%	39%
51B_School_Cl6-7_U	1.98%	MHD/School Bus	20%	37%	70%
52B_School_Cl4-5_U	0.07%	LHD/School Bus	20%	37%	70%
53B_School_Cl2b-3_U	0.07%	LHD/School Bus	20%	37%	70%
54Tractor_SC_Cl8	0.00%	SC	0%	0%	0%
55B_Shuttle_Cl2b-3_MP	0.31%	LHD	20%	37%	70%
56B_Shuttle_Cl4-5_U	0.53%	LHD	20%	37%	70%
57B_Shuttle_Cl2b-3_U	0.53%	LHD	20%	37%	70%
58B_Shuttle_Cl6-7_MP	0.01%	MHD	20%	26%	39%
59B_Shuttle_Cl6-7_U	0.07%	MHD	14%	14%	14%
60S_Plow_Cl6-7_MP	0.08%	MHD	20%	26%	39%
61S_Plow_Cl8_MP	0.05%	HHD	0%	14%	5%
62S_Plow_Cl6-7_U	0.08%	MHD	14%	14%	14%
63S_Plow_Cl8_U	0.05%	HHD	5%	14%	5%
64V_Step_Cl6-7_MP	0.77%	MHD	20%	37%	70%
65V_Step_Cl4-5_MP	1.69%	LHD	20%	37%	70%
66V_Step_Cl2b-3_MP	0.30%	LHD	20%	37%	70%
67V_Step_Cl6-7_U	0.77%	MHD	20%	37%	70%
68V_Step_Cl4-5_U	1.69%	LHD	20%	37%	70%
69V_Step_Cl2b-3_U	0.30%	LHD	20%	37%	70%
70S_Sweep_Cl6-7_U	0.77%	MHD	20%	37%	70%
71T_Tanker_Cl8_R	0.34%	HHD	5%	26%	14%
72T_Tanker_Cl8_MP	0.34%	HHD	20%	37%	70%
73T_Tanker_Cl8_U	0.34%	HHD	14%	26%	39%
74T_Tow_Cl8_R	0.34%	HHD	5%	14%	14%
75T_Tow_Cl6-7_R	0.77%	MHD	0%	0%	0%
76T_Tow_Cl8_U	0.34%	HHD	14%	14%	14%
77T_Tow_Cl6-7_U	0.77%	MHD	5%	5%	5%
78Tractor_SC_Cl8	5.30%	SC	0%	26%	39%
79Tractor_SC_Cl8	10.90%	SC	0%	0%	14%
80Tractor_DC_Cl8	0.34%	HH Tractor	5%	14%	14%
81Tractor_DC_Cl7	1.04%	DC	0%	37%	70%
82Tractor_DC_Cl8	1.51%	DC	0%	37%	70%
83Tractor_DC_Cl7	1.70%	DC	5%	14%	14%
84Tractor_DC_Cl8	3.70%	DC	0%	37%	70%
85B_Transit_Cl8_MP	2.27%	HHD/Other Bus	14%	26%	39%
86B_Transit_Cl6-7_MP	0.01%	MHD/Other Bus	5%	5%	5%
87B_Transit_Cl8_U	0.80%	HHD/Other Bus	14%	26%	39%
88B_Transit_Cl6-7_U	0.01%	MHD/Other Bus	5%	5%	5%
89T_Utility_Cl8_MP	0.34%	HHD	20%	37%	70%
90T_Utility_Cl8_R	0.34%	HHD	0%	14%	5%
91T_Utility_Cl6-7_MP	0.77%	MHD	20%	37%	39%
92T_Utility_Cl6-7_R	0.77%	MHD	0%	14%	14%
93T_Utility_Cl4-5_MP	1.69%	LHD	20%	37%	70%

Vehicle ID*	Sales %	Regulatory Group[a]	MY 2027 ZEV Percentage	MY 2030 ZEV Percentage	MY 2032 ZEV Percentage
94T_Utility_Cl2b-3_MP	1.69%	LHD	14%	37%	70%
95T_Utility_Cl4-5_R	0.30%	LHD	0%	14%	14%
96T_Utility_Cl2b-3_R	0.30%	LHD	0%	14%	14%
97T_Utility_Cl8_U	0.34%	HHD	0%	14%	14%
98T_Utility_Cl6-7_U	0.77%	MHD	20%	37%	70%
99T_Utility_Cl4-5_U	1.69%	LHD	20%	37%	70%
100T_Utility_Cl2b-3_U	1.69%	LHD	14%	37%	70%
101Tractor_DC_Cl8	0.37%	DC	14%	37%	39%

[a] All vocational vehicle types are assigned to either LHD, MHD, or HHD regulatory grouping. Some vehicle types are also assigned to a second regulatory grouping for calculating the appropriate Optional Custom Chassis adoption rate, as shown in Table 2-103.

Next, we aggregated the projected ZEVs for the specific vehicle types into their respective regulatory groupings relative to the vehicle's sales weighting. The results for MYs 2027, 2030, and 2032 are shown in Table 2-103. As proposed, we are retaining the Phase 2 MY 2027 emission standards for the optional custom chassis standards for emergency vehicles, mixed use vehicles, and motorhomes. In the final rule, as discussed in Chapter 2.9.1.1 and 2.9.1.2 we have also determined it is appropriate to retain the Phase 2 MY 2027 standards for optional custom chassis concrete mixers and coach buses. Therefore, those vehicle types are not shown in the table below.

Table 2-103 HD TRUCS Results: Percentage of ZEVs in MYs 2027, 2030, and 2032

Regulatory Grouping	MY 2027	MY 2030	MY 2032
LHD Vocational	17%	33%	61%
MHD Vocational	13%	25%	41%
HHD Vocational	11%	22%	32%
MHD All Cab and HHD Day Cab Tractor	3%	26%	41%
Sleeper Cab Tractors	0%	13%	25%
Heavy Haul Tractors	5%	14%	14%
Optional Custom Chassis: School Bus	20%	36%	67%
Optional Custom Chassis: Other Bus	14%	26%	39%
Optional Custom Chassis: Refuse Hauler	14%	25%	16%

2.10 Supporting the Feasibility of the Final CO_2 Standards

As described in Preamble Section II.F and G, after extensive analysis, EPA determined the final CO_2 standards for each subcategory, giving appropriate consideration to costs, lead time, and other factors. Similar to the approach we used to support the HD GHG Phase 2 vehicle and proposed Phase 3 CO_2 emission standards, we developed a modeled potential compliance pathway's technology package for each regulatory subcategory of vocational vehicles and tractors to support the final standards. We also assessed the feasibility of those standards under the modeled potential compliance pathway considering cost and lead time, considering among other factors described in this section, technology costs for manufacturers and costs to purchasers and operators, as described in preamble Section II. We applied these technology packages to nationwide heavy-duty vehicle production volumes to support the final Phase 3 GHG vehicle standards. The technology packages utilize the averaging portion of EPA's longstanding ABT program, and thus that part of ABT is reflected in the technology packages supporting the stringency of the final standards.

Our modeled potential compliance pathway projects that manufacturers will produce a mix of HD vehicles that utilize ICE-powered vehicle technologies and ZEV technologies, with specific adoption rates foreach regulatory subcategory of vocational vehicles and tractors for each MY. Note that we have analyzed a potential compliance pathway to support the feasibility and appropriateness of the level of stringency for each of the final standards,[1267] but manufacturers will be able to use many different compliance pathways, that may include a combination of HD engine or vehicle GHG-reducing technologies (including zero-emission and vehicles with ICE technologies), to meet the standards. Furthermore, for the analysis for the final standards, we also have evaluated additional example potential compliance pathways' technology packages with only ICE vehicle with ICE technologies, as described in Chapter 2.11.

We discuss the calculation of the standards in detail in the following subsection.

2.10.1 Technology Packages to Support the Final Standards

The technology packages for our modeled potential compliance pathway includes vehicles with ICE powertrains and vehicles with ZEV powertrains. In our analysis, the ICE vehicles include a suite of technologies that represent a vehicle that meets the MY 2027 Phase 2 CO_2 emission standards. These technologies exist today and continue to evolve to improve the efficiency of the engine, transmission, drivetrain, aerodynamics, and tire rolling resistance in HD vehicles and therefore reduce their CO_2 emissions. As discussed in Chapter 2.11, there are opportunities for further adoption of these Phase 2 ICE technologies beyond the adoption rates used in the HD GHG Phase 2 rule, In addition, the heavy-duty industry continues to develop CO_2-reducing technologies such as hybrid powertrains and H2-ICE powered vehicles, also discussed in Chapter 2.11. These further technology improvements are not part of the modeled potential compliance pathway's technology packages that support the final standards, but are available to any manufacturer determining its own compliance pathway.

To determine the numerical values of the final emission standards, we adjusted some of the adoption rates shown in Table 2-103 downward, which means we are finalizing standards that are less stringent than the HD TRUCS results support, as a conservative approach to setting standards. Even though the results from HD TRUCS are reasonable and supportable, we made specific changes to certain regulatory groupings for the following reasons: (1) The MY 2030 vocational vehicle and day cab technology adoption rates were lowered to slow the phase in to approximately 33% of the difference between the MY 2027 and MY 2032 adoption rates in Table 2-103. This has the effect of phasing in the standards more slowly early in the program. (2) The MY 2030 sleeper cab tractor technology adoption rates were reduced to provide more time for the BEV public charging infrastructure and hydrogen infrastructure to develop. (3) Heavy haul tractors were lowered to 0% in MYs 2027 and 2028, consistent with the decision discussed below about delaying the heavy heavy-duty vocational vehicle standards, since both vehicle types have large energy demands. For the same reason, we lowered both the MY 2030 and MY 2032 heavy haul tractor standards.

[1267] Note that our modeled potential compliance pathway considers and costs only availability of averaging within the ABT program and does not rely on any other flexibility under the ABT program.

For the proposal, the optional chassis subcategories were calculated using the sales weighted average results from HD TRUCS for each optional chassis application. This meant that the optional chassis standards could be more stringent than their corresponding primary vocational vehicle standards. For the final rule, we have taken a more conservative approach. The companies that certify vehicles to the optional custom chassis standards have more restrictive ABT provisions than those provisions available to companies with vehicles certified under the primary vocational vehicle standards. Therefore, for Phase 3, we limited the increase in stringency to the optional custom chassis standards to be no greater than the increase in stringency of the corresponding primary vocational vehicle standards. Each optional custom chassis subcategory corresponds to either the MHD or HHD vehicle service class.[1268] Thus, the adoption rates for the optional chassis standards for school buses were lowered to match the rates for MHD vocational adoption rates. Similarly, the adoption rates for the optional chassis standards for other buses were lowered to the match rates for HHD vocational vehicles. Lastly, the adoption rates for MY 2027 and MY 2030 of the optional chassis standards for refuse haulers were lowered to match the rates for HHD vocational.

Table 2-104 Percentage of ZEVs in the MYs 2027, 2030 and 2032 Technology Packages before Product Lead Time Adjustments

Regulatory Grouping	MY 2027	MY 2030	MY 2032
LHD Vocational	17%	32%	60%
MHD Vocational	13%	22%	40%
HHD Vocational	10%	15%	30%
MHD All Cab and HHD Day Cab Tractor	3%	16%	40%
Sleeper Cab Tractors	0%	6%	25%
Heavy Haul Tractors	0%	1%	5%
Optional Custom Chassis: School Bus	13%	22%	40%
Optional Custom Chassis: Other Bus	10%	15%	30%
Optional Custom Chassis: Coach Bus	0%	0%	0%
Optional Custom Chassis: Refuse Hauler	10%	15%	16%
Optional Custom Chassis: Concrete Mixer	0%	0%	0%
Optional Custom Chassis: Motorhomes	0%	0%	0%
Optional Custom Chassis: Emergency Vehicles	0%	0%	0%

To calculate the final adoption rates for all model years, we interpolated the intervening model years between MYs 2027 and 2030 and between MYs 2030 and 2032. In general, the standards for MY 2028 and MY 2029 are phased in by a linear interpolation between MY 2027 and MY 2030, and the standards for MY 2031 are a linear interpolation between MY 2030 and MY 2032. However, because ZEV sleeper cab tractor operation may rely most heavily on public charging and hydrogen fueling, to allow for more infrastructure development, we are phasing in the standards at a slower rate for MY 2031 at 33% of the difference between MY 2030 and MY 2032. We are providing additional lead time in the final standards for some of the categories when compared to the HD TRUCS results (Table 2-103) and our downward adjustments (Table 2-104). As described in the preamble in Section II.F, we will commence the Phase 3 HHD vocational standards in MY 2029 to provide additional lead time for these heavy heavy-duty vehicle categories. Consistent with the HHD vocational standards, we have delayed the start of

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[1268] See 40 CFR 1037.105(h), Table 5. The optional chassis school bus subcategory is assigned to MHD; The optional chassis other bus and refuse hauler subcategories are assigned to HHD.

the optional chassis other bus standards until MY 2029 because they are typically HHD vocational vehicles. Also as discussed in preamble Section II.F, the Phase 3 day cab standards will begin in MY 2028 to also provide additional lead time for development of these vehicles. For the optional custom chassis refuse haulers, we also delayed the start of the standards to MY 2028, consistent with the day cab tractor approach because refuse haulers also consist of both MHD and HHD vehicles.

The resulting ZEV adoption rates in our technology packages for MYs 2027–2032 by regulatory group are shown in Table 2-105. The remaining portion of vehicles in each technology package are projected to be ICE vehicles, as shown in Table 2-106, that achieve a level of CO_2 emissions performance equal to the Phase 2 MY 2027 emission standards.

Table 2-105 Percentage of ZEVs in the Modeled Potential Compliance Pathway's MYs 2027–2032 Technology Packages

Regulatory Group	MY 2027 ZEV Adoption	MY 2028 ZEV Adoption	MY 2029 ZEV Adoption	MY 2030 ZEV Adoption	MY 2031 ZEV Adoption	MY 2032 ZEV Adoption
LHD Vocational	17%	22%	27%	32%	46%	60%
MHD Vocational	13%	16%	19%	22%	31%	40%
HHD Vocational	0%	0%	13%	15%	23%	30%
MHD All Cab and HHD Day Cab Tractors	0%	8%	12%	16%	28%	40%
Sleeper Cab Tractors	0%	0%	0%	6%	12%	25%
Heavy Haul Tractors	0%	0%	1%	1%	3%	5%
Optional Custom Chassis: School Bus	13%	16%	19%	22%	31%	40%
Optional Custom Chassis: Other Bus	0%	0%	13%	15%	23%	30%
Optional Custom Chassis: Coach Bus	0%	0%	0%	0%	0%	0%
Optional Custom Chassis: Refuse Hauler	0%	5%	10%	15%	16%	16%
Optional Custom Chassis: Concrete Mixer	0%	0%	0%	0%	0%	0%
Optional Custom Chassis: Motor Home	0%	0%	0%	0%	0%	0%
Optional Custom Chassis: Mixed Use Vehicle	0%	0%	0%	0%	0%	0%
Optional Custom Chassis: Emergency Vehicle	0%	0%	0%	0%	0%	0%

Table 2-106 Percentage of ICE Vehicles in the Modeled Potential Compliance Pathway's MYs 2027–2032 Technology Packages

Regulatory Group	MY 2027 ZEV Adoption	MY 2028 ZEV Adoption	MY 2029 ZEV Adoption	MY 2030 ZEV Adoption	MY 2031 ZEV Adoption	MY 2032 ZEV Adoption
LHD Vocational	83%	78%	73%	68%	54%	40%
MHD Vocational	87%	84%	81%	78%	69%	60%
HHD Vocational	100%	100%	87%	85%	77%	70%
MHD All Cab and HHD Day Cab Tractors	100%	92%	88%	84%	72%	60%
Sleeper Cab Tractors	100%	100%	100%	94%	88%	75%
Heavy Haul Tractors	100%	100%	99%	99%	97%	95%
Optional Custom Chassis: School Bus	87%	84%	81%	78%	69%	60%
Optional Custom Chassis: Other Bus	100%	100%	87%	85%	77%	70%
Optional Custom Chassis: Coach Bus	100%	100%	100%	100%	100%	100%
Optional Custom Chassis: Refuse Hauler	100%	95%	90%	85%	84%	84%
Optional Custom Chassis: Concrete Mixer	100%	100%	100%	100%	100%	100%
Optional Custom Chassis: Motor Home	100%	100%	100%	100%	100%	100%
Optional Custom Chassis: Mixed Use Vehicle	100%	100%	100%	100%	100%	100%
Optional Custom Chassis: Emergency Vehicle	100%	100%	100%	100%	100%	100%

2.10.2 Battery Pack Production Levels to Support the Technology Packages

Using the modeled potential compliance pathway's technology packages for MYs 2027–2032, we determined the total number of gigawatt-hours (GWh) of batteries that will need to be produced to support these levels of sales of BEVs and FCEVs. Table 2-107 shows the sales-weighted average battery pack size and vehicle sales for MY 2027 and MY 2032 BEVs and FCEVs used to determine the HD vehicle total. Based on our analysis, 11 GWh of batteries will be required in MY 2027 and 58 GWh of batteries in MY 2032.

Table 2-107 Sales-Weighted Battery Pack Size and MOVES MY2027 and MY2032 Vehicle Sales

Source TypeID	Reg ClassID	2027 Sales-weighted Average Battery Size per BEV (kWh)	2027 MOVES BEV Vehicle Sales	2032 Sales-weighted Average Battery Size per BEV (kWh)	2032 MOVES BEV Vehicle Sales	2032 Sales-weighted Average Battery Size per FCEV (kWh)	2032 MOVES FCEV Vehicle Sales
41	42	155	1262	155	4484	55	0
41	46	245	54	245	83	35	0
41	47	0	821	710	1558	33	759
42	42	164	389	164	1381	55	0
42	46	295	12	283	27	35	0
42	47	472	0	472	0	56	0
42	48	472	253	472	1557	56	0
43	42	112	371	112	1262	55	0
43	46	160	5022	160	17448	35	0
43	47	255	88	256	552	56	0
51	46	288	131	287	280	35	0
51	47	355	108	355	1210	56	0
52	42	110	33438	110	115613	55	0
52	46	189	9702	176	27017	35	0
52	47	297	1446	287	8933	55	0
53	42	104	737	108	3059	55	0
53	46	183	486	183	1342	35	0
53	47	252	64	252	552	56	0
54	42	365	3024	365	9268	55	0
54	46	574	969	574	2869	35	0
54	47	564	239	564	666	56	0
61	46	355	2225	475	6641	67	2239
61	47	334	3226	444	28271	98	1125
62	46	0	12	881	444	58	259
62	47	0	246	881	9628	58	5618

2.10.3 EVSE Production Levels to Support the Technology Packages

We determined the total number of EVSE ports that will be required to support the depot-charged BEVs in the modeled potential compliance pathway’s technology packages that support the MY 2027–2032 standards. We project about 520,000 EVSE ports will be needed across all six model years As described in Chapter 2.8.7.2,to estimate the EVSE port counts for depot charging, we first assign the lowest-cost EVSE option that can meet each BEV’s charging needs, allowing multiple BEVs to share an EVSE port (up to a cap) when feasible.[1269] Then we use the projected BEV sales by model year[1270] for each depot-charged vehicle type in our analysis and divide by the number of vehicles that can share a port of the assigned type. Lastly, we sum these across all depot-charged vehicle types. The results are shown in Table 2-108. The majority (88 percent) are Level 2 ports, followed by lower-power DCFCs. We project 51 DC-350 kW ports will be needed at depots. Table 2-108 shows the total EVSE ports by type for MY 2027 through MY 2032 BEVs.

Table 2-108 EVSE Port Counts for Depot Charging Analysis

EVSE Type	MY 2027	MY 2028	MY 2029	MY 2030	MY 2031	MY 2032	Total
Level 2 (19.2 kW)	38,726	50,360	61,404	71,432	101,720	133,230	456,872
DC-50 kW	2,981	3,892	6,344	6,998	9,075	11,271	40,561
DC-150 kW	1,867	3,106	5,007	3,323	4,148	5,024	22,475
DC-350 kW	-	2	4	5	15	25	51

Taking into account the approximately 633,000 of MY2027–2032 BEVs that we project will use depot charging, we estimate an overall ratio of 1.2 BEVs per depot EVSE port. See RIA Chapter 1.6.2.3 for a discussion of how these estimates compare to charging infrastructure need assessments in the literature.

2.10.4 Calculation of the Final CO_2 Standards

The heavy-duty vehicle CO_2 emission standards are in grams per ton-mile, which represents the grams of CO_2 emitted to move one ton of payload a distance of one mile. The final Phase 3 vehicle standards fall into two major categories: tractors and vocational vehicles and are then further subdivided into standards for each regulatory subcategory. The following sections describe how the final Phase 3 vehicle standards within each regulatory subcategory are calculated.

2.10.4.1 Calculation of the Final Tractor Standards

The final tractor CO_2 emission standards for each model year are calculated by multiplying the fraction of ICE-powered vehicles in each technology package by the corresponding Phase 2 MY 2027 CO_2 emission standards, as shown in Table 2-109. The final standards are presented in RIA Chapter 2.10.5. We note that this is a description of how the level of the standard is calculated and supported under the modeled potential compliance pathway. It is not a description of how the EPA determined that the final standards are feasible and appropriate, which is explained in preamble Section II.G.

[1269] These results are summarized in Table 2-78.

[1270] Estimates of new heavy-duty vehicle sales are sourced from MOVES for each model between 2027 and 2032. BEV adoption shares by vehicle type are from HD TRUCS.

Table 2-109 Phase 2 MY 2027 Tractor CO_2 Emission Standards (g/ton-mile)

	Class 7 (All Cab Styles)	Class 8 (Day Cab)	Class 8 (Sleeper Cab)	Heavy Haul
Low Roof	96.2	73.4	64.1	48.3
Mid Roof	103.4	78.0	69.6	
High Roof	100.0	75.7	64.3	

2.10.4.2 Calculation of the Final Vocational Vehicle Standards

Consistent with the final tractor standards, the final CO_2 emission standards for the vocational vehicles regulatory subcategories are calculated from technology packages that consist of both ICE-powered vehicle technologies and ZEV technologies. The projected fraction of ZEVs that emit zero grams CO_2/ton-mile at the tailpipe in the technology packages are shown in Table 2-105. The remaining fraction of vehicles in the technology package are ICE-powered vehicles that include the technologies listed in the Preamble in Table II-1 (reflecting the GEM inputs for the individual technologies that make up the technology packages that meets the Phase 2 MY 2027 CO_2 vocational vehicles emission standards). Thus, as noted above, in the technology packages, the ICE-powered vehicles emit at the applicable Phase 2 MY 2027 CO_2 emission standards, as shown in Table 2-110.

Table 2-110 Phase 2 MY 2027 Vocational Vehicle CO_2 Emission Standards (g/ton-mile)

		CI Light Heavy	CI Medium Heavy	CI Heavy Heavy	SI Light Heavy	SI Medium Heavy
Urban		367	258	269	413	297
Multi-Purpose		330	235	230	372	268
Regional		291	218	189	319	247
Optional Custom Chassis:	School Bus	271				
	Other Bus	286				
	Coach Bus	205				
	Refuse Hauler	298				
	Concrete Mixer	316				
	Motor Home	226				
	Mixed-Use Vehicle	316				
	Emergency Vehicle	319				

2.10.4.2.1 Vocational Vehicles - Primary Program

The HD GHG Phase 2 structure enables the technologies that perform best during urban driving or the technologies that perform best at highway driving to each be properly recognized over the appropriate drive cycles. The HD GHG Phase 2 structure was developed recognizing that there is not a single package of engine, transmission, and driveline technologies that is suitable for all ICE-powered vocational vehicle applications. In the proposal we recognized the variety in vocational vehicle CO_2 emissions may no longer be necessary for ZEVs because ZEVs are deemed to have zero CO_2 emissions. Similarly, the SI and CI distinction within the vocational vehicle regulatory subcategory structure is not relevant for vocational ZEVs because they cannot be technically described as either SI-powered or CI-powered. We requested comment on possible alternative vocational vehicle regulatory subcategory structures, such as reducing the number of vocational vehicle subcategories to only include the multi-purpose standards in each weight class, and/or maintaining urban, multi-purpose, and Regional but combining SI and CI into a standard for each weight class. 88 FR at 22995. After considering the comments and the final levels of stringency that reflect a continued significant volume of ICE vehicle production during the Phase 3 timeframe, and as discussed further in the next paragraphs, we are finalizing a structure, as we proposed, to maintain the existing HD GHG Phase 2 vocational vehicle regulatory subcategories.

We also proposed to calculate vocational vehicle standards for the primary program, within each weight class by calculating a g/ton-mile value based on the CI multi-purpose Phase 2 MY 2027 standard and subtracting this value from each of the Phase 2 MY 2027 standards within a weight class. As part of the same approach, we proposed that ZEV ABT credits would be generated relative to that single subcategory's (CI-MP) emission standard (rather than urban, regional, or multi purpose). Specifically, as part of the process used in the proposal to calculate the proposed standards, EPA also proposed to revise the definition of the variable "Std" in 40 CFR 1037.705 to establish a common reference emission standard for vocational vehicles with tailpipe CO_2 emissions deemed to be zero (i.e., BEVs, FCEVs, and vehicles with engines fueled with pure hydrogen). This approach was proposed in order to create a level playing field for potential compliance strategies that included ZEVs; however, some manufacturers pointed out that restricting ZEV compliance to only the multi-purpose category could prevent manufacturers from earning full credits from ZEV vehicles[1271] with the intended use that best matches other subcategories of vehicles.[1272]

One commenter said that EPA should continue to use the Phase 2 approach that allows manufacturers to use good engineering judgement to determine the appropriate vocational vehicle subcategory for ZEVs and to therefore retain the urban, regional, multipurpose subcategories. The commenter stated that collapsing the subcategories penalizes manufacturers with higher ZEV production levels in a subcategory other than multipurpose. Another commenter also requested that OEMs be allowed to classify their ZEVs "according to their intended use" noting that the proposal would reduce credits earned for ZEVs in the disfavored subcategories and would not provide enough lead time for manufacturers unless implementation was delayed until MY 2030. One commenter also raised concerns with the vocational vehicle standard setting process used by EPA in the NPRM and suggested we re-evaluate the approach for the final rule considering the potential impacts on each of the vocational vehicle subcategories, noting that the proposed approach inherently disfavored manufacturers of vocational vehicles in existing subcategories other than multipurpose.

[1271] ABT CO_2 emission credits are determined using the equation in 40 CFR 1037.705. The credits are calculated based on the difference between the applicable standard for the vehicle and the vehicle's family emission limit multiplied by the vehicle's regulatory payload and useful life miles.

[1272] Since, in the Phase 2 MY 2027 standards, the vocational vehicle urban standards for each weight class are numerically higher than the multi-purpose standards, it is ZEVs that manufacturers would have certified to the urban category that would earn fewer credits under the proposed approach. We note that under the proposed approach manufacturers would earn more credits than for ZEVs the manufacturer would have otherwise certified to the regional standards.

After considering comments we are not finalizing the proposed revision to the ABT credit calculation regulations[1273] with regard to the appropriate vocational vehicle subcategory to which manufacturers would certify ZEVs and are not using the proposed change to the ABT calculations in demonstrating the feasibility of or setting the vocational vehicle standards. We agree that there are legitimate concerns for manufacturers of urban ZEV vocational vehicles under the proposed approach regarding an even playing field. After considering comments, we are not finalizing the proposed approach of setting all the vocational vehicle standards relative to the CI multi-purpose regulatory subcategory.

We recognize that we project in the technology packages that the majority of vocational vehicles will continue to use ICE vehicle technologies during the implementation of Phase 3. However, we continue to be concerned about the possibility of allowing a loophole in the regulations that would allow manufacturers to receive more credits by assigning vocational vehicle ZEVs to an inappropriate subcategory when complying with the Phase 3 standards. We are thus retaining the existing requirement that ZEVs be subject to the CI standard.[1274] Even though ZEVs are neither CI nor SI, we are maintaining the reasonable approach of selecting a single certification pathway for ZEVs, and since CI is the most common application for heavy-duty vocational vehicles, it is reasonable to continue with this existing approach.

For the final rule, we therefore calculate the primary program vocational standards for CI vehicles just as we did for tractors, where the final CO_2 emission standards for the CI regulatory subcategories are calculated by determining the CO_2 emissions from a technology package that consists of both ICE-powered vehicles and ZEVs. The projected fraction of ZEVs that emit zero grams CO_2/ton-mile at the tailpipe are shown in Table 2-105. The remaining fraction of vehicles in the technology package are ICE-powered vehicles that include the technologies listed in the Preamble in Table II-1 (reflecting the GEM inputs for the individual technologies that make up the technology packages that meet the Phase 2 MY 2027 CO_2 CI vocational emission standards). Thus, as noted above, in the technology packages, the ICE-powered vehicles emit at the applicable Phase 2 MY 2027 CO_2 emission standards, as shown in Table 2-110.

To calculate the standards for the primary program for SI vehicles, we are finalizing an approach that sets the stringency of SI LHD and SI MHD vocational standards such that the technology package for modeled potential compliance pathway has the same fraction of ICE and ZEV vehicles regardless of whether a manufacturer is certifying SI or CI vocational vehicles; this is similar to the proposed approach but is more targeted at address manufacturers concerns, and it will appropriately reflect the urban, multi-purpose and regional categories. This is described in greater detail below.

To calculate the LHD and MHD SI vocational standards, the fraction of ZEV vehicles in the technology package (found in Table 2-105) is used to calculate a g/mi value based on each of the urban, multi-purpose, and regional Phase 2 MY 2027 CI LHD and MHD standards. These values are then subtracted from each of the corresponding urban, multi-purpose, and regional Phase 2 MY 2027 SI standards within the corresponding weight class. Equations are shown below for MY 2032. The Phase 2 MY 2027 standards can be found in Table 2-110, and the ZEV adoption

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[1273] We are not finalizing the proposed revision to the definition of the variable “Std” in 40 CFR 1037.705 to establish a common reference emission standard for vocational vehicles with tailpipe CO_2 emissions deemed to be zero (i.e., BEVs, FCEVs, and vehicles with engines fueled with pure hydrogen).

[1274] See 40 CFR 1037.615(f).

rates in the technology package can be found in Table 2-105 (the ZEV adoption rates for MY 2032 are also shown in the example equations below).

Equation 2-82 Calculation for MY 2032 SI LHD Urban Standard

$$MY2032\ Std_{\text{LHD SI Urban}} = P2\ MY2027\ Std_{\text{LHD SI Urban}} - (P2\ MY2027\ Std_{\text{LHD CI Urban}} * 60\%)$$

Equation 2-83 Calculation for MY 2032 SI LHD Multi-Purpose Standard

$$MY2032\ Std_{\text{LHD SI MP}} = P2\ MY2027\ Std_{\text{LHD SI MP}} - (P2\ MY2027\ Std_{\text{LHD CI MP}} * 60\%)$$

Equation 2-84 Calculation for MY 2032 SI LHD Regional Standard

$$MY2032\ Std_{\text{LHD SI Regional}} = \\ P2\ MY2027\ Std_{\text{LHD SI Regional}} - (P2\ MY2027\ Std_{\text{LHD CI Regional}} * 60\%)$$

Equation 2-85 Calculation for MY 2032 SI MHD Urban Standard

$$MY2032\ Std_{\text{MHD SI Urban}} = P2\ MY2027\ Std_{\text{MHD SI Urban}} - (P2\ MY2027\ Std_{\text{MHD CI Urban}} * 40\%)$$

Equation 2-86 Calculation for MY 2032 SI MHD Multi-Purpose Standard

$$MY2032\ Std_{\text{MHD SI MP}} = P2\ MY2027\ Std_{\text{MHD SI MP}} - (P2\ MY2027\ Std_{\text{MHD CI MP}} * 40\%)$$

Equation 2-87 Calculation for MY 2032 SI MHD Regional Standard

$$MY2032\ Std_{\text{MHD SI Regional}} = \\ P2\ MY2027\ Std_{\text{MHD SI Regional}} - (P2MY\ 2027\ Std_{\text{MHD CI Regional}} * 40\%)$$

This approach will continue to allow manufactures to certify ZEVs to the most appropriate urban, regional, or multi-purpose subcategory, using good engineering judgement, so the commenters concern about potential inequities for certifying categories other than multi-purpose is addressed with this solution. It also has the benefit of maintaining the existing, clear approach for certifying ZEVs to the CI standard. Lastly, this approach has the benefit of ensuring that manufacturer compliance strategies that include utilization of ZEV technologies will be able to comply with the same fraction of ZEVs regardless of whether the manufacturer also produces SI or CI vehicles. We recognize that this approach corresponds to a decrease in the numerical stringency of the SI standards compared to a calculation method that is comparable to the way the CI standards are calculated; however, this approach is reasonable because SI applications are a smaller portion of the fleet.

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2.10.4.2.2 Vocational Vehicles – Optional Custom Chassis Program

The HD GHG Phase 2 program includes optional custom chassis emission standards for eight specific vocational vehicle types. Those vehicle types may either meet the primary vocational vehicle program standards or, at the vehicle manufacturer's option, they may comply with these optional standards. The Phase 2 optional custom chassis standards are numerically less stringent than the primary HD GHG Phase 2 vocational vehicle standards, but the ABT program is more restrictive for vehicles certified to these optional standards. Banking and trading of credits is not permitted, with the exception that small businesses may use traded credits to comply. Averaging is only allowed within each subcategory for vehicles certified to these optional standards. If a manufacturer wishes to generate tradeable credits from the production of these vehicles, they may certify them to the primary vocational vehicle standards.

In this final action, we are adopting more stringent standards for some, but not all, of these optional custom chassis subcategories. We are revising MY 2027 emission standards and setting new MY 2028 through MY 2032 and later emission standards for the school bus, other bus, and refuse hauler optional custom chassis regulatory subcategories. We are not finalizing any changes to the existing ABT program restrictions for the optional custom chassis regulatory subcategories. Because vehicles certified to the optional custom chassis standards will continue to have restricted credit use and can only be used for averaging within a specific custom chassis regulatory subcategory, we do not have the same potential concern with respect to credit generation as we do for the primary vocational vehicle standards regarding designation of subcategory (i.e., regional, urban, or multi-purpose).

We determined the final optional custom chassis emission standards by multiplying the fraction of ICE-powered vehicles in the technology package (by model year) by the applicable Phase 2 MY 2027 CO_2 emission standards, like we did for determining the tractor and vocational vehicle emission standards. The fraction of ICE-powered vehicles is 1 minus the fraction of ZEV-powered vehicles shown in Table 2-105.

As proposed, we are not setting new standards for motor homes certified to the optional custom chassis regulatory subcategory, as described in RIA Chapter 2.9.1. Furthermore, we also are not finalizing new standards for emergency vehicles certified to the optional custom chassis regulatory subcategory due to our assessment that these vehicles have unpredictable operational requirements and may have limited access to recharging facilities while handling emergency situations in the MYs 2027–2032 timeframe. Finally, we are not adopting new standards for mixed-use vehicle optional custom chassis regulatory subcategory because these vehicles are designed to work inherently in an off-road environment (such as hazardous material equipment or off-road drill equipment) or be designed to operate at low speeds such that it is unsuitable for normal highway operation and therefore may have limited access to on-site depot or public charging facilities in the MYs 2027–2032 timeframe.[1275] We do not have concerns that manufacturers could inappropriately circumvent the final vocational vehicle standards or final optional custom chassis standards because vocational vehicles are built to serve a purpose. For example, a manufacturer cannot certify a box truck to the emergency vehicle custom chassis standards.

[1275] Mixed-use vehicles must meet the criteria as described in 40 CFR 1037.105(h)(1), 1037.631(a)(1), and 1037.631(a)(2).

We are not finalizing new standards for the optional custom chassis categories of Coach Buses, Concrete Mixers/Pumpers and Mixed-Use Vehicles, as described in RIA Chapter 2.9.1 and 2.9.2; these optional standards will remain unchanged from the Phase 2 MY 2027+ CO_2 emission standards.

2.10.5 Final CO_2 Standards

We phased in the final standards gradually between MYs 2027 and 2032 to address potential lead time concerns associated with feasibility under the modeled potential compliance pathway for manufacturers to deploy ZEV technologies that include consideration of time necessary to ramp up battery production, including the need to increase the availability of critical raw materials, assure more resilient supply chains, and expand battery production facilities, as discussed in Preamble Section II.D.2.ii. We also phased in the final standards recognizing that under the modeled potential compliance pathway it will take time for installation of EVSE and necessary supporting electrical infrastructure by the BEV purchasers and the associated electrical utility. We projected BEV adoption starting in MY 2027 for certain applications where we projected use of depot charging, and we project adoption of BEV in applications that will depend on public charging and FCEVs in the technology packages starting in MY 2030 for select applications that travel longer distances (i.e., sleeper cab tractors, and certain day cab tractors). There has been only limited development of FCEVs for the HD market to date; therefore, our assessment is that it is appropriate to provide manufacturers with additional lead time to design, develop, and manufacture FCEV models, but that it is feasible to do so by MY 2030, as discussed in Preamble Section II.D.3. With substantial Federal investment in low-GHG hydrogen production (see RIA Chapter 1.8.2), we anticipate that the price of hydrogen fuel will fall in the 2030 to 2035 timeframe to make HD FCEVs cost-competitive with comparable ICE vehicles for some duty cycles. We also note that the hydrogen infrastructure is expected to need additional time to further develop, as discussed in greater detail in RIA Chapter 1.8, but we expect the refueling needs can be met by MY 2030. We also recognize the positive market signal that regulations can have on technology and recharging/refueling infrastructure development and deployment.

The final standards are shown in Table 2-111 and Table 2-112 for vocational vehicles and Table 2-113 and Table 2-114 for tractors.

Table 2-111 Final MY 2027 through 2032+ Vocational Vehicle CO_2 Emission Standards (grams/ton-mile)

Model Year	Subcategory	CI Light Heavy	CI Medium Heavy	CI Heavy Heavy	SI Light Heavy	SI Medium Heavy
2027	Urban	305	224	269	351	263
	Multi-Purpose	274	204	230	316	237
	Regional	242	190	189	270	219
2028	Urban	286	217	269	332	256
	Multi-Purpose	257	197	230	299	230
	Regional	227	183	189	255	212
2029	Urban	268	209	234	314	248
	Multi-Purpose	241	190	200	283	223
	Regional	212	177	164	240	206
2030	Urban	250	201	229	296	240
	Multi-Purpose	224	183	196	266	216
	Regional	198	170	161	226	199
2031	Urban	198	178	207	244	217
	Multi-Purpose	178	162	177	220	195
	Regional	157	150	146	185	179
2032 and later	Urban	147	155	188	193	194
	Multi-Purpose	132	141	161	174	174
	Regional	116	131	132	144	160

Table 2-112 Final MY 2027 through 2032+ Optional Custom Chassis Vocational Vehicle CO_2 Emission Standards (grams/ton-mile)

Optional Custom Chassis Vehicle Category	MY 2027	MY 2028	MY 2029	MY 2030	MY 2031	MY 2032 and Later
School Bus	236	228	220	211	187	163
Other Bus	286	286	249	243	220	200
Coach Bus	205	205	205	205	205	205
Refuse Hauler	298	283	268	253	250	250
Concrete Mixer	316	316	316	316	316	316
Motor home	226	226	226	226	226	226
Mixed-use vehicle	316	316	316	316	316	316
Emergency vehicle	319	319	319	319	319	319

Table 2-113 Final MY 2027 through MY 2032+ Tractor CO_2 Emission Standards (grams/ton-mile)

Model Year	Roof Height	Class 7 All Cab Styles	Class 8 Day Cab	Class 8 Sleeper Cab
2027	Low Roof	96.2	73.4	64.1
	Mid Roof	103.4	78.0	69.6
	High Roof	100.0	75.7	64.3
2028	Low Roof	88.5	67.5	64.1
	Mid Roof	95.1	71.8	69.6
	High Roof	92.0	69.6	64.3
2029	Low Roof	84.7	64.6	64.1
	Mid Roof	91.0	68.6	69.6
	High Roof	88.0	66.6	64.3
2030	Low Roof	80.8	61.7	60.3
	Mid Roof	86.9	65.5	65.4
	High Roof	84.0	63.6	60.4
2031	Low Roof	69.3	52.8	56.4
	Mid Roof	74.4	56.2	61.2
	High Roof	72.0	54.5	56.6
2032 and Later	Low Roof	57.7	44.0	48.1
	Mid Roof	62.0	46.8	52.2
	High Roof	60.0	45.4	48.2

Table 2-114 Final MY 2027 through MY 2032+ Heavy-Haul Tractor CO_2 Emission Standards (grams/ton-mile)

Model Year	CO_2 Emission Standards (grams/ton-mile)
2027	48.3
2028	48.3
2029	47.8
2030	47.8
2031	46.9
2032 and Later	45.9

2.10.6 Summary of Costs to Meet the Final Emission Standards

In this subsection we show the cost of compliance for manufacturers for the final standards as well as costs for purchasers.

In our analysis, the ICE vehicles include a suite of technologies that represent a vehicle that meets the MY 2027 Phase 2 CO_2 emission standards and HD 2027 NOx emission standards. We accounted for these technology costs as part of the HD GHG Phase 2 final rule and the HD 2027 NOx rule. Therefore, our technology costs for the ICE vehicles in our analysis are considered to be $0 because we did not add additional CO_2-reducing technologies to the ICE vehicles in the technology packages for this final rule beyond those already required under the existing regulations. The incremental cost of a heavy-duty ZEV in our analysis is the marginal cost of ZEV powertrain components compared to ICE powertrain components on a comparable ICE vehicle. This includes the removal of the associated costs of ICE-specific components from the baseline vehicle and the addition of the ZEV components and associated costs. Chapter 2.3.2 and 2.4.3 includes the ICE powertrain and BEV powertrain cost estimates for each of the 101 HD vehicle types. Chapter 2.5.2 includes the FCEV powertrain cost projections for the coach buses and some tractors.

2.10.6.1 Manufacturer Costs

Table 2-115 through Table 2-117 show the incremental ZEV RPE costs that include the direct manufacturing costs that reflect learning effects, the indirect costs, and the IRA section 13502 Advanced Manufacturing Production Credit for each of the HD TRUCS vehicle types for MYs 2027, 2030, and 2032.[1276] These values were then aggregated by regulatory group as shown in Table 2-118 through Table 2-120 which show the ZEV technology costs for manufacturers, relative to the reference case described in the Preamble in Section V.A.1 and Chapter 4.3.1. The vocational vehicle costs are presented in these tables at the regulatory group level (e.g., LHD), if they were instead presented at the regulatory subcategory level (e.g. CI LHD MP, CI, LHD R, and CI LHD U) the costs for each regulatory subcategory would be the same as the respective regulatory group costs. The incremental ZEV adoption rates in these tables reflect the difference between the ZEV adoption rates in the technology packages that support our final standards and the reference case.

Table 2-115 Incremental ZEV RPE Costs for MY 2027 (2022$)

Vehicle ID	Regulatory Group	ZEV Adoption Rate Relative to HD Fleet Sales	ICE PT RPE (per vehicle)	ZEV PT RPE Including Battery Tax Credit (per vehicle)	Incremental ZEV RPE (per vehicle)
01V_Amb_Cl4-5_MP	LHD	0.24%	$43,486	$38,606	-$4,879
02V_Amb_Cl2b-3_MP	LHD	0.35%	$41,518	$37,528	-$3,990
03V_Amb_Cl4-5_U	LHD	0.35%	$43,486	$37,369	-$6,117
04V_Amb_Cl2b-3_U	LHD	0.35%	$41,518	$36,254	-$5,264
05T_Box_Cl8_MP	HHD	0%	$82,838	$66,617	-$16,221
06T_Box_Cl8_R	HHD	0.04%	$82,838	$67,835	-$15,003
07T_Box_Cl6-7_MP	MHD	0.10%	$46,632	$48,579	$1,947
08T_Box_Cl6-7_R	MHD	0.08%	$46,632	$50,816	$4,184
09T_Box_Cl8_U	HHD	0%	$73,222	$65,465	-$7,757
10T_Box_Cl6-7_U	MHD	0.15%	$46,632	$47,652	$1,020
11T_Box_Cl2b-3_U	LHD	0.35%	$40,843	$35,644	-$5,200
12T_Box_Cl2b-3_R	LHD	0.35%	$40,843	$38,360	-$2,483
13T_Box_Cl2b-3_MP	LHD	0.35%	$40,843	$36,941	-$3,902
14T_Box_Cl4-5_U	LHD	0.35%	$40,982	$35,644	-$5,339
15T_Box_Cl4-5_R	LHD	0.24%	$40,982	$38,360	-$2,622
16T_Box_Cl4-5_MP	LHD	0.35%	$40,982	$36,941	-$4,041
17B_Coach_Cl8_R	HHD	0%	$65,186	NA	NA
18B_Coach_Cl8_MP	HHD	0%	$65,186	NA	NA
19C_Mix_Cl8_MP	HHD	0%	$73,222	$94,505	$21,283
20T_Dump_Cl8_U	HHD	0%	$82,838	$72,505	-$10,333
21T_Dump_Cl8_MP	HHD	0%	$82,838	$73,058	-$9,779
22T_Dump_Cl6-7_MP	MHD	0.20%	$46,370	$64,952	$18,581
23T_Dump_Cl8_U	HHD	0%	$73,222	$72,505	-$717

[1276] Indirect costs are described in detail in RIA Chapter 3.2.2.

24T_Dump_Cl6-7_U	MHD	0.07%	$46,370	$62,261	$15,891
25T_Fire_Cl8_MP	HHD	0%	$82,838	$75,222	-$7,616
26T_Fire_Cl8_U	HHD	0%	$73,222	$75,317	$2,095
27T_Flat_Cl6-7_MP	MHD	0.10%	$46,370	$48,440	$2,070
28T_Flat_Cl6-7_R	MHD	0.04%	$46,370	$50,676	$4,306
29T_Flat_Cl6-7_U	MHD	0.15%	$46,370	$46,471	$101
30Tractor_DC_Cl8	DC	0%	$87,274	$91,169	$3,895
31Tractor_DC_Cl7	DC	0%	$68,631	$78,218	$9,587
32Tractor_SC_Cl8	SC	0%	$90,534	NA	NA
33Tractor_DC_Cl8	DC	0%	$69,467	NA	NA
34T_Ref_Cl8_MP	HHD	0%	$68,925	$82,018	$13,093
35T_Ref_Cl6-7_MP	MHD	0.01%	$46,370	$66,829	$20,459
36T_Ref_Cl8_U	HHD	0%	$68,925	$82,018	$13,093
37T_Ref_Cl6-7_U	MHD	0.01%	$46,370	$66,249	$19,878
38RV_Cl8_R	HHD	0%	$48,454	$112,615	$64,160
39RV_Cl6-7_R	MHD	0.00%	$46,487	$114,050	$67,563
40RV_Cl4-5_R	LHD	0.00%	$40,117	$78,307	$38,190
41Tractor_DC_Cl7	DC	0%	$68,631	NA	NA
42RV_Cl8_MP	HHD	0%	$48,454	$112,615	$64,160
43RV_Cl6-7_MP	MHD	0.00%	$46,487	$106,485	$59,997
44RV_Cl4-5_MP	LHD	0.00%	$40,117	$73,481	$33,364
45Tractor_DC_Cl8	DC	0.00%	$90,534	NA	NA
46B_School_Cl8_MP	HHD	0%	$48,454	$67,496	$19,042
47B_School_Cl6-7_MP	MHD	0.38%	$46,487	$47,480	$992
48B_School_Cl4-5_MP	LHD	0.01%	$40,117	$38,606	-$1,510
49B_School_Cl2b-3_MP	LHD	0.01%	$42,042	$37,719	-$4,323
50B_School_Cl8_U	HHD	0%	$48,454	$65,364	$16,910
51B_School_Cl6-7_U	MHD	0.38%	$46,487	$47,480	$992
52B_School_Cl4-5_U	LHD	0.01%	$40,117	$37,369	-$2,748
53B_School_Cl2b-3_U	LHD	0.01%	$42,042	$36,445	-$5,598
54Tractor_SC_Cl8	SC	0%	$90,534	NA	$121,435
55B_Shuttle_Cl2b-3_MP	LHD	0.06%	$42,042	$45,493	$3,451
56B_Shuttle_Cl4-5_U	LHD	0.11%	$40,117	$44,478	$4,361
57B_Shuttle_Cl2b-3_U	LHD	0.11%	$42,042	$43,554	$1,511
58B_Shuttle_Cl6-7_MP	MHD	0.00%	$46,487	$63,142	$16,655
59B_Shuttle_Cl6-7_U	MHD	0.01%	$46,487	$60,251	$13,763
60S_Plow_Cl6-7_MP	MHD	0.02%	$46,370	$53,150	$6,780
61S_Plow_Cl8_MP	HHD	0%	$82,838	$89,436	$6,598
62S_Plow_Cl6-7_U	MHD	0.01%	$46,370	$51,239	$4,869
63S_Plow_Cl8_U	HHD	0%	$73,222	$88,426	$15,204
64V_Step_Cl6-7_MP	MHD	0.15%	$46,271	$48,529	$2,258
65V_Step_Cl4-5_MP	LHD	0.35%	$40,117	$36,941	-$3,175
66V_Step_Cl2b-3_MP	LHD	0.06%	$41,518	$36,878	-$4,640
67V_Step_Cl6-7_U	MHD	0.15%	$46,271	$46,545	$274
68V_Step_Cl4-5_U	LHD	0.35%	$40,117	$35,644	-$4,473
69V_Step_Cl2b-3_U	LHD	0.06%	$41,518	$35,580	-$5,938
70S_Sweep_Cl6-7_U	MHD	0.15%	$46,370	$50,519	$4,149
71T_Tanker_Cl8_R	HHD	0%	$82,838	$70,513	-$12,325

72T_Tanker_Cl8_MP	HHD	0%	$73,222	$69,756	-$3,466
73T_Tanker_Cl8_U	HHD	0%	$73,222	$69,547	-$3,675
74T_Tow_Cl8_R	HHD	0%	$85,428	$92,282	$6,854
75T_Tow_Cl6-7_R	MHD	0.00%	$46,370	$68,491	$22,121
76T_Tow_Cl8_U	HHD	0%	$73,222	$90,284	$17,062
77T_Tow_Cl6-7_U	MHD	0.04%	$46,370	$62,432	$16,062
78Tractor_SC_Cl8	SC	0%	$90,534	NA	NA
79Tractor_SC_Cl8	SC	0%	$90,534	NA	NA
80Tractor_DC_Cl8	DC	0%	$91,562	$133,921	$42,359
81Tractor_DC_Cl7	DC	0%	$68,631	NA	NA
82Tractor_DC_Cl8	DC	0%	$90,534	NA	NA
83Tractor_DC_Cl7	DC	0%	$68,631	$99,726	$31,095
84Tractor_DC_Cl8	DC	0%	$84,968	NA	NA
85B_Transit_Cl8_MP	HHD	0%	$65,186	$98,682	$33,496
86B_Transit_Cl6-7_MP	MHD	0.00%	$46,487	$79,671	$33,183
87B_Transit_Cl8_U	HHD	0%	$64,405	$98,682	$34,277
88B_Transit_Cl6-7_U	MHD	0.00%	$46,487	$74,923	$28,435
89T_Utility_Cl8_MP	HHD	0%	$82,838	$68,241	-$14,597
90T_Utility_Cl8_R	HHD	0%	$82,838	$69,220	-$13,618
91T_Utility_Cl6-7_MP	MHD	0.15%	$46,370	$50,884	$4,514
92T_Utility_Cl6-7_R	MHD	0.00%	$46,370	$52,973	$6,603
93T_Utility_Cl4-5_MP	LHD	0.35%	$43,486	$38,663	-$4,822
94T_Utility_Cl2b-3_MP	LHD	0.24%	$41,518	$37,666	-$3,852
95T_Utility_Cl4-5_R	LHD	0.00%	$43,486	$39,916	-$3,569
96T_Utility_Cl2b-3_R	LHD	0.00%	$41,518	$39,853	-$1,665
97T_Utility_Cl8_U	HHD	0%	$73,222	$67,577	-$5,645
98T_Utility_Cl6-7_U	MHD	0.15%	$46,370	$49,260	$2,890
99T_Utility_Cl4-5_U	LHD	0.35%	$43,486	$37,623	-$5,863
100T_Utility_Cl2b-3_U	LHD	0.24%	$41,518	$36,486	-$5,032
101Tractor_DC_Cl8	DC	0%	$84,968	$79,329	-$5,639

Note: The NA values represent vehicles that are either considered to be FCEVs or publicly-charged BEVs and therefore are not included in the MY 2027 technology package

Table 2-116 Incremental ZEV RPE Costs for MY 2030 (2022$)

Vehicle ID	Regulatory Group	ZEV Adoption Rate	ICE PT RPE (per vehicle)	ZEV PT RPE Including Battery Tax Credit (per vehicle)	Incremental ZEV RPE (per vehicle)
01V_Amb_Cl4-5_MP	LHD	0.60%	$43,051	$31,360	-$11,691
02V_Amb_Cl2b-3_MP	LHD	0.60%	$41,103	$30,552	-$10,551
03V_Amb_Cl4-5_U	LHD	0.60%	$43,051	$30,441	-$12,610
04V_Amb_Cl2b-3_U	LHD	0.60%	$41,103	$29,606	-$11,497
05T_Box_Cl8_MP	HHD	0.08%	$82,009	$53,225	-$28,784
06T_Box_Cl8_R	HHD	0.05%	$82,009	$54,129	-$27,880
07T_Box_Cl6-7_MP	MHD	0.25%	$46,166	$39,065	-$7,100
08T_Box_Cl6-7_R	MHD	0.13%	$46,166	$40,726	-$5,440

09T_Box_Cl8_U	HHD	0.06%	$72,490	$52,370	-$20,120
10T_Box_Cl6-7_U	MHD	0.25%	$46,166	$38,377	-$7,789
11T_Box_Cl2b-3_U	LHD	0.60%	$40,435	$29,160	-$11,275
12T_Box_Cl2b-3_R	LHD	0.60%	$40,435	$31,177	-$9,258
13T_Box_Cl2b-3_MP	LHD	0.60%	$40,435	$30,124	-$10,311
14T_Box_Cl4-5_U	LHD	0.60%	$40,573	$29,160	-$11,413
15T_Box_Cl4-5_R	LHD	0.60%	$40,573	$31,177	-$9,396
16T_Box_Cl4-5_MP	LHD	0.60%	$40,573	$30,124	-$10,449
17B_Coach_Cl8_R	HHD	0.02%	$64,534	$103,599	$39,065
18B_Coach_Cl8_MP	HHD	0.01%	$64,534	$119,961	$55,427
19C_Mix_Cl8_MP	HHD	0.06%	$72,490	$73,931	$1,442
20T_Dump_Cl8_U	HHD	0.10%	$82,009	$57,596	-$24,413
21T_Dump_Cl8_MP	HHD	0.13%	$82,009	$58,008	-$24,002
22T_Dump_Cl6-7_MP	MHD	0.18%	$45,906	$51,205	$5,299
23T_Dump_Cl8_U	HHD	0.05%	$72,490	$57,596	-$14,893
24T_Dump_Cl6-7_U	MHD	0.06%	$45,906	$49,207	$3,301
25T_Fire_Cl8_MP	HHD	0.03%	$82,009	$59,614	-$22,396
26T_Fire_Cl8_U	HHD	0.03%	$72,490	$59,685	-$12,805
27T_Flat_Cl6-7_MP	MHD	0.25%	$45,906	$38,945	-$6,961
28T_Flat_Cl6-7_R	MHD	0.10%	$45,906	$40,606	-$5,300
29T_Flat_Cl6-7_U	MHD	0.25%	$45,906	$37,484	-$8,423
30Tractor_DC_Cl8	DC	0.53%	$86,401	$72,729	-$13,672
31Tractor_DC_Cl7	DC	0.27%	$67,944	$62,202	-$5,742
32Tractor_SC_Cl8	SC	0.47%	$89,628	$140,669	$51,040
33Tractor_DC_Cl8	DC	0.34%	$68,773	$90,955	$22,182
34T_Ref_Cl8_MP	HHD	0.04%	$68,236	$64,494	-$3,742
35T_Ref_Cl6-7_MP	MHD	0.00%	$45,906	$52,600	$6,693
36T_Ref_Cl8_U	HHD	0.04%	$68,236	$64,494	-$3,742
37T_Ref_Cl6-7_U	MHD	0.01%	$45,906	$52,168	$6,262
38RV_Cl8_R	HHD	0.00%	$47,970	$87,083	$39,113
39RV_Cl6-7_R	MHD	0.00%	$46,022	$87,687	$41,664
40RV_Cl4-5_R	LHD	0.00%	$39,716	$60,837	$21,121
41Tractor_DC_Cl7	DC	0.03%	$67,944	$114,640	$46,695
42RV_Cl8_MP	HHD	0.00%	$47,970	$87,083	$39,113
43RV_Cl6-7_MP	MHD	0.00%	$46,022	$82,070	$36,047
44RV_Cl4-5_MP	LHD	0.00%	$39,716	$57,254	$17,538
45Tractor_DC_Cl8	DC	0.00%	$89,629	$151,102	$61,473
46B_School_Cl8_MP	HHD	0.01%	$47,970	$53,583	$5,613
47B_School_Cl6-7_MP	MHD	0.65%	$46,022	$38,259	-$7,763
48B_School_Cl4-5_MP	LHD	0.03%	$39,716	$31,360	-$8,356
49B_School_Cl2b-3_MP	LHD	0.03%	$41,622	$30,716	-$10,906
50B_School_Cl8_U	HHD	0.03%	$47,970	$52,000	$4,030
51B_School_Cl6-7_U	MHD	0.65%	$46,022	$38,259	-$7,763
52B_School_Cl4-5_U	LHD	0.03%	$39,716	$30,441	-$9,275
53B_School_Cl2b-3_U	LHD	0.03%	$41,622	$29,770	-$11,852
54Tractor_SC_Cl8	SC	0.00%	$89,628	$162,140	$72,512
55B_Shuttle_Cl2b-3_MP	LHD	0.11%	$41,622	$36,488	-$5,134
56B_Shuttle_Cl4-5_U	LHD	0.19%	$39,716	$35,719	-$3,996
57B_Shuttle_Cl2b-3_U	LHD	0.19%	$41,622	$35,048	-$6,574

58B_Shuttle_Cl6-7_MP	MHD	0.00%	$46,022	$49,888	$3,866
59B_Shuttle_Cl6-7_U	MHD	0.01%	$46,022	$47,742	$1,719
60S_Plow_Cl6-7_MP	MHD	0.02%	$45,906	$42,443	-$3,463
61S_Plow_Cl8_MP	HHD	0.00%	$82,009	$70,168	-$11,842
62S_Plow_Cl6-7_U	MHD	0.01%	$45,906	$41,024	-$4,883
63S_Plow_Cl8_U	HHD	0.00%	$72,490	$69,418	-$3,072
64V_Step_Cl6-7_MP	MHD	0.25%	$45,808	$39,001	-$6,807
65V_Step_Cl4-5_MP	LHD	0.60%	$39,716	$30,124	-$9,592
66V_Step_Cl2b-3_MP	LHD	0.11%	$41,103	$30,069	-$11,034
67V_Step_Cl6-7_U	MHD	0.25%	$45,808	$37,528	-$8,281
68V_Step_Cl4-5_U	LHD	0.60%	$39,716	$29,160	-$10,556
69V_Step_Cl2b-3_U	LHD	0.11%	$41,103	$29,106	-$11,997
70S_Sweep_Cl6-7_U	MHD	0.25%	$45,906	$40,489	-$5,417
71T_Tanker_Cl8_R	HHD	0.06%	$82,009	$56,117	-$25,892
72T_Tanker_Cl8_MP	HHD	0.08%	$72,490	$55,556	-$16,934
73T_Tanker_Cl8_U	HHD	0.06%	$72,490	$55,400	-$17,089
74T_Tow_Cl8_R	HHD	0.03%	$84,574	$72,281	-$12,293
75T_Tow_Cl6-7_R	MHD	0.00%	$45,906	$53,833	$7,927
76T_Tow_Cl8_U	HHD	0.03%	$72,490	$70,797	-$1,693
77T_Tow_Cl6-7_U	MHD	0.03%	$45,906	$49,335	$3,428
78Tractor_SC_Cl8	SC	0.66%	$89,628	$125,005	$35,376
79Tractor_SC_Cl8	SC	0.00%	$89,628	$153,939	$64,310
80Tractor_DC_Cl8	DC	0.00%	$90,646	$104,227	$13,581
81Tractor_DC_Cl7	DC	0.23%	$67,944	$86,275	$18,330
82Tractor_DC_Cl8	DC	0.34%	$89,629	$105,831	$16,202
83Tractor_DC_Cl7	DC	0.14%	$67,944	$78,172	$10,228
84Tractor_DC_Cl8	DC	0.82%	$84,119	$72,499	-$11,620
85B_Transit_Cl8_MP	HHD	0.40%	$64,534	$76,738	$12,204
86B_Transit_Cl6-7_MP	MHD	0.00%	$46,022	$62,160	$16,138
87B_Transit_Cl8_U	HHD	0.14%	$63,761	$76,738	$12,977
88B_Transit_Cl6-7_U	MHD	0.00%	$46,022	$58,635	$12,613
89T_Utility_Cl8_MP	HHD	0.08%	$82,009	$54,431	-$27,579
90T_Utility_Cl8_R	HHD	0.03%	$82,009	$55,157	-$26,852
91T_Utility_Cl6-7_MP	MHD	0.25%	$45,906	$40,760	-$5,146
92T_Utility_Cl6-7_R	MHD	0.10%	$45,906	$42,312	-$3,595
93T_Utility_Cl4-5_MP	LHD	0.60%	$43,051	$31,402	-$11,649
94T_Utility_Cl2b-3_MP	LHD	0.60%	$41,103	$30,654	-$10,449
95T_Utility_Cl4-5_R	LHD	0.04%	$43,051	$32,333	-$10,718
96T_Utility_Cl2b-3_R	LHD	0.04%	$41,103	$32,278	-$8,825
97T_Utility_Cl8_U	HHD	0.03%	$72,490	$53,937	-$18,552
98T_Utility_Cl6-7_U	MHD	0.25%	$45,906	$39,555	-$6,352
99T_Utility_Cl4-5_U	LHD	0.60%	$43,051	$30,630	-$12,421
100T_Utility_Cl2b-3_U	LHD	0.60%	$41,103	$29,778	-$11,325
101Tractor_DC_Cl8	DC	0.08%	$84,119	$63,828	-$20,290

Table 2-117 Incremental ZEV RPE Costs for MY 2032 (2022$)

Vehicle ID	Regulatory Group	ZEV Adoption Rate	ICE PT RPE (per vehicle)	ZEV PT RPE Including Battery Tax Credit (per vehicle)	Incremental ZEV RPE (per vehicle)
01V_Amb_Cl4-5_MP	LHD	1.16%	$42,616	$31,938	-$10,679
02V_Amb_Cl2b-3_MP	LHD	1.16%	$40,688	$31,044	-$9,643
03V_Amb_Cl4-5_U	LHD	1.16%	$42,616	$30,911	-$11,706
04V_Amb_Cl2b-3_U	LHD	1.16%	$40,688	$29,987	-$10,701
05T_Box_Cl8_MP	HHD	0.23%	$81,181	$54,950	-$26,231
06T_Box_Cl8_R	HHD	0.11%	$81,181	$55,961	-$25,220
07T_Box_Cl6-7_MP	MHD	0.30%	$45,699	$40,148	-$5,551
08T_Box_Cl6-7_R	MHD	0.22%	$45,699	$42,004	-$3,695
09T_Box_Cl8_U	HHD	0.13%	$71,758	$53,995	-$17,763
10T_Box_Cl6-7_U	MHD	0.53%	$45,699	$39,378	-$6,321
11T_Box_Cl2b-3_U	LHD	1.16%	$40,026	$29,479	-$10,547
12T_Box_Cl2b-3_R	LHD	1.16%	$40,026	$31,733	-$8,293
13T_Box_Cl2b-3_MP	LHD	1.16%	$40,026	$30,556	-$9,471
14T_Box_Cl4-5_U	LHD	1.16%	$40,163	$29,479	-$10,684
15T_Box_Cl4-5_R	LHD	0.65%	$40,163	$31,733	-$8,430
16T_Box_Cl4-5_MP	LHD	1.16%	$40,163	$30,556	-$9,607
17B_Coach_Cl8_R	HHD	0.03%	$63,882	$111,645	$47,763
18B_Coach_Cl8_MP	HHD	0.03%	$63,882	$113,169	$49,287
19C_Mix_Cl8_MP	HHD	0.13%	$71,758	$78,093	$6,335
20T_Dump_Cl8_U	HHD	0.20%	$81,181	$59,836	-$21,345
21T_Dump_Cl8_MP	HHD	0.36%	$81,181	$60,296	-$20,885
22T_Dump_Cl6-7_MP	MHD	0.20%	$45,443	$53,738	$8,296
23T_Dump_Cl8_U	HHD	0.07%	$71,758	$59,836	-$11,922
24T_Dump_Cl6-7_U	MHD	0.07%	$45,443	$51,505	$6,062
25T_Fire_Cl8_MP	HHD	0.05%	$81,181	$62,091	-$19,090
26T_Fire_Cl8_U	HHD	0.05%	$71,758	$62,170	-$9,588
27T_Flat_Cl6-7_MP	MHD	0.30%	$45,443	$40,036	-$5,407
28T_Flat_Cl6-7_R	MHD	0.11%	$45,443	$41,892	-$3,551
29T_Flat_Cl6-7_U	MHD	0.53%	$45,443	$38,402	-$7,041
30Tractor_DC_Cl8	DC	0.46%	$85,528	$75,533	-$9,995
31Tractor_DC_Cl7	DC	0.23%	$67,258	$64,983	-$2,275
32Tractor_SC_Cl8	SC	1.07%	$88,723	$151,842	$63,119
33Tractor_DC_Cl8	DC	1.03%	$68,078	$96,273	$28,195
34T_Ref_Cl8_MP	HHD	0.03%	$67,547	$67,766	$220
35T_Ref_Cl6-7_MP	MHD	0.01%	$45,443	$55,297	$9,854
36T_Ref_Cl8_U	HHD	0.03%	$67,547	$67,766	$220
37T_Ref_Cl6-7_U	MHD	0.01%	$45,443	$54,815	$9,372
38RV_Cl8_R	HHD	0.00%	$47,485	$93,186	$45,700
39RV_Cl6-7_R	MHD	0.00%	$45,558	$94,477	$48,919
40RV_Cl4-5_R	LHD	0.00%	$39,314	$64,883	$25,568
41Tractor_DC_Cl7	DC	0.40%	$67,258	$109,002	$41,744
42RV_Cl8_MP	HHD	0.00%	$47,485	$93,186	$45,700
43RV_Cl6-7_MP	MHD	0.00%	$45,558	$88,199	$42,641
44RV_Cl4-5_MP	LHD	0.00%	$39,314	$60,878	$21,564

45Tractor_DC_Cl8	DC	0.21%	$88,723	$143,789	$55,065
46B_School_Cl8_MP	HHD	0.02%	$47,485	$55,744	$8,258
47B_School_Cl6-7_MP	MHD	1.37%	$45,558	$39,233	-$6,324
48B_School_Cl4-5_MP	LHD	0.05%	$39,314	$31,938	-$7,377
49B_School_Cl2b-3_MP	LHD	0.05%	$41,201	$31,198	-$10,004
50B_School_Cl8_U	HHD	0.05%	$47,485	$53,974	$6,489
51B_School_Cl6-7_U	MHD	1.37%	$45,558	$39,233	-$6,324
52B_School_Cl4-5_U	LHD	0.05%	$39,314	$30,911	-$8,404
53B_School_Cl2b-3_U	LHD	0.05%	$41,201	$30,140	-$11,061
54Tractor_SC_Cl8	SC	0.00%	$88,723	$175,840	$87,117
55B_Shuttle_Cl2b-3_MP	LHD	0.21%	$41,201	$37,649	-$3,552
56B_Shuttle_Cl4-5_U	LHD	0.36%	$39,314	$36,810	-$2,504
57B_Shuttle_Cl2b-3_U	LHD	0.36%	$41,201	$36,040	-$5,162
58B_Shuttle_Cl6-7_MP	MHD	0.00%	$45,558	$52,231	$6,673
59B_Shuttle_Cl6-7_U	MHD	0.01%	$45,558	$49,832	$4,274
60S_Plow_Cl6-7_MP	MHD	0.03%	$45,443	$43,945	-$1,498
61S_Plow_Cl8_MP	HHD	0.00%	$81,181	$73,887	-$7,294
62S_Plow_Cl6-7_U	MHD	0.01%	$45,443	$42,359	-$3,084
63S_Plow_Cl8_U	HHD	0.00%	$71,758	$73,048	$1,291
64V_Step_Cl6-7_MP	MHD	0.53%	$45,345	$40,113	-$5,233
65V_Step_Cl4-5_MP	LHD	1.16%	$39,314	$30,556	-$8,759
66V_Step_Cl2b-3_MP	LHD	0.20%	$40,688	$30,505	-$10,183
67V_Step_Cl6-7_U	MHD	0.53%	$45,345	$38,466	-$6,879
68V_Step_Cl4-5_U	LHD	1.16%	$39,314	$29,479	-$9,836
69V_Step_Cl2b-3_U	LHD	0.20%	$40,688	$29,428	-$11,260
70S_Sweep_Cl6-7_U	MHD	0.53%	$45,443	$41,761	-$3,681
71T_Tanker_Cl8_R	HHD	0.05%	$81,181	$58,183	-$22,998
72T_Tanker_Cl8_MP	HHD	0.23%	$71,758	$57,555	-$14,202
73T_Tanker_Cl8_U	HHD	0.13%	$71,758	$57,382	-$14,376
74T_Tow_Cl8_R	HHD	0.05%	$83,719	$76,248	-$7,471
75T_Tow_Cl6-7_R	MHD	0.00%	$45,443	$56,675	$11,233
76T_Tow_Cl8_U	HHD	0.05%	$71,758	$74,590	$2,833
77T_Tow_Cl6-7_U	MHD	0.04%	$45,443	$51,648	$6,205
78Tractor_SC_Cl8	SC	2.10%	$88,723	$134,335	$45,612
79Tractor_SC_Cl8	SC	1.55%	$88,723	$145,647	$56,924
80Tractor_DC_Cl8	DC	0.02%	$89,730	$111,064	$21,334
81Tractor_DC_Cl7	DC	0.71%	$67,258	$91,888	$24,630
82Tractor_DC_Cl8	DC	1.03%	$88,723	$112,326	$23,603
83Tractor_DC_Cl7	DC	0.23%	$67,258	$82,832	$15,574
84Tractor_DC_Cl8	DC	2.53%	$83,269	$75,423	-$7,846
85B_Transit_Cl8_MP	HHD	0.84%	$63,882	$81,623	$17,741
86B_Transit_Cl6-7_MP	MHD	0.00%	$45,558	$65,947	$20,389
87B_Transit_Cl8_U	HHD	0.30%	$63,117	$81,623	$18,506
88B_Transit_Cl6-7_U	MHD	0.00%	$45,558	$62,007	$16,449
89T_Utility_Cl8_MP	HHD	0.23%	$81,181	$56,298	-$24,883
90T_Utility_Cl8_R	HHD	0.02%	$81,181	$57,110	-$24,071
91T_Utility_Cl6-7_MP	MHD	0.30%	$45,443	$42,064	-$3,379

92T_Utility_Cl6-7_R	MHD	0.11%	$45,443	$43,798	-$1,645
93T_Utility_Cl4-5_MP	LHD	1.16%	$42,616	$31,985	-$10,631
94T_Utility_Cl2b-3_MP	LHD	1.16%	$40,688	$31,159	-$9,529
95T_Utility_Cl4-5_R	LHD	0.04%	$42,616	$33,025	-$9,591
96T_Utility_Cl2b-3_R	LHD	0.04%	$40,688	$32,974	-$7,714
97T_Utility_Cl8_U	HHD	0.05%	$71,758	$55,746	-$16,011
98T_Utility_Cl6-7_U	MHD	0.53%	$45,443	$40,717	-$4,726
99T_Utility_Cl4-5_U	LHD	1.16%	$42,616	$31,122	-$11,495
100T_Utility_Cl2b-3_U	LHD	1.16%	$40,688	$30,179	-$10,508
101Tractor_DC_Cl8	DC	0.14%	$83,269	$65,732	-$17,537

Table 2-118 Manufacturer Costs to Meet the Final MY 2027 Standards Relative to the Reference Case (2022$)

Regulatory Group	Incremental ZEV Adoption Rate in Technology Package	Per-ZEV Manufacturer RPE on Average	Fleet-Average Per-Vehicle Manufacturer RPE
LHD Vocational Vehicles	7%	-$4,100	-$283
MHD Vocational Vehicles	6%	$3,959	$242
HHD Vocational Vehicles	0%	N/A	$0
Day Cab and Heavy Haul Tractors	0%	N/A	$0
Sleeper Cab Tractors	0%	N/A	$0

Note: The average costs represent the average across the regulatory group. For example, the first row represents the average across all LHD vocational vehicles

Table 2-119 Manufacturer Costs to Meet the Final MY 2030 Standards Relative to the Reference Case (2022$)

Regulatory Group	Incremental ZEV Adoption Rate in Technology Package	Per-ZEV Manufacturer RPE on Average	Fleet-Average Per-Vehicle Manufacturer RPE
LHD Vocational Vehicles	7%	-$10,637	-$723
MHD Vocational Vehicles	5%	-$6,164	-$296
HHD Vocational Vehicles	4%	-$7,582	-$273
Day Cab and Heavy Haul Tractors	7%	$32	$2
Sleeper Cab Tractors	4%	$41,877	$1,717

Note: The average costs represent the average across the regulatory group. For example, the first row represents the average across all LHD vocational vehicles

Table 2-120 Manufacturer Costs to Meet the Final MY 2032 Standards Relative to the Reference Case (2022$)

Regulatory Group	Incremental ZEV Adoption Rate in Technology Package	Per-ZEV Manufacturer RPE on Average	Fleet-Average Per-Vehicle Manufacturer RPE
LHD Vocational Vehicles	30%	-$9,776	-$2,923
MHD Vocational Vehicles	20%	-$5,033	-$981
HHD Vocational Vehicles	16%	-$3,989	-$654
Day Cab and Heavy Haul Tractors	30%	$10,816	$3,202
Sleeper Cab Tractors	20%	$53,295	$10,819

Note: The average costs represent the average across the regulatory group. For example, the first row represents the average across all LHD vocational vehicles.

2.10.6.2 Purchaser Costs

We also evaluated the costs of the final standards for purchasers on average by regulatory group. Our assessment of the upfront purchaser costs includes the incremental cost of a ZEV relative to a comparable ICE vehicle after accounting for the two IRA tax credits (IRA section 13502, “Advanced Manufacturing Production Credit,” and IRA section 13403, “Qualified Commercial Clean Vehicles”) and the associated EVSE costs (including the tax credit under IRA section 13404, “Alternative Fuel Refueling Property Credit”), if applicable. We also assessed the incremental annual operating savings of a ZEV relative to a comparable ICE vehicle. The payback periods shown reflect the number of years it will take for the annual operating savings to offset the increase in total upfront costs for the purchaser. The results of this analysis are shown in Table 2-121 through Table 2-123.

Table 2-121 MY 2027 Purchaser Per-ZEV Upfront Costs, Operating Costs, and Payback Period (2022$)

Regulatory Group	Adoption Rate in Technology Package	Incremental Per-ZEV RPE Cost on Average (before IRA Purchase Tax Credit and Taxes)	EVSE Costs Per-ZEV on Average	Total Incremental Upfront Per-ZEV Costs on Average Including Taxes	Annual Incremental Operating Costs Per-ZEV on Average	Payback Period (year) on Average
LHD Vocational Vehicles	17%	-$4,100	$11,623	$7,165	-$3,383	3
MHD Vocational Vehicles	13%	$3,959	$17,084	$17,283	-$4,692	5
HHD Vocational Vehicles	0%	N/A	N/A	N/A	N/A	N/A
Day Cab and Heavy Haul Tractors	0%	N/A	N/A	N/A	N/A	N/A
Sleeper Cab Tractors	0%	N/A	N/A	N/A	N/A	N/A

Note: The average costs represent the average across the regulatory group, for example the first row represents the average across all LHD vocational vehicles.

Table 2-122 MY 2030 Purchaser Per-ZEV Upfront Costs, Operating Costs, and Payback Period (2022$)

Regulatory Group	Adoption Rate in Technology Package	Incremental Per-ZEV RPE Cost on Average (before IRA Purchase Tax Credit and Taxes)	EVSE Costs Per-ZEV on Average	Total Incremental Upfront Per-ZEV Costs on Average Including Taxes	Annual Incremental Operating Costs Per-ZEV on Average	Payback Period (year) on Average
LHD Vocational Vehicles	32%	-$10,637	$11,800	$629	-$3,626	1
MHD Vocational Vehicles	22%	-$6,164	$16,133	$9,325	-$5,020	3
HHD Vocational Vehicles	15%	-$7,582	$48,099	$34,532	-$10,412	4
Day Cab and Heavy Haul Tractors	16%	$32	$14,272	$7,168	-$5,708	3
Sleeper Cab Tractors	6%	$41,877	$0	$11,709	-$9,034	3

Note: The average costs represent the average across the regulatory group, for example the first row represents the average across all LHD vocational vehicles.

Table 2-123 MY 2032 Purchaser Per-ZEV Upfront Costs, Operating Costs, and Payback Period (2022$)

Regulatory Group	Adoption Rate in Technology Package	Incremental Per-ZEV RPE Cost on Average (before IRA Purchase Tax Credit and Taxes)	EVSE Costs Per-ZEV on Average	Total Incremental Upfront Per-ZEV Costs on Average Including Taxes	Annual Incremental Operating Costs on Average	Payback Period (year) on Average
LHD Vocational Vehicles	60%	-$9,776	$11,736	$1,470	-$3,682	2
MHD Vocational Vehicles	40%	-$5,033	$15,304	$9,678	-$5,132	3
HHD Vocational Vehicles	30%	-$3,989	$46,204	$34,505	-$10,514	4
Day Cab and Heavy Haul Tractors	40%	$10,816	$5,952	$4,418	-$5,516	2
Sleeper Cab Tractors	25%	$53,295	$0	$22,366	-$8,303	5

Note: The average costs represent the average across the regulatory group, for example the first row represents the average across all LHD vocational vehicles.

As shown in Table 2-123, under the final rule, we estimate that the average upfront cost per vehicle to purchase a new MY 2032 vocational ZEV and associated EVSE compared to a comparable ICE vehicle (after accounting for three IRA tax credits: IRA section 13502, "Advanced Manufacturing Production Credit;" IRA section 13403, "Qualified Commercial Clean Vehicles;" and IRA section 13404, "Alternative Fuel Refueling Property Credit"), will be offset by operational costs (i.e., savings that come from the lower costs to operate, maintain, and repair ZEV technologies), such that we expect the upfront cost increase will be recouped due to operating savings in two to four years, on average for vocational vehicles. For a new MY 2032 day cab tractor ZEV and associated EVSE as applicable, we estimate the average incremental upfront cost per vehicle will be recovered in two years, on average. Similarly, for sleeper cab tractors, we estimate that the initial cost increase will be recouped in five years.

2.11 Additional Example Compliance Pathway Technology Packages to Support the Final Standards

While the potential compliance pathway's technology packages that include both vehicles with ICE and ZEV technologies discussed in preamble Section II.F.1 and RIA Chapter 2.10 support the feasibility of the final standards and was modeled for rulemaking purposes, there are many other examples of possible compliance pathways for meeting the final standards that do not involve the widespread adoption of BEV and FCEV technologies. In this section and preamble Section II.F.4, we provide further support for the feasibility of the final standards by describing examples of additional potential compliance pathways that are based on nationwide production volumes, including compliance pathways that involve only technologies for vehicles with ICE across a range of electrification (i.e., without producing additional ZEVs to comply with this rule).

In this section, we discuss our analysis for the technologies included in the additional example compliance pathway of the impacts on reductions of GHG emissions; the technical feasibility and technology effectiveness; the lead time necessary to implement the technologies; costs to manufacturers; and willingness to purchase (including purchaser costs and payback). In short, EPA finds that, even without manufacturers producing additional ZEVs to comply with this rule, it would be technologically feasible to meet the final standards in the lead time provided and taking into consideration compliance costs. Regarding reductions of GHG emissions, these additional example potential compliance pathways meet the final Phase 3 MY 2027 through MY 2032 and later CO_2 emission standards, and therefore achieve the same level of vehicle CO_2 emission reductions and downstream CO_2 emission reductions as presented in preamble Section V and RIA Chapter 4. Regarding technical feasibility and lead time, depending on the technology, we determined that either no further development of the technology is required (only further application) or the technology is technically feasible and being actively developed by manufacturers to be commercially available for MY 2027 and later, and that there is sufficient lead time. Similar to the approach we considered for BEVs and FCEVs in this preamble Section II, for relevant technologies we also included a phased approach to provide lead time to meet the corresponding charging and refueling infrastructure needs under the final rule's additional example potential compliance pathways. Regarding costs of compliance, consistent with our Phase 2 assessment, we conclude that the estimated costs for all model years are reasonable for one of the additional example potential compliance pathways, for example based on our estimate that the MY 2032 fleet average per-vehicle cost to manufacturers by regulatory group will be \$3,800 for LHD; \$7,600 for MHD vocational vehicles; and \$7,700 for HHD vocational vehicles, and range between \$10,300 for day cab tractors and \$10,400 for sleeper cab tractors. For another additional example potential compliance pathway, which we developed and assessed because manufacturers may choose to offer technologies (such as PHEVs) that have a higher projected upfront cost but also have a shorter payback period, we estimated higher costs of compliance (e.g., approximately 18 percent of the price of a new tractor for MY 2032) and conclude these costs are also reasonable here given consideration of the corresponding business case for manufacturers to successfully deploy these technologies when considering willingness to purchase, including the payback period of these technologies and the IRA purchaser tax credits for PHEVs. Regarding our assessment of impacts on purchasers and willingness to purchase, the technologies we assessed generally pay back within 10 years or less. As we explain elsewhere in this preamble Section II, businesses that operate HD vehicles are under competitive pressure to reduce operating costs, which should encourage purchasers to identify and adopt vehicle technologies that provide a reasonable payback period. For H2-ICE tractors, our assessment is that the operating costs exceed the operating costs of ICE tractors, but there may be other reasons that purchasers would consider this technology such as the vehicles emit nearly zero CO_2 emissions at the tailpipe, the low engine-out exhaust emissions from H2-ICE vehicles provide the opportunity for efficient and durable after-treatment systems, and the efficiency of H2-ICE vehicles may continue to improve with time. Overall, the fact that such a fleet as the examples assessed in this section are possible underscores both the feasibility and the flexibility of the performance-based standards, and confirms that manufacturers are likely to continue to offer vehicles with a diverse range of technologies, including advanced vehicle with ICE technologies as well as ZEVs for the duration of these standards and beyond.

The vehicles considered in these additional pathways include a suite of technologies ranging from improvements in aerodynamics and tire rolling resistance in ICE tractors, to the use of lower carbon fuels like CNG and LNG, to hybrid powertrains (HEV and PHEV) and H2-ICE. As described below these technologies either exist today or are actively being developed by manufacturers to be commercially available for MY 2027 and later.

This section presents our analysis of the effectiveness of reducing CO_2 emissions, the associated lead time, and the technology package costs for the technologies considered in these additional possible pathways in Chapter 2.11.1 and 2.11.2 (we discuss the technologies themselves in preamble RIA Chapter 1). We then created technology packages based on adoption rates of aggregated individual technologies into three scenarios for MYs 2027, 2030, and 2032 that represent additional example potential compliance pathways that further support the feasibility of the final standards in Chapter 2.11.3. The technology packages and adoption rates include a mix of vehicles with ICE technologies. For example, the additional example potential compliance pathways include some vocational vehicles with the technology package that supported the Phase 2 MY 2027 CO_2 vocational vehicle emission standards (shown in Chapter 2.3, and that include technologies such as low rolling resistance tires; tire inflation systems; efficient engines, transmissions, and drivetrains; weight reduction; and idle reduction technologies) as well as additional natural gas engine, H2-ICE vehicle, hybrid powertrain, and PHEV technologies for vocational vehicles. For another example, the additional example potential compliance pathways include tractors with further aerodynamic and tire improvements in addition to the technology package that supported the Phase 2 MY 2027 CO_2 tractor emission standards (shown in Chapter 2.3, and that include technologies such as improved aerodynamics; low rolling resistance tires; tire inflation systems; efficient engines, transmissions, drivetrains, and accessories; and extended idle reduction for sleeper cabs) as well as additional natural gas engine, H2-ICE vehicle, hybrid powertrain, and PHEV technologies for tractors. The technology packages also include our projected reference case (see RIA Chapter 4) ZEV adoption rates.

Scenario 1 meets the MY 2032 standards with higher adoption of vehicles with H2-ICE technology. Scenario 2 meets the MY 2032 standards with higher adoption of PHEV technology. We also developed another set of technology packages that do not include our projected reference case ZEV adoption rates (i.e., they are potential compliance pathways that support the feasibility of the standards with only technologies for vehicles with ICE, with zero nationwide adoption of ZEV technologies) is also presented in RIA Chapter 2.11.3. Finally, we assessed the manufacturer costs under these additional example potential compliance pathways, in Chapter 2.11.4, and purchaser costs and payback in Chapter 2.11.5.

The vehicle manufacturers that certified to EPA standards for MY 2022 and/or MY 2023 are those listed in Table 2-124. Manufacturers used a wide variety of technologies to meet the standards. The manufacturer names with '*' indicate that they have EPA certifications for vehicles that use natural gas. The manufacturer names with '^' indicate they have EPA certifications for vehicles with hybrid powertrains. Since the public certification data for these MYs doesn't identify which vehicles are certified with hybrid powertrains, we relied on information identified in Chapter 1.4 of the RIA. As for hydrogen-fueled internal combustion engines, no manufacturers have certified to EPA standards for MY 2022 with the technology, however a number of manufacturers have indicated that they are developing an engine that can run on hydrogen.[1277] Finally, there are a number of manufacturers that have certified ICE vehicles that have projected CO_2 FEL that are lower than the Phase 2 MY 2027 standards. The manufacturer names with '#' indicate that they have one or more vehicles families that currently meet the Phase 2 MY 2027 standards, and which we thus project will have CO_2 FEL that are lower than the Phase 2 MY 2027 standards in MY 2027.

Table 2-124 Vehicle Manufacturers Certified to EPA HDV Emission Standards in MY 2022

ARBOC Specialty Vehicles, LLC *	General Motors LLC $^{\#}$	Rosenbauer Motors LLC
Autocar, LLC *$^{\#}$	Gillig LLC *^	SEA Electric
Battle Motors, Inc.*	Global Environment Product Inc *	Seagrave Fire Apparatus LLC
Blue Bird Body Company *	Grove US LLC	Spartan Fire LLC
BYD Auto Industry Company Ltd	Hino Motors, Ltd $^{\#}$	Temsa Skoda Sabanci Ulasim Araclari A.S. $^{\#}$
Daimler Coaches North America *	HME Inc	Terex Corporation
Daimler Truck North America LLC $^{\#}$	Isuzu Motors Limited $^{\#}$	The Shyft Group
Dennis Eagle Inc *	Motor Coach Industries *	Tifton Motor Homes Inc
Eldorado National-California Inc *	Navistar, Inc $^{\#}$	Van Hool N.V.
Envirotech Drive Systems Inc	New Flyer of America, Inc *^	Vicinity Motor (Bus) Corp *
E-One Inc	Nikola Corporation	Volvo Group Trucks, Technology, Powertrain Engineering, a Division of Mack Trucks *^$^{\#}$
FCA US LLC $^{\#}$	Oshkosh Corporation ^	XOS, Inc
Ferrara Fire Apparatus Inc	PACCAR Inc *$^{\#}$	Zeus Electric Chassis, Inc
Ford Motor Co $^{\#}$	Proterra Operating Company, Inc	

[1277] Cummins. "Cummins to Reveal Zero-Carbon H2-ICE Concept Truck at IAA Expo Powered by the B6.7H Hydrogen Engine". September 13, 2022. Available Online: https://www.cummins.com/news/releases/2022/09/13/cummins-reveal-zero-carbon-h2-ice-concept-truck-iaa-expo-powered-b67h.

2.11.1 Technology Effectiveness and Lead Time

We evaluated the potential for lower CO_2 emissions from further aerodynamic and tire improvements to ICE tractors as well as natural gas engine, H2-ICE vehicle, hybrid powertrain, and PHEV technologies for both vocational vehicles and tractors, as discussed in Section II.D.1. See Chapter 1.4 for further discussion of EPA's assessment that these technologies are technically feasible.

2.11.1.1 Aerodynamic and Tire Improvements for Tractors

In these additional technology pathways, for further aerodynamic and tire improvements to the technology packages that supported the Phase 2 MY 2027 CO_2 emission standards we evaluated technologies to reduce CO_2 emissions from ICE tractors. We note that in these additional pathways, like in our modeled compliance pathway, the ICE vocational vehicles portion of the pathway emit at the Phase 2 MY 2027 level. Therefore, we did not add any additional technologies or costs associated with the vocational ICE vehicles with Phase 2 MY 2027 technologies. We also note that the Phase 2 standards for vocational vehicles did not include the use of aerodynamic technologies and were projected to be met with the use of improvements in tire rolling resistance and other technologies.

Tractors with ICEs have the potential to have lower CO_2 emissions than required by the Phase 2 MY 2027 CO_2 emission standards by further reducing the aerodynamic drag of the tractor and by reducing the tire rolling resistance. These technologies are being used by manufacturers to certify their tractors to the Phase 2 standards. Therefore, EPA assessed this potential technology package applicable to tractors through a combination of aerodynamic improvements and lower rolling resistant tires.

For this Phase 3 analysis, consistent with our approach in Phase 2 for evaluating technology effectiveness, we evaluated the technologies to reduce aerodynamic drag, as discussed in preamble Section II.D.1.i. The aerodynamic drag performance is determined through aerodynamic testing. The results of the test determine the aerodynamic bin (Bin I through VII) and therefore input to GEM that is used to determine a vehicle's CO_2 emissions. The aerodynamic Bin I level represents tractor bodies which prioritize appearance or special duty capabilities over aerodynamics. These Bin I tractors incorporate few, if any, aerodynamic features and may have several features which detract from aerodynamics, such as bug deflectors, custom sunshades, B-pillar exhaust stacks, and others. Bin V represents the most aerodynamic MY 2022 tractors.

The aerodynamic technology already exists for the tractors to achieve Bin IV and Bin V performance in MY 2021, therefore, our assessment is that there is sufficient lead time for tractor manufacturers to increase application of these aerodynamic designs by MY 2027 and to produce more low and mid roof tractors at a Bin IV level of performance and more high roof tractors at a Bin V performance. Because no further development of aerodynamic technology is required, only further application of the technologies, under the additional example potential compliance pathways our assessment is that there is sufficient lead time to include in those technology packages the entire tractor aerodynamic performance to the levels shown in Table 2-125.

Table 2-125: Aerodynamic Technology Package Adoption Rates for an Additional Compliance Pathway

	Class 7			Class 8					
	Day Cab			Day Cab			Sleeper Cab		
	Low Roof	Mid Roof	High Roof	Low Roof	Mid Roof	High Roof	Low Roof	Mid Roof	High Roof
Bin I	0%	0%	0%	0%	0%	0%	0%	0%	0%
Bin II	0%	0%	0%	0%	0%	0%	0%	0%	0%
Bin III	0%	0%	0%	0%	0%	0%	0%	0%	0%
Bin IV	100%	100%	0%	100%	100%	0%	100%	100%	0%
Bin V	0%	0%	100%	0%	0%	100%	0%	0%	100%
Bin VI	0%	0%	0%	0%	0%	0%	0%	0%	0%
Bin VII	0%	0%	0%	0%	0%	0%	0%	0%	0%

For this Phase 3 analysis, we also evaluated technologies to reduce tire rolling resistance on tractors, as discussed in Section II.D.1.ii of the preamble. In Phase 2, we developed four levels of tire rolling resistance. The baseline tire rolling resistance level represents the average tire rolling resistance on tractors in 2010. Levels 1, 2, and 3 are lower rolling resistance tires, with each level representing approximately 15 percent lower rolling resistance than the previous level. In the MY 2021 certification data, we found that the average rolling resistance of the steer tires installed on the day cab and sleeper cab tractors was approximately Level 2. The average rolling resistance of the drive tires installed on day cab and sleeper cab tractors was between Level 1 and Level 2 performance. The exception was for high roof sleeper cabs where the average drive tire rolling resistance was at Level 2. The lowest rolling resistance tires used on each of the day cab and sleeper cab configurations was 4.7 N/kN and 4.8 N/kN ton rolling resistance of the steer and drive tires, respectively, which is better than the Level 3 performance. Our assessment for the additional example potential compliance pathways is that tractor tire rolling resistance can shift to a 50/50 split of Level 2 and Level 3 tire rolling resistance for both the steer and drive tires in MY 2027, as shown in Table 2-126.

Table 2-126 Tire Rolling Resistance Technology Package Adoption Rates for an Additional Compliance Pathway

	Class 7			Class 8					
	Day Cab			Day Cab			Sleeper Cab		
	Low Roof	Mid Roof	High Roof	Low Roof	Mid Roof	High Roof	Low Roof	Mid Roof	High Roof
Steer Tires (CRR)									
Base	0%	0%	0%	0%	0%	0%	0%	0%	0%
Level 1	0%	0%	0%	0%	0%	0%	0%	0%	0%
Level 2	50%	50%	50%	50%	50%	50%	50%	50%	50%
Level 3	50%	50%	50%	50%	50%	50%	50%	50%	50%
Drive Tires (CRR)									
Base	0%	0%	0%	0%	0%	0%	0%	0%	0%
Level 1	0%	0%	0%	0%	0%	0%	0%	0%	0%
Level 2	50%	50%	50%	50%	50%	50%	50%	50%	50%
Level 3	50%	50%	50%	50%	50%	50%	50%	50%	50%

We used the technology effectiveness inputs and technology adoption rates discussed in this section of the preamble for aerodynamics and tire rolling resistance, along with the other vehicle technologies used in the Phase 2 MY 2027 technology package to demonstrate compliance with the Phase 2 MY 2027 tractor standards to develop the GEM inputs for each subcategory of Class 7 and 8 tractors. The set of GEM inputs are shown in Table 2-127. Note that we have analyzed one technology pathway for each level of stringency, but tractor manufacturers are free to use any combination of technologies that meet the standards on average.

Table 2-127 GEM Inputs for Tractor ICE Vehicle Technologies that Achieve a 4% CO2 Reduction Relative to the Phase 2 MY 2027 Standards

Class 7			**Class 8**					
Day Cab			**Day Cab**			**Sleeper Cab**		
Low Roof	**Mid Roof**	**High Roof**	**Low Roof**	**Mid Roof**	**High Roof**	**Low Roof**	**Mid Roof**	**High Roof**
Engine Fuel Map								
2027MY 11L Engine 350 HP	2027MY 11L Engine 350 HP	2027MY 11L Engine 350 HP	2027MY 15L Engine 455 HP	2027MY 15L Engine 455 HP	2027MY 15L Engine 455 HP	2027MY 15L Engine 455 HP	2027MY 15L Engine 455 HP	2027MY 15L Engine 455 HP
Aerodynamics (C_dA in m^2)								
4.75	5.85	5.70	4.75	5.85	5.20	4.75	5.85	4.90
Steer Tire Rolling Resistance (CRR in kg/metric ton)								
5.3	5.3	5.3	5.3	5.3	5.3	5.3	5.3	5.3
Drive Tire Rolling Resistance (CRR in kg/metric ton)								
5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5
Extended Idle Reduction Weighted Effectiveness								
N/A	N/A	N/A	N/A	N/A	N/A	3%	3%	3%
Transmission = 10 speed Manual Transmission Gear Ratios = 12.8, 9.25, 6.76, 4.90, 3.58, 2.61, 1.89, 1.38, 1.00, 0.73								
Drive Axle Ratio = 3.21 for day cabs, 3.16 for sleeper cabs								
6x2 Axle Weighted Effectiveness								
N/A	N/A	N/A	0.6%	0.6%	0.6%	0.6%	0.6%	0.6%
Transmission Type Weighted Effectiveness = 1.6%								
Neutral Idle Weighted Effectiveness								
0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.03%	0.03%	0.03%
Direct Drive Weighted Effectiveness = 1.0%								
Transmission Efficiency Weighted Effectiveness = 0.7%								
Axle Efficiency Improvement = 1.6%								
Air Conditioner Efficiency Improvements = 0.3%								
Accessory Improvements = 0.2%								
Predictive Cruise Control =0.8%								
Automatic Tire Inflation Systems = 0.4%								
Tire Pressure Monitoring System = 0.7%								

The results from GEM for this technology package are shown in Table 2-128. As shown, this technology package within the additional example potential compliance pathway achieves 4 percent lower CO_2 emissions than the Phase 2 MY 2027 tractor standards.

Table 2-128 GEM Results for Phase 3 Additional Compliance Pathway for Tractors

Class 7			Class 8					
Day Cab			Day Cab			Sleeper Cab		
Low Roof	Mid Roof	High Roof	Low Roof	Mid Roof	High Roof	Low Roof	Mid Roof	High Roof
Phase 2 MY 2027 Standards (g CO2/ton-mile)								
96.2	103.4	100.0	73.4	78.0	75.7	64.1	69.6	64.3
Phase 3 MY 2027 Additional Pathway GEM Results (g CO2/ton-mile)								
91.4	98.7	95.2	70.1	74.7	72.6	61.2	66.6	61.9

As previously noted, the corresponding ICE vehicle technology package used within the additional example compliance pathway analysis for a portion of the vocational vehicles is the same technology package used to demonstrate compliance with the Phase 2 MY 2027 standards, as shown in Table 2-129.

Table 2-129 GEM Inputs for Vehicles Meeting the Phase 2 MY 2027 Vocational Vehicle CO_2 Emission Standards

LHD (Class 2b-5)			MHD (Class 6-7)			HHD (Class 8)		
Urban	Multi-Purpose	Regional	Urban	Multi-Purpose	Regional	Urban	Multi-Purpose	Regional
SI Engine Fuel Map								
2018 MY 6.8L, 300 hp engine								
CI Engine Fuel Map								
2027 MY 7L, 200 hp Engine			2027 MY 7L, 270 hp Engine			2027 MY 11L, 350 hp Engine	2027 MY 11L, 350 hp Engine and 2027 MY 15L 455hp Engine	
Torque Converter Lockup in 1st Gear (adoption rate)								
50%	50%	50%	50%	50%	50%	30%	30%	0%
6x2 Disconnect Axle (adoption rate)								
0%	0%	0%	0%	0%	0%	0%	25%	30%
Automatic Engine Shutdown (adoption rate)								
70%	70%	90%	70%	70%	90%	70%	70%	90%
Stop-Start (adoption rate)								
30%	30%	0%	30%	30%	0%	20%	20%	0%
Neutral Idle (adoption rate)								
60%	60%	0%	60%	60%	0%	70%	70%	0%
Steer Tire Rolling Resistance (CRR kg/metric ton)								
6.8	6.2	6.2	6.7	6.2	6.2	6.2	6.2	6.2
Drive Tire Rolling Resistance (CRR kg/metric ton)								
6.9	6.9	6.9	7.5	6.9	6.9	7.5	6.9	6.9
Weight Reduction (pounds)								
75	75	75	75	75	75	125	125	125

In conclusion, under the additional example compliance pathways we project that improvements in ICE vehicle technologies above and beyond the improvements needed to meet the Phase 2 MY 2027 standards will be available for manufacturers to use for tractors and estimate use of those improvements would result in an additional emissions reduction of 4 percent.

2.11.1.2 Natural Gas Fueled Internal Combustion Engines

To estimate the technology effectiveness of natural gas-fueled engines compared to diesel fueled engines in the Phase 3 additional example potential compliance pathways, we used the publicly available MY 2023 heavy-duty engine certification data for CO_2 emissions.[1278] We compared GHG certification data between three engines of similar displacement, power ratings, and intended model application fueled on CNG and conventional diesel. Family Certification CO_2 Levels for the transient Federal Test Procedure (FTP) and Supplemental Emission Test (SET) duty cycles were compared to determine the CO_2 reductions possible by applying natural gas engine technology, as shown in Table 2-130. The comparison shows that natural gas engine technology could achieve CO_2 reductions up to 7 percent for vocational vehicles and 6 percent for tractors compared to a similar diesel fueled ICE.

Table 2-130 Heavy-Duty Engine CO_2 Comparison

	CNG FTP CO_2 (g/hphr)	CNG SET CO_2 (g/hphr)	Diesel FTP CO_2 (g/hphr)	Diesel SET CO_2 (g/hphr)	% Average CO_2 Reduction
Vocational	514	424	524	478	7%
Tractor	501	427	518	470	6%

We also considered the availability of the natural gas fueling stations. According to the U.S. Department of Energy there are 1,464 compressed natural gas and liquified natural gas filling stations in the United States.[1279] Of these stations, approximately 90 percent of them are CNG stations and 10 percent are LNG stations. These stations are a combination of publicly accessible (783) and privately operated (681). Of the publicly accessible fueling stations, all will accommodate Class 3 through 5 HD vehicles and 1,246 will accommodate HD Class 5 through 8 vehicles. After evaluating the existing, and taking into account potential future, natural gas refueling infrastructure, similar to the approach we considered for BEVs and FCEVs in this preamble Section II to ensure adequate lead time for corresponding infrastructure,, we determined that there was adequate lead time for 5 percent adoption of natural gas vehicles in the additional example potential compliance pathways based on our balancing that these technologies are currently available and used as well as the additional consideration of the corresponding infrastructure needed for the level of adoption under these pathways by MY 2027.

2.11.1.3 Hydrogen-Fueled Internal Combustion Engines

Since neat hydrogen fuel does not contain any carbon, H2-ICE fueled with neat hydrogen produce zero HC, CH_4, CO, and CO_2 engine-out emissions.[1280] However, as explained in Section III.C.2.xviii, we recognize that, like CI ICE, there may be negligible, but non-zero, CO_2 emissions at the tailpipe of H2-ICE that use SCR and are fueled with neat hydrogen due to contributions from the aftertreatment system from urea decomposition; thus, for purposes of 40

[1278] US EPA. “Annual Certification Data for Heavy-Duty Vehicles”. January 2023. Available Online: https://www.epa.gov/system/files/documents/2023-01/heavy-duty-gas-and-diesel-engines-2015-present.xlsx

[1279] Department of Energy, Energy Efficiency and Renewable Energy, Alternative Fuels Data Center, Alternative Fuel Station Locator. February 2024. Available online: https://afdc.energy.gov/stations/#/find/nearest?fuel=CNG&country=US.

[1280] Note, NOx and PM emission testing is required under existing 40 CFR part 1036 for engines fueled with neat hydrogen.

CFR 1036 we are finalizing an engine testing default CO_2 emission value (3 g/hp-hr) option (though manufacturers may instead conduct testing to demonstrate that the CO_2 emissions for their engine is below 3 g/hp-hr). Under this final rule, consistent with treatments of such contributions from the aftertreatment system from urea decomposition for diesel ICE vehicles, we are not including such contributions as vehicle emissions for H2-ICE vehicles.[1281] Thus, H2-ICE technologies that run on neat hydrogen, as defined in 40 CFR 1037.150(f) and discussed in Section III.C.3.ii of the preamble, have HD vehicle CO_2 emissions that are deemed to be zero for purposes of 40 CFR 1037. Therefore, the technology effectiveness (in other words CO_2 emission reduction) for the vehicles that are powered by this technology is 100%.

The lead time consideration for H2-ICE vehicles consists of two parts. The first part is the engine technology design and development, along with the integration of the engine, aftertreatment, and fuel storage integration into the vehicle. The second part is the hydrogen refueling infrastructure availability.

An H2-ICE is very similar to existing ICEs and engine manufacturers can leverage the extensive technical expertise they have developed with existing products. Many H2-ICE engine components can be produced using an engine manufacturer's existing tooling and manufacturing processes. Similarly, H2-ICE vehicles can be built on the same assembly lines as other ICE vehicles, by the same workers and with many of the same component suppliers. For example, Cummins has announced the launch of a fuel-agnostic combustion engine X10 for MY 2026 that can run on hydrogen fuel.[1282] Many design aspects of the integration of a H2-ICE into a vehicle can be done in parallel with the H2-ICE ramp up to the production launch of the engine. However, there may be final validation vehicle development steps that will require the final H2-ICE and therefore may take an additional year after the launch of the H2-ICE. Therefore, from the technology development perspective, we project H2-ICE technology will be available in MYs 2027 and later.

The discussion in RIA Chapter 1.8.3 details our assessment of hydrogen refueling infrastructure. After evaluating the existing and projected future hydrogen refueling infrastructure and similar to the approach we considered for publicly-charged BEVs and FCEVs in this preamble Section II, we considered H2-ICE vehicle technology only in the MY 2030 and later timeframe for the additional example potential compliance pathways, to better ensure that our additional example potential compliance pathways provide adequate time for early hydrogen market infrastructure development. We included the H2-ICE technology in the additional compliance pathway relative to the reference case in MY 2031 and later, which provides nearly seven years of lead time for the H2 refueling infrastructure buildout to phase in.

2.11.1.4 Hybrid and Plug-in Hybrid Powertrains

As discussed in Section II.D.1.v, hybrid powertrains have lower CO2 emissions than ICE powertrains due to a combination of regenerative braking and the ability to optimize the ICE

[1281] The results from the fuel mapping test procedures prescribed in 40 CFR 1036.535, 40 CFR 1036.540, and 40 CFR 1036.545, are fuel consumption values; therefore, the CO_2 emissions from urea decomposition is not included in the results.

[1282] Cummins. "Cummins Announces New X10 Engine, Next in The Fuel-Agnostic Series, Launching in North America in 2026." February 2023. Available Online: https://www.cummins.com/news/releases/2023/02/13/cummins-announces-new-x10-engine-next-fuel-agnostic-series-launching-north operation within the hybrid powertrain system. For this Phase 3 analysis we used the approach described in Chapter 2.2.2.1.3 of the RIA to determine the effectiveness of hybrids based on the amount of braking energy recovered from regenerative braking. In summary, to calculate percent energy recovery available, we estimated the braking energy and divided by the total tractive energy (i.e., the energy required to move the vehicle) for each drive cycle and then weighted the results using the respective GEM test cycle weighting factors. We then multiplied these values by the weighted energy consumption per mile to get energy recovered per mile from regenerative braking. The average regeneration energy as a percentage of total tractive energy was 10 percent and 5 percent, for vocational vehicles and tractors, respectively. For both tractors and vocational vehicles, we project that hybrid technology can achieve an additional 5 percent of effectiveness by optimizing how the engine is operated. For example, the engine could be operated in the minimum brake-specific fuel consumption region of the engine more often in a hybrid powertrain. In addition, the electric motor could be used to limit engine transient operation, or the engine could be downsized. This leads to an overall CO_2 emission reduction of 15 percent for vocational vehicle hybrids and 10 percent for tractor hybrids.

For hybrid electric vehicles, the projected effectiveness is further supported by powertrain testing that was conducted by Eaton at Argonne National Laboratory. The testing was performed with a Cummins X15 engine and three transmissions. The transmissions were an Eaton P2/P3 hybrid, Eaton Endurant, and an Allison 4500 RDS. For each of the three powertrain configurations, the test procedures prescribed in 40 CFR 1036.545 were followed to generate powertrain fuel maps. Each of these fuel maps were input into GEM Version 3.5.1 to determined gCO2/ton-mile emissions from a number of representative vehicle configurations. For the heavy heavy-duty vocational vehicles, the average CO_2 emission reductions were 22, 8, and 25 percent for multi-purpose, regional, and urban regulatory subcategories respectively. The average CO_2 reductions for day cab and sleeper cab tractors was 9 percent. The data from the powertrain tests supports the estimated CO_2 emission reduction of 15 percent for vocational vehicle hybrids, as it is expected that vocational vehicle hybrids will be certified as multi-purpose or urban. The data from the powertrain tests also supports the estimated CO_2 emission reduction of 10 percent for tractor hybrids, since many of the individual tractors had greater than 10 percent CO_2 emission reduction, with the average at 9 percent.

In addition, other studies have also shown CO_2 emission reductions from heavy-duty hybrid vehicles. For example, a New Flyer hybrid transit bus achieves 10-29 percent reduction, depending on route.[1283] Similarly, a NovaBus hybrid transit bus found up to 30 percent reduction in CO_2 emissions at speeds ranging between 9-18 mph.[1284] A NREL report of a reduction of 75 percent CO_2 in idle emissions during PTO use[1285] where idle operation is over 30 percent of vehicle operating time and uses 10 percent of the fuel.[1286] A study with a Pierce Manufacturing

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[1283] New Flyer. “Hybrid-electric mobility.” Available online: https://www.newflyer.com/bus/xcelsior-hybrid/.

[1284] NovaBus. “Nova LFS HEV”. Available online: https://novabus.com/blog/bus/lfs_hev/

[1285] Ragatz, Adam, Jonathan Burton, Eric Miller, and Matthew Thornton. “Investigation of Emissions Impacts from Hybrid Powertrains” National Renewable Energy Lab. January 2020. Available online: https://www.nrel.gov/docs/fy20osti/75782.pdf.

[1286] Konan, Arnaud, Adam Duran, Kenneth Kelly, Eric Miller, and Robert Prohaska. “Characterization of PTO and Idle Behavior for Utility Vehicles”. National Renewable Energy Lab. Available online: https://www.nrel.gov/docs/fy17osti/66747.pdf.

hybrid fire truck showed 1,500 gallons of diesel saved in one month which also leads to a reduction in CO_2 emissions.[1287]

Hybrid technology is currently being used on heavy-duty vehicles. RIA Chapter 1.4.5 details the HD truck and bus models that are currently offered as hybrid vehicles. As shown, both Allison and BAE offer heavy-duty hybrid systems for use in vehicles. Our assessment, based on currently available hybrid technology that is being produced in vehicles today, is that there is adequate lead time for manufacturers to increase the adoption of the technology for LHD and MHD vocational vehicles in MY 2027 and for HHD vocational vehicles and tractors in MY 2030 to the adoption levels included in the additional pathways.

Plug-in hybrid electric vehicles run on both electricity and fuel. The utility factor is the fraction of miles the vehicle travels in electric mode relative to the total miles traveled. The percent CO_2 emission reduction is directly related to the utility factor. The greater the utility factor, the lower the tailpipe CO_2 emissions from the vehicle. The utility factor depends on the size of the battery and the operator's driving habits. For PHEVs, we project that for MY 2027 and MY 2032 tractors, a CO_2 emission reduction (effectiveness) of 30 percent is achievable by adding a high-voltage battery that could achieve a utility factor of 22 percent. For MY 2027 vocational vehicles, we project an effectiveness of 30 percent could be achieved by adding a high-voltage battery with a utility factor of 18 percent. For MY 2030 vocational vehicles, we project an effectiveness of 50 percent could be achieved by adding a high-voltage battery with a utility factor of 41 percent. With utility factors between 18 to 41 percent, a significantly smaller battery would be needed for a PHEV in comparison to the battery needed for a corresponding battery electric vehicle.

For heavy-duty PHEVs, the projected effectiveness is further supported by powertrain testing that was conducted by Eaton at Argonne National Laboratory. To evaluate the emissions reductions of a plug-in hybrid powertrain, Eaton used a combination of GEM simulations and powertrain test results. The results of the analysis showed that a vocational vehicle with a plug-in hybrid powertrain could reduce CO_2 emission by 52 percent.[1288]

In our lead time assessment for PHEVs, we believe it will take longer for vehicle manufacturers to integrate this technology into vehicles than it will for hybrid technologies. We determined that approximately 3-4 years would be necessary to develop this technology. Therefore, we conservatively included PHEVs in limited applications (HHD vocational vehicle and day cab tractors) beginning in MY 2030 and included a scenario in MY 2032 with and without PHEVs in the technology packages that also include our projected reference case ZEV adoption rates.

PHEVs, like BEVs, require an external charging source to provide electricity to the vehicle. However, the recharging demand for a PHEV is much lower than a comparable BEV. Therefore, most heavy-duty PHEVs could use Level 1 charging by plugging it into a 240 V outlet. Truck operators would have access to these outlets at depots and other businesses without having to

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[1287] Pierce. "Pierce Volterra Platform of Electric Vehicles". Available online: https://www.piercemfg.com/electric-fire-trucks/pierce-volterra.

[1288] Sanchez, James. Memorandum to Docket EPA-HQ-OAR-2022-0985. "Eaton Hybrid Powertrain Results" February 2024.

require special installation of EVSE equipment. Operators would need to create access to such an outlet, but this would not be a constraining factor for lead time and such costs would be low for purchasers. Similar to the approach we considered for BEVs and FCEVs in this preamble Section II, we determined there is adequate lead time to meet the projected charging infrastructure needs that correspond to the technology packages for the final rule's additional example potential compliance pathways. Furthermore, because the recharging demand for PHEVs will be lower than the levels for BEVs in our modeled potential compliance pathway, the demand on the grid would be less than assessed with our modeled potential compliance pathway.

2.11.1.5 Summary of the Technology Effectiveness

Table 2-131 shows the summary of the technology effectiveness (percent CO_2 emission reduction) of each of the technologies discussed in this subsection relative to the Phase 2 MY 2027 standards.

Table 2-131 Effectiveness of Technologies of Vehicles with ICE Relative to the MY 2027 Phase 2 Standards

Vehicle Type	Model Year	ICE Vehicle Improvements	Natural Gas ICE Vehicle	HEV	PHEV	H2 ICE Vehicle
Tractor	MY 2027	4%	6%	10%	30%	100%
	MY 2030	4%	6%	10%	30%	100%
	MY 2032	4%	6%	10%	30%	100%
Vocational	MY 2027	0%	7%	15%	30%	100%
	MY 2030	0%	7%	15%	50%	100%
	MY 2032	0%	7%	15%	50%	100%

2.11.2 Technology Package Costs

In this section, we present the incremental technology package costs for each technology relative to the comparable baseline vehicles that meet the Phase 2 MY 2027 emission standards.[1289]

2.11.2.1 ICE Vehicle Improvements

The costs for the additional aerodynamic and low rolling resistance tire costs were developed based on the cost assessment in the Phase 2 final rule.[1290] The tractor aerodynamic technology costs for MY 2027 for each bin represent the values shown in the Phase 2 RIA Tables 2-256 through 2-259 on pages 2-337 through 2-340. The tractor tire technology costs for MY 2027 came from the Phase 2 RIA Tables 2-227 through 2-232 on pages 2-325 through 2-328. These technology costs developed for the Phase 2 analysis remain appropriate because the technologies are the same and the costs including learning through MY 2027. These values were used to develop the Phase 3 technology package costs and then the incremental cost was calculated from the Phase 2 technology package costs for MY 2027 shown on Table 2-50 on page 2-147 of the Phase 2 RIA. The technology costs in the Phase 2 RIA were in 2013$ and therefore a conversion

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[1289] The costs presented in this section do not include the learning effects after MY 2027, and therefore are higher than they would be if they included learning (i.e., are conservative in the overestimating sense).

[1290] US EPA. Regulatory Impact Analysis Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles - Phase 2. Chapter 2. EPA-420-R-16-900. August 2016.

factor of 1.2503 was used to convert the costs to 2022$. Table 2-132 through Table 2-135 show the incremental vehicle technology package cost for each of the tractor subcategories.

Table 2-132 MY 2027 and Later Incremental Technology Package Cost

Sleeper Cab High Roof Tractors

Technology	2013$	2022$
Phase 3 Aero Tech Package Cost	$2,176	$2,721
Phase 2 Aero Package Cost	$639	$799
Incremental Aero Cost Increase		$1,922
Phase 3 Tire Tech Package	$44.50	$56
Total Phase 3 Tech Package Cost		$1,978

Table 2-133 MY 2027 and Later Incremental Technology Package Cost

Sleeper Cab Low/Mid Roof Tractors

Technology	2013$	2022$
Phase 3 Aero Tech Package Cost	$1,903	$2,379
Phase 2 Aero Package Cost	$415	$519
Incremental Aero Cost Increase		$1,861
Phase 3 Tire Tech Package	$44.50	$56
Total Phase 3 Tech Package Cost		$1,917

Table 2-134 MY 2027 and Later Incremental Technology Package Cost

Day Cab Low/Mid Roof Tractors

Technology	2013$	2022$
Phase 3 Tech Package	$1,663	$2,079
Phase 2 Aero Package Cost	$453	$566
Incremental Cost Increase		$1,513
Phase 3 Tire Tech Package	$44.50	$56
Total Phase 3 Tech Package Cost		$1,569

Table 2-135 MY 2027 and Later Incremental Technology Package Cost

Day Cab High Roof Tractors

Technology	2013$	2022$
Phase 3 Tech Package	$1,874	$2,343
Phase 2 Aero Package Cost	$547	$684
Incremental Cost Increase		$1,659
Phase 3 Tire Tech Package	$44.50	$56
Total Phase 3 Tech Package Cost		$1,715

2.11.2.2 Natural Gas Fueled Internal Combustion Engines

EPA contracted FEV to conduct a technology and cost study for a variety of powertrains applicable to Class 4, 5, 7, and 8 heavy-duty vehicles.[1291] Vehicles studied include those listed in Table 2-136. FEV also costed three (15L for Class 8, 10L for Class 7, and 6.6L for Class 4/5) diesel ICE powertrains that would meet the emission standards as required by the Low NOx Rule and the Phase 2 CO_2 emission standards in MY 2027. These were used to calculate the incremental cost of the alternative powertrain to the comparable diesel ICE powertrain baseline.

Table 2-136 FEV Vehicle Class and Application used for each Regulatory Category

Regulatory Category	Vehicle Class	Application
Light Heavy-Duty Vocational	4, 5	box trucks
		step vans
Medium Heavy-Duty Vocational	7	box trucks
		transit bus
		vocational vehicles
		school buses
Heavy Heavy-Duty Vocational	8	vocational vehicles
		coach bus
Short-Haul Tractors	8	day cab
Long-Haul Tractors	8	long haul

The costs presented in Table 2-137 include both the direct and indirect costs of compliance for manufacturers and represent a market stable scenario where the technologies are mature, which is appropriate because natural gas technologies have been used in the heavy-duty marketplace for decades. The LHD vocational cost represents an average of the Class 4/5 box truck and step van applications. Similarly, the MHD and HHD vocational vehicle costs are an average of the corresponding applications shown in Table 2-136. The costs represent the incremental costs of a spark-ignited (SI) CNG engine because that is the predominant technology being offered today in the heavy-duty market.[1292]

[1291] Task Order “Heavy Duty Vehicles: Industry Characterization, Technology Assessment and Costing” of EPA Contract 68HERC19D008. 2024.

[1292] Cummins. Natural Gas Engine Portfolio. Available online: https://mart.cummins.com/imagelibrary/data/assetfiles/0063969.pdf.

One difference in costs between a CNG powertrain and the baseline diesel powertrain is the fuel 'tank.' A CNG vehicle requires pressurized fuel tanks typically made with carbon fiber in order to hold the fuel at required pressures of 250 bar. These tank types are much higher in cost than a tank to hold diesel fuel which does not require the capability to store fuel under pressure. The larger the vehicle and/or the longer the distance traveled per day dictates the number and size of the tanks required. Cost of tanks for the CNG Class 8 day cab and sleeper cab tractor powertrains were estimated to be $10,000-$16,500.[1293]

Another area of difference is in the aftertreatment required on CNG powertrains compared to a diesel. The current diesel powertrain contains a DOC, DPF, SCR and associated urea injection/mixing system. Spark-ignited CNG engines run stoichiometric combustion and therefore only require a three way catalyst to reduce HC, CO and NOx, similar to gasoline-fueled ICE vehicles. Engine-out PM from SI-CNG fueled vehicles meet the exhaust emission standards without additional aftertreatment. Therefore, spark-ignited CNG vehicles do not require a DPF, DOC, SCR or the DEF and urea mixing system and a significant cost reduction compared to the diesel powertrain baseline is realized. Another cost reduction comes from the fuel injection system. The diesel system has a fuel injection system used to atomize the diesel fuel as it goes into the combustion chamber. These components are not needed on a gaseous fuel as it is already in combustible form.

Table 2-137 Summary of the MY 2027 and Later Incremental Costs for Natural Gas Fueled Vehicles (2022$)

Vehicle Type	Total
Light Heavy-Duty Vocational	$ (7,163)
Medium Heavy-Duty Vocational	$ (4,690)
Heavy Heavy-Duty Vocational	$ (3,282)
Day Cab Tractors	$ 75
Sleeper Cab Tractors	$ 1,888

2.11.2.3 Hydrogen-Fueled Internal Combustion Engines

We used the same FEV cost study to develop the incremental technology costs for H2-ICE vehicles, as shown in Table 2-138.[1294]

As with CNG, a major difference between H2-ICE powertrains and the baseline diesel powertrain is the fuel 'tank.' The H2-ICE requires pressurized fuel tanks typically made with carbon fiber and many other considerations in order to hold the fuel at required pressures. The H2 tanks used in the FEV cost study are designed to store H2 at 700 bar so that they can hold sufficient hydrogen. These tank types are much higher in cost than a tank to hold diesel fuel because the fuel is pressurized. The cost of the tanks on the Class 8 sleeper cab tractors can add on $30,000in low volumes to the H2-ICE powertrain costs.

Also similar to CNG, a significant cost decrease compared to the baseline powertrain is due to the difference in the aftertreatment required on H2-ICE fueled powertrains compared to the baseline diesel powertrain. The baseline diesel powertrain contains a DOC, DPF, SCR and an

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[1293] Caffrey, Cheryl. Memorandum to the docket EPA-HQ-OAR-2022-0985. "Alternative Powertrain Costs" February 2024

[1294] Caffrey, Cheryl. Memorandum to the docket EPA-HQ-OAR-2022-0985. "Alternative Powertrain Costs" February 2024.

associated urea mixing/dosing system. These aftertreatment components work to reduce hydrocarbons, carbon monoxide, particulate matter and NOx, respectively. Only DOC and SCR aftertreatment is required on a H2-ICE fueled with neat H2 in order to reduce NOx. In developing the aftertreatment cost for the H2-ICE, an exhaust gas heater was also included in order to reduce NOx at idle and during low power operation. Another cost decrease compared to the baseline powertrain comes from the fuel injection system. The baseline diesel system has a number of components to atomize the diesel fuel as it goes into the combustion chamber. These components are not needed on a H2-ICE because the H2 is a gaseous fuel in combustible form.

Table 2-138 Summary of the MY 2030 and Later Incremental Costs for Hydrogen Fueled ICE Vehicles (2022$)

Vehicle Type	Total
Light Heavy-Duty Vocational	$ 3,872
Medium Heavy-Duty Vocational	$ 14,100
Heavy Heavy-Duty Vocational	$ 27,873
Day Cab Tractors	$ 26,936
Sleeper Cab Tractors	$ 44,919

2.11.2.4 Hybrids and Plug-in Hybrid Powertrains

To determine the hybrid powertrain costs, we relied on the Autonomie study results published with the 2023 DOE VTO/HFTO Transportation Decarbonization Analysis.[1295] The results include vehicle costs for conventional vehicles and parallel hybrid vehicles for each vehicle class. To determine the incremental powertrain costs for each hybrid powertrain, first the chassis costs were subtracted from the total vehicle costs to isolate the costs of the powertrain. Second, the conventional powertrain costs were subtracted from the hybrid costs to determine the incremental cost for the hybrid powertrain. There were two scenarios evaluated in the Autonomie study - a high technology and a low technology scenario. Consistent with our approach for developing incremental costs for BEV components discussed in RIA Chapter 2.4.3, we used an average of the high and low cost scenarios. The report included costs for both spark-ignition and compression-ignition engines, however for this analysis we only relied on the results from the compression-ignition engines. The specific vehicle class and application (referred to as purpose in the Autonomie results) from the Autonomie results for each regulatory category is outline in Table 2-139. Finally, the costs were aggregated by regulatory category by averaging together the high and low costs of each application within a regulatory category together. The Autonomie results included data for MY 2025 and MY 2030, so the MY 2027 costs were determined by interpolating the results for MY 2025 and MY 2030. The summary of the hybrid vehicles is in Table 2-140.

[1295] US Department of Energy. Available online: https://anl.box.com/s/hv4kufocq3leoijt6v0wht2uddjuiff4 and https://anl.box.com/s/oy04bje3ltc21rz5py4bq1ed4s4bn0vo.

Table 2-139 Autonomie Vehicle Class and Application used for each Regulatory Category

Regulatory Category	Vehicle Class	Application
Light Heavy-Duty Vocational	4, 5	box trucks
		step vans
		service trucks
		utility trucks
Medium Heavy-Duty Vocational	6, 7	box trucks
		step vans
		vocational vehicles
		school buses
Heavy Heavy-Duty Vocational	8	vocational vehicles
		transit
Day Cab Tractors Day Cab Tractors	7, 8	tractors
		beverage
		drayage
		regional
Day Cab Tractors	8	long haul

Table 2-140 Summary of MY 2027 and Later Direct and Indirect Manufacturing Costs for Hybrid Electric Vehicles (2022$)

Vehicle Type	Direct Manufacturing Costs	Indirect Manufacturing Costs	Total
Light Heavy-Duty Vocational	$5,617	$2,359	$7,976
Medium Heavy-Duty Vocational	$8,436	$3,543	$11,979
Heavy Heavy-Duty Vocational	$11,936	$5,013	$16,949
Day Cab Tractors	$9,359	$3,931	$13,290
Sleeper Cab Tractors	$11,324	$4,756	$16,080

The PHEV technology combines an ICE powertrain with a BEV powertrain. Therefore, we calculated the incremental costs of the PHEV technology using a similar approach as we did for BEVs and ICEVs in HD TRUCS for each of the 101 vehicle types, as detailed in RIA Chapter 2.3.2 and 2.4.3. We used the same component costs for the ICE powertrain, except replaced the ICE accessory costs with the electrified accessory component costs used in BEVs. For the electrified portion of the PHEV, we also included the electric motor, onboard charger, and power converter costs for a similar BEV. The key difference between the BEV and PHEV powertrain costs is due to the size of the battery. We reduced the size of the battery for the PHEV relative to a BEV to reflect a utility factor of 41 percent for vocational vehicles and 22 percent for tractors and we conservatively estimated that the depth of discharge of a PHEV battery would be only 60 percent compared to the BEV battery depth of discharge of 90 percent. The incremental component costs for each of the HD TRUCS 101 vehicle types are shown in Table 2-141.

Table 2-141 MY 2030 Incremental PHEV Component Costs for Each HD TRUCS Vehicle Type (2022$)

Vehicle ID	Direct Manufacturing Cost						Battery Tax Credit
	Battery	Motor	On-board Charger	Power Converter	Incremental Electric Accessories	Incremental PHEV Powertrain	
01V_Amb_Cl4-5_MP	$ 7,577	$4,374	$515	$1,440	$2,478	$16,384	$2,481
02V_Amb_Cl2b-3_MP	$ 7,153	$4,374	$515	$1,440	$2,439	$15,922	$2,342
03V_Amb_Cl4-5_U	$ 7,060	$4,374	$515	$1,440	$2,478	$15,867	$2,312
04V_Amb_Cl2b-3_U	$ 6,620	$4,374	$515	$1,440	$2,439	$15,389	$2,168
05T_Box_Cl8_MP	$ 15,450	$5,755	$515	$1,440	$2,632	$25,792	$5,059
06T_Box_Cl8_R	$ 15,958	$5,755	$515	$1,440	$2,632	$26,300	$5,226
07T_Box_Cl6-7_MP	$ 10,665	$3,638	$515	$1,440	$2,555	$18,813	$3,493
08T_Box_Cl6-7_R	$ 11,600	$3,638	$515	$1,440	$2,555	$19,748	$3,799
09T_Box_Cl8_U	$ 14,968	$5,755	$515	$1,440	$2,632	$25,310	$4,902
10T_Box_Cl6-7_U	$ 10,278	$3,638	$515	$1,440	$2,555	$18,426	$3,366
11T_Box_Cl2b-3_U	$ 6,339	$4,374	$515	$1,440	$2,478	$15,146	$2,076
12T_Box_Cl2b-3_R	$ 7,474	$4,374	$515	$1,440	$2,478	$16,281	$2,448
13T_Box_Cl2b-3_MP	$ 6,881	$4,374	$515	$1,440	$2,478	$15,688	$2,253
14T_Box_Cl4-5_U	$ 6,339	$4,374	$515	$1,440	$2,478	$15,146	$2,076
15T_Box_Cl4-5_R	$ 7,474	$4,374	$515	$1,440	$2,478	$16,281	$2,448
16T_Box_Cl4-5_MP	$ 6,881	$4,374	$515	$1,440	$2,478	$15,688	$2,253
17B_Coach_Cl8_R	$ 45,031	$5,755	$515	$1,440	$2,824	$55,565	$14,746
18B_Coach_Cl8_MP	$ 66,676	$5,755	$515	$1,440	$2,824	$77,210	$21,834
19C_Mix_Cl8_MP	$ 27,105	$5,755	$515	$1,440	$2,632	$37,447	$8,876
20T_Dump_Cl8_U	$ 17,910	$5,755	$515	$1,440	$2,632	$28,252	$5,865
21T_Dump_Cl8_MP	$ 18,142	$5,755	$515	$1,440	$2,632	$28,484	$5,941
22T_Dump_Cl6-7_MP	$ 17,566	$3,638	$515	$1,440	$2,555	$25,714	$5,753
23T_Dump_Cl8_U	$ 17,910	$5,755	$515	$1,440	$2,632	$28,252	$5,865
24T_Dump_Cl6-7_U	$ 16,442	$3,638	$515	$1,440	$2,555	$24,590	$5,384
25T_Fire_Cl8_MP	$ 19,046	$5,755	$515	$1,440	$2,632	$29,388	$6,237
26T_Fire_Cl8_U	$ 19,086	$5,755	$515	$1,440	$2,632	$29,428	$6,250
27T_Flat_Cl6-7_MP	$ 10,665	$3,638	$515	$1,440	$2,555	$18,813	$3,493
28T_Flat_Cl6-7_R	$ 11,600	$3,638	$515	$1,440	$2,555	$19,748	$3,799
29T_Flat_Cl6-7_U	$ 9,842	$3,638	$515	$1,440	$2,555	$17,990	$3,223
30Tractor_DC_Cl8_MP	$ 11,941	$9,445	$515	$1,440	$2,632	$25,973	$3,910
31Tractor_DC_Cl6-7_MP	$ 10,792	$6,563	$515	$1,440	$2,555	$21,865	$3,534
32Tractor_SC_Cl8_U	$ 33,089	$7,152	$515	$1,440	$2,670	$44,867	$10,836
33Tractor_DC_Cl8_U	$ 18,064	$9,857	$515	$1,440	$2,555	$32,431	$5,915
34T_Ref_Cl8_MP	$ 22,482	$5,755	$515	$1,440	$2,670	$32,863	$7,362
35T_Ref_Cl6-7_MP	$ 18,351	$3,638	$515	$1,440	$2,555	$26,499	$6,010
36T_Ref_Cl8_U	$ 22,482	$5,755	$515	$1,440	$2,670	$32,863	$7,362
37T_Ref_Cl6-7_U	$ 18,109	$3,638	$515	$1,440	$2,555	$26,257	$5,930
38RV_Cl8_R	$ 35,734	$5,755	$515	$1,440	$2,824	$46,268	$11,702
39RV_Cl6-7_R	$ 37,992	$3,638	$515	$1,440	$2,747	$46,332	$12,441
40RV_Cl4-5_R	$ 24,170	$4,374	$515	$1,440	$2,478	$32,977	$7,915
41Tractor_DC_Cl7_R	$ 25,317	$6,563	$515	$1,440	$2,555	$36,390	$8,291
42RV_Cl8_MP	$ 35,734	$5,755	$515	$1,440	$2,824	$46,268	$11,702
43RV_Cl6-7_MP	$ 34,830	$3,638	$515	$1,440	$2,747	$43,170	$11,406
44RV_Cl4-5_MP	$ 22,153	$4,374	$515	$1,440	$2,478	$30,960	$7,255
45Tractor_DC_Cl8_R	$ 30,296	$9,445	$515	$1,440	$2,624	$44,320	$9,921
46B_School_Cl8_MP	$ 16,876	$5,755	$515	$1,440	$2,824	$27,410	$5,526
47B_School_Cl6-7_MP	$ 10,168	$3,638	$515	$1,440	$2,747	$18,509	$3,330
48B_School_Cl4-5_MP	$ 7,577	$4,374	$515	$1,440	$2,478	$16,384	$2,481

Vehicle ID	Direct Manufacturing Cost						Battery Tax Credit
	Battery	Motor	On-board Charger	Power Converter	Incremental Electric Accessories	Incremental PHEV Powertrain	
49B_School_Cl2b-3_MP	$ 7,153	$4,374	$515	$1,440	$2,555	$16,037	$2,342
50B_School_Cl8_U	$ 15,985	$5,755	$515	$1,440	$2,824	$26,519	$5,235
51B_School_Cl6-7_U	$ 10,168	$3,638	$515	$1,440	$2,747	$18,509	$3,330
52B_School_Cl4-5_U	$ 7,060	$4,374	$515	$1,440	$2,478	$15,867	$2,312
53B_School_Cl2b-3_U	$ 6,620	$4,374	$515	$1,440	$2,555	$15,505	$2,168
55B_Shuttle_Cl2b-3_MP	$ 10,402	$4,374	$515	$1,440	$2,555	$19,287	$3,406
56B_Shuttle_Cl4-5_U	$ 10,031	$4,374	$515	$1,440	$2,478	$18,838	$3,285
57B_Shuttle_Cl2b-3_U	$ 9,592	$4,374	$515	$1,440	$2,555	$18,476	$3,141
58B_Shuttle_Cl6-7_MP	$ 16,715	$3,638	$515	$1,440	$2,747	$25,055	$5,474
59B_Shuttle_Cl6-7_U	$ 15,506	$3,638	$515	$1,440	$2,747	$23,846	$5,078
60S_Plow_Cl6-7_MP	$ 12,634	$3,638	$515	$1,440	$2,555	$20,782	$4,137
61S_Plow_Cl8_MP	$ 24,987	$5,755	$515	$1,440	$2,632	$35,329	$8,183
62S_Plow_Cl6-7_U	$ 11,835	$3,638	$515	$1,440	$2,555	$19,983	$3,876
63S_Plow_Cl8_U	$ 24,565	$5,755	$515	$1,440	$2,632	$34,907	$8,044
64V_Step_Cl6-7_MP	$ 10,743	$3,638	$515	$1,440	$2,555	$18,891	$3,518
65V_Step_Cl4-5_MP	$ 6,881	$4,374	$515	$1,440	$2,478	$15,688	$2,253
66V_Step_Cl2b-3_MP	$ 6,881	$4,374	$515	$1,440	$2,439	$15,650	$2,253
67V_Step_Cl6-7_U	$ 9,914	$3,638	$515	$1,440	$2,555	$18,062	$3,246
68V_Step_Cl4-5_U	$ 6,339	$4,374	$515	$1,440	$2,478	$15,146	$2,076
69V_Step_Cl2b-3_U	$ 6,339	$4,374	$515	$1,440	$2,439	$15,108	$2,076
70S_Sweep_Cl6-7_U	$ 11,534	$3,638	$515	$1,440	$2,555	$19,682	$3,777
71T_Tanker_Cl8_R	$ 17,078	$5,755	$515	$1,440	$2,632	$27,420	$5,593
72T_Tanker_Cl8_MP	$ 16,762	$5,755	$515	$1,440	$2,632	$27,104	$5,489
73T_Tanker_Cl8_U	$ 16,674	$5,755	$515	$1,440	$2,632	$27,016	$5,460
74T_Tow_Cl8_R	$ 26,176	$5,755	$515	$1,440	$2,632	$36,518	$8,572
75T_Tow_Cl6-7_R	$ 19,046	$3,638	$515	$1,440	$2,555	$27,194	$6,237
76T_Tow_Cl8_U	$ 25,341	$5,755	$515	$1,440	$2,632	$35,683	$8,299
77T_Tow_Cl6-7_U	$ 16,513	$3,638	$515	$1,440	$2,555	$24,662	$5,408
78Tractor_SC_Cl8_MP	$ 28,357	$7,152	$515	$1,440	$2,670	$40,135	$9,286
79Tractor_SC_Cl8_R	$ 39,574	$7,152	$515	$1,440	$2,670	$51,352	$12,959
80Tractor_DC_Cl8_HH	$ 22,000	$8,046	$515	$1,440	$2,632	$34,634	$7,205
81Tractor_DC_Cl7_R	$ 18,063	$6,563	$515	$1,440	$2,555	$29,136	$5,915
82Tractor_DC_Cl8_R	$ 21,599	$9,445	$515	$1,440	$2,624	$35,623	$7,073
83Tractor_DC_Cl7_U	$ 15,616	$6,563	$515	$1,440	$2,555	$26,689	$5,114
84Tractor_DC_Cl8_U	$ 12,117	$9,445	$515	$1,440	$2,632	$26,150	$3,968
85B_Transit_Cl8_MP	$ 29,910	$5,755	$515	$1,440	$2,824	$40,444	$9,795
86B_Transit_Cl6-7_MP	$ 23,623	$3,638	$515	$1,440	$2,747	$31,963	$7,736
87B_Transit_Cl8_U	$ 29,910	$5,755	$515	$1,440	$2,824	$40,444	$9,795
88B_Transit_Cl6-7_U	$ 21,638	$3,638	$515	$1,440	$2,747	$29,979	$7,086
89T_Utility_Cl8_MP	$ 16,128	$5,755	$515	$1,440	$2,632	$26,470	$5,282
90T_Utility_Cl8_R	$ 16,537	$5,755	$515	$1,440	$2,632	$26,879	$5,416
91T_Utility_Cl6-7_MP	$ 11,687	$3,638	$515	$1,440	$2,555	$19,835	$3,827
92T_Utility_Cl6-7_R	$ 12,560	$3,638	$515	$1,440	$2,555	$20,708	$4,113
93T_Utility_Cl4-5_MP	$ 7,601	$4,374	$515	$1,440	$2,478	$16,408	$2,489
94T_Utility_Cl2b-3_MP	$ 7,210	$4,374	$515	$1,440	$2,439	$15,979	$2,361
95T_Utility_Cl4-5_R	$ 8,125	$4,374	$515	$1,440	$2,478	$16,932	$2,661
96T_Utility_Cl2b-3_R	$ 8,125	$4,374	$515	$1,440	$2,439	$16,893	$2,661
97T_Utility_Cl8_U	$ 15,851	$5,755	$515	$1,440	$2,632	$26,193	$5,191
98T_Utility_Cl6-7_U	$ 11,008	$3,638	$515	$1,440	$2,555	$19,156	$3,605
99T_Utility_Cl4-5_U	$ 7,166	$4,374	$515	$1,440	$2,478	$15,973	$2,347

Vehicle ID	Direct Manufacturing Cost						Battery Tax Credit
	Battery	Motor	On-board Charger	Power Converter	Incremental Electric Accessories	Incremental PHEV Powertrain	
100T_Utility_Cl2b-3_U	$ 6,717	$4,374	$515	$1,440	$2,439	$15,486	$2,200
101Tractor_DC_Cl8_U	$ 9,498	$9,445	$515	$1,440	$2,632	$23,531	$3,110

The individual vehicles were aggregated into the corresponding regulatory class.[1296] The incremental retail price equivalent (RPE) using the 1.42 multiplier for MY 2030 PHEVs by regulatory group are shown in Table 2-142.

Table 2-142 Summary of MY 2030 Incremental RPE for Plug-in Hybrid Electric Vehicles (2022$)

Regulatory Group	RPE Costs
Light Heavy-Duty Vocational	$21,774
Medium Heavy-Duty Vocational	$28,552
Heavy Heavy-Duty Vocational	$40,627
Day Cab Tractors	$37,224
Sleeper Cab Tractors	$53,514

2.11.2.5 Summary of Technology Costs

A summary of the per vehicle incremental technology costs for each of the technologies is shown in Table 2-143.

Table 2-143 Per Vehicle Cost of Technologies Relative to the MY 2027 Phase 2 Standards (2022$)

Vehicle Type	ICE Vehicles	Natural Gas	HEV	PHEV	H2 ICE
Light Heavy-Duty Vocational	$0	($7,163)	$7,976	$21,774	$3,872
Medium Heavy-Duty Vocational	$0	($4,690)	$11,979	$28,552	$19,785
Heavy Heavy-Duty Vocational	$0	($3,232)	$16,949	$40,627	$27,356
Day Cab Tractors	$1,715	$75	$13,290	$37,224	$26,936
Sleeper Cab Tractors	$1,978	$1,888	$16,080	$53,514	$44,919

2.11.3 Technology Adoption Rates in the Additional Potential Compliance Pathways

For the additional example potential compliance pathways to support the feasibility of the final standards, we developed technology packages relative to our reference case and not relative to our reference case (i.e., with zero ZEVs). Both are presented in this section.

As we did for the modeled potential compliance pathway, for these additional example potential compliance pathway we determined the technology mix of technologies for vehicles with ICE across a range of electrification, which for this additional pathway consists of a mix of adoption of natural gas vehicles, hybrid vehicles, plug-in hybrid vehicles, H2-ICE vehicles, and aerodynamic and tire rolling resistant improvements for tractors for MYs 2027, 2030 and 2032, and including those ZEVs from our projected reference case ZEV adoption rates as described in

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[1296] The sleeper cab tractor costs were calculated using Vehicles 32, 78, and 79.

RIA Chapter 4. These values represent the total national HD vehicle sales, including those accounted for in the reference case. However, for this first additional example compliance pathway, the portion of the overall HD sales that are projected to be ZEVs in the reference case are the same portion projected to be ZEVs under the final rule (i.e., no additional ZEVs are included to meet the final Phase 3 standards). Thus, this additional example compliance pathway supports the feasibility of the Phase 3 standards relative to the "no action" projection of ZEV adoption nationwide. We considered two scenarios for the adoption rates in MY 2032. The adoption rates for this pathway are shown in Table 2-144 through Table 2-146.

Table 2-144 Adoption Rates of Technologies to meet Final Standards for MY 2027 Relative to Reference Case

Vehicle Type	Reference Case ZEVs	ICE Vehicles	Natural Gas	HEV	PHEV	H2 ICE
Light Heavy-Duty Vocational	10%	33%	5%	52%	0%	0%
Medium Heavy-Duty Vocational	7%	48%	5%	40%	0%	0%
Heavy Heavy-Duty Vocational	N/A, standards begin in MY 2029					
Day Cab Tractors	N/A, standards begin in MY 2028					
Sleeper Cab Tractors	N/A, standards begin in MY 2030					

Table 2-145 Adoption Rates of Technologies to meet Final Standards for MY 2030 Relative to Reference Case

Vehicle Type	Reference Case ZEVs	ICE Vehicles	Natural Gas	HEV	PHEV	H2 ICE
Light Heavy-Duty Vocational	25%	27%	5%	43%	0%	0%
Medium Heavy-Duty Vocational	17%	48%	5%	30%	0%	0%
Heavy Heavy-Duty Vocational	11%	71%	5%	10%	3%	0%
Day Cab Tractors	9%	74%	5%	0%	12%	0%
Sleeper Cab Tractors	2%	91%	5%	2%	0%	0%

Table 2-146 Adoption Rates of Technologies to meet Final Standards for MY 2032 and later Relative to Reference Case

Vehicle Type	Reference Case ZEVs	ICE Vehicles	Natural Gas	HEV	PHEV	H2 ICE
Scenario 1 (H2-ICE focus)						
Light Heavy-Duty Vocational	30%	1%	5%	40%	0%	24%
Medium Heavy-Duty Vocational	21%	18%	5%	44%	0%	13%
Heavy Heavy-Duty Vocational	14%	42%	5%	27%	0%	12%
Day Cab Tractors	10%	39%	5%	20%	0%	26%
Sleeper Cab Tractors	5%	64%	5%	10%	0%	17%
Scenario 2 (PHEV focus)						
Light Heavy-Duty Vocational	30%	5%	5%	0%	60%	0%
Medium Heavy-Duty Vocational	21%	19%	5%	24%	32%	0%
Heavy Heavy-Duty Vocational	14%	13%	5%	50%	18%	0%
Day Cab Tractors	10%	0%	5%	20%	55%	10%
Sleeper Cab Tractors	5%	5%	5%	30%	55%	0%

The technology packages for this additional example potential compliance pathway assumed no ZEV sales in the heavy-duty market in MYs 2027-2032. The pathways consist of a mix of adoption of natural gas vehicles, hybrid vehicles, plug-in hybrid vehicles, H2-ICE vehicles, and aerodynamic and tire rolling resistant improvements for tractors.

The technology adoption rates for each of the regulatory groupings for MYs 2027 and 2030 are shown in Table 2-147and Table 2-148, respectively. We considered two scenarios for the adoption rates in MY 2032, as shown in Table 2-149. Scenario 1 represents a package with more H2-ICE vehicles, whereas Scenario 2 represents a package with more PHEVs.

Table 2-147 Adoption Rates of Technologies to meet Final Standards for MY 2027 Relative to No ZEV Baseline

Vehicle Type	ICE Vehicles	Natural Gas	HEV	PHEV	H2 ICE
Light Heavy-Duty Vocational	17%	5%	48%	30%	0%
Medium Heavy-Duty Vocational	32%	5%	40%	23%	0%
Heavy Heavy-Duty Vocational	N/A, standards begin in MY 2029				
Day Cab Tractors	N/A, standards begin in MY 2028				
Sleeper Cab Tractors	N/A, standards begin in MY 2030				

Table 2-148 Adoption Rates of Technologies to meet Final Standards for MY 2030 Relative to No ZEV Baseline

Vehicle Type	ICE Vehicles	Natural Gas	HEV	PHEV	H2 ICE
Light Heavy-Duty Vocational	2%	5%	45%	48%	0%
Medium Heavy-Duty Vocational	23%	5%	40%	32%	0%
Heavy Heavy-Duty Vocational	68%	5%	10%	7%	10%
Day Cab Tractors	60%	5%	20%	5%	10%
Sleeper Cab Tractors	72%	5%	20%	3%	0%

Table 2-149 Adoption Rates of Technologies to meet Final Standards for MY 2032 and later Relative to No ZEV Baseline

Vehicle Type	ICE Vehicles	Natural Gas	HEV	PHEV	H2 ICE
Scenario 1 *(H2-ICE focus)*					
Light Heavy-Duty Vocational	10%	5%	0%	50%	35%
Medium Heavy-Duty Vocational	41%	5%	0%	28%	26%
Heavy Heavy-Duty Vocational	65%	5%	0%	0%	30%
Day Cab Tractors	56%	5%	0%	2%	37%
Sleeper Cab Tractors	73%	5%	0%	0%	22%
Scenario 2 *(PHEV focus)*					
Light Heavy-Duty Vocational	0%	5%	0%	70%	25%
Medium Heavy-Duty Vocational	0%	5%	24%	70%	1%
Heavy Heavy-Duty Vocational	7%	5%	51%	30%	7%
Short-Haul tractors	0%	5%	30%	40%	25%
Long-Haul tractors	25%	5%	32%	25%	13%

2.11.4 Additional Example Potential Compliance Pathways – Manufacturer Costs to Meet the Final Standards

The fleet average per-vehicle technology costs of the additional example potential compliance pathway relative to the reference case (that includes ZEV adoption in the reference case, at the adoption rates of our "no action" reference case in RIA Chapter 4) are shown in Table 2-150 for MYs 2027, 2030 and 2032.

Table 2-150 Average Technology Package Cost Per Vehicle to Meet the MY 2027, MY 2030, and MY 2032 Final Standards (2022$) Relative to Reference Case

Regulatory Group	MY 2027	MY 2030	MY 2032	
			Scenario 1 (H2-ICE focus)	Scenario 2 (PHEV focus)
Light Heavy-Duty Vocational	$3,789	$ 3,072	$ 3,762	$ 12,706
Medium Heavy-Duty Vocational	$4,557	$ 3,359	$ 7,608	$ 11,777
Heavy Heavy-Duty Vocational	N/A	$ 2,752	$ 7,697	$ 15,626
Day Cab Tractors	N/A	$ 5,745	$ 10,327	$ 25,822
Sleeper Cab Tractors	N/A	$ 2,218	$ 10,376	$ 34,456

The fleet average per-vehicle technology costs for the additional example potential compliance pathway with zero ZEVs are shown in Table 2-151 for MYs 2027, 2030 and 2032. These costs assume no ZEVs in the nationwide volumes of the baseline (i.e., "No ZEV baseline").

Table 2-151 Average Technology Package Cost Per Vehicle to Meet the MY 2027, MY 2030, and MY 2032 Final Standards (2022$) Relative to No ZEV Baseline

Vehicle Type	MY 2027	MY 2030	MY 2032	
			Scenario 1 (H2-ICE focus)	Scenario 2 (PHEV focus)
Light Heavy-Duty Vocational	$ 10,002	$ 13,682	$ 11,884	$ 15,851
Medium Heavy-Duty Vocational	$ 11,124	$ 13,694	$ 12,904	$ 22,825
Heavy Heavy-Duty Vocational	N/A	$ 7,113	$ 8,045	$ 22,586
Day Cab Tractors	N/A	$ 8,246	$ 11,675	$ 25,614
Sleeper Cab Tractors	N/A	$ 6,340	$ 11,421	$ 24,952

2.11.5 Additional Example Potential Compliance Pathways – Purchaser Cost Considerations

In this section, we discuss items associated with the purchaser costs for each of the technologies considered. Under this approach for vehicles with ICE technologies, our evaluation of payback focuses on whether the technology pays back within the period of first ownership. Consistent with our Phase 2 approach to vehicles with ICE technologies, if the vehicle with ICE technology pays back within this period, then we consider that technology within the additional example potential compliance pathways. We also evaluate payback period, consistent with our approach to consideration of payback in Phase 2 for vehicles with ICE technologies.[1297] See also our discussion of first ownership in Section II.F.1 of the preamble. We also evaluated and included vehicle with ICE technologies if we assessed there may be other reasons that purchasers would consider such technologies, such as that the vehicles emit nearly zero CO_2 emissions at the tailpipe, low engine-out exhaust emissions provide the opportunity for efficient and durable after-treatment systems, and the potential for future efficiency improvements within the lead time provided.

2.11.5.1 ICE Vehicles

Reducing the energy required to move a tractor down the road through aerodynamic improvements and reductions in tire rolling resistance will lead to reduction in operating costs. Our technology packages that include additional improvements to ICE vehicles reduced the CO_2 emissions, and therefore energy consumption, by 4 percent. The cost savings related to the reduction in fuel and DEF consumed depends on the number of miles driven, among other factors. The average DEF and diesel fuel costs for each of the baseline diesel-fueled ICE vehicle applications in HD TRUCS were developed as discussed in RIA Chapter 2.3.4. As shown in Table 2-152, the average operating cost savings varies depending on the vehicle ID, ranging from approximately $280 to $1,800 per year. The average annual operating savings for a day cab tractor is $700 and is $1,600 for a sleeper cab tractor. Based on the technology package costs

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[1297] See 81 FR at 73621-622 (tractors) and 73718-19 (vocational vehicles).

shown in Chapter 2.11.2.1 for additional ICE vehicle improvements, the payback period for the technology improvements would be less than three years for day cab tractors and less than two years for sleeper cab tractors.

Table 2-152 Annual Operating Savings of Tractors with Aerodynamic and Tire Rolling Resistance Improvements (2022$)

Vehicle ID	Average Annual DEF Cost ($/year)	Average Annual Diesel Cost ($/year)	Average Operating Cost Savings ($/year)
30Tractor_DC_Cl8	$618	$10,839	$458
31Tractor_DC_Cl6-7	$542	$9,501	$402
32Tractor_SC_Cl8	$2,452	$42,985	$1,817
33Tractor_DC_Cl8	$1,374	$24,102	$1,019
41Tractor_DC_Cl7	$1,204	$21,119	$893
45Tractor_DC_Cl8	$1,373	$24,097	$1,019
78Tractor_SC_Cl8	$1,751	$30,704	$1,298
79Tractor_SC_Cl8	$2,452	$42,985	$1,817
80Tractor_DC_Cl8_HH	$984	$17,256	$730
81Tractor_DC_Cl7	$1,204	$21,119	$893
82Tractor_DC_Cl8	$1,373	$24,097	$1,019
83Tractor_DC_Cl7	$672	$11,783	$498
84Tractor_DC_Cl8	$764	$13,408	$567
101Tractor_DC_Cl8	$385	$6,747	$285

2.11.5.2 Natural Gas Fueled Vehicles

The operating savings of NG vehicles come from both the elimination of the DEF costs because these vehicles use three-way catalysts and from the reduced fueling costs. When comparing fuel efficiency between diesel and SI natural gas powered HD vehicles, dependent on vehicle and duty cycle, natural gas returns 7 percent to 12 percent less fuel economy.[1298] Therefore, we calculated the natural gas consumption using a conversion factor of 139.3 standard cubic feet (scf) to diesel gallon equivalent and applying a 10 percent fuel economy penalty to the diesel fuel consumption.[1299] The average diesel fuel consumption, diesel fuel costs, and DEF costs for each of the baseline diesel-fueled ICE vehicle applications in HD TRUCS were developed as discussed in RIA Chapter 2.3.4. We then calculated the average annual natural gas fuel costs for each of the HD TRUCS applications by vehicle ID using $18.23/thousand cubic feet price, as shown in Table 2-153.[1300] The natural gas powered vehicles have immediate paybacks for some vehicle categories and payback periods of less than one year for all applications when the operating savings are compared to the upfront incremental costs of the NG vehicles, as shown in Chapter 2.11.2.2.

[1298] Department of Energy, Energy Efficiency and Renewable Energy, Alternative Fuel Data Center, Vehicle and Infrastructure Cash-Flow Evaluation Tool (VICE), https://afdc.energy.gov/vice_model/, accessed February 17, 2024.

[1299] U.S. DOE. Available online: https://afdc.energy.gov/fuels/equivalency_methodology.html

[1300] U.S. DOE/Energy Information Administration. Annual Energy Outlook 2023. Reference Case. Table 13. Transportation Natural Gas Spot Price for 2022. Available online: https://www.eia.gov/outlooks/aeo/data/browser/#/?id=13-AEO2023&cases=ref2023&sourcekey=0

Table 2-153 Annual Operating Savings of Natural Gas Heavy-Duty Vehicles (2022$)

Vehicle ID	Diesel ICE Vehicle Average Annual DEF Cost ($/year)	Diesel ICE Vehicle Average Annual Diesel Cost ($/year)	Diesel ICE Vehicle Annual Diesel Consumption (gallons)	CNG Vehicle Annual CNG Consumpt. (scf)	CNG Vehicle Annual CNG Fuel Costs ($/year)	Average Operating Savings ($/year)
01V_Amb_Cl4-5_MP	$148	$2,481	662	102,510	$1,869	$760
02V_Amb_Cl2b-3_MP	$216	$3,781	965	149,315	$2,722	$1,275
03V_Amb_Cl4-5_U	$189	$3,317	846	130,999	$2,388	$1,118
04V_Amb_Cl2b-3_U	$193	$3,375	861	133,300	$2,430	$1,138
05T_Box_Cl8_MP	$512	$8,981	2,292	354,711	$6,466	$3,027
06T_Box_Cl8_R	$443	$7,766	1,982	306,820	$5,593	$2,616
07T_Box_Cl6-7_MP	$247	$4,326	1,104	170,872	$3,115	$1,458
08T_Box_Cl6-7_R	$235	$4,125	1,053	162,957	$2,971	$1,389
09T_Box_Cl8_U	$636	$11,147	2,844	440,236	$8,026	$3,757
10T_Box_Cl6-7_U	$265	$4,650	1,186	183,635	$3,348	$1,567
11T_Box_Cl2b-3_U	$287	$5,037	1,285	198,932	$3,627	$1,697
12T_Box_Cl2b-3_R	$242	$4,246	1,084	167,708	$3,057	$1,431
13T_Box_Cl2b-3_MP	$259	$4,541	1,159	179,329	$3,269	$1,531
14T_Box_Cl4-5_U	$184	$3,234	825	127,732	$2,329	$1,089
15T_Box_Cl4-5_R	$156	$2,726	696	107,683	$1,963	$919
16T_Box_Cl4-5_MP	$166	$2,915	744	115,145	$2,099	$982
17B_Coach_Cl8_R	$1,109	$19,420	4,955	766,875	$13,980	$6,549
18B_Coach_Cl8_MP	$1,109	$19,420	4,955	766,875	$13,980	$6,549
19C_Mix_Cl8_MP	$1,523	$26,700	3,952	611,615	$11,150	$17,073
20T_Dump_Cl8_U	$453	$7,948	1,724	266,810	$4,864	$3,537
21T_Dump_Cl8_MP	$365	$6,404	1,389	214,976	$3,919	$2,850
22T_Dump_Cl6-7_MP	$409	$7,176	1,557	240,917	$4,392	$3,193
23T_Dump_Cl8_U	$453	$7,948	1,724	266,810	$4,864	$3,537

Vehicle ID	Diesel ICE Vehicle Average Annual DEF Cost ($/year)	Diesel ICE Vehicle Average Annual Diesel Cost ($/year)	Diesel ICE Vehicle Annual Diesel Consumption (gallons)	CNG Vehicle Annual CNG Consumpt. (scf)	CNG Vehicle Annual CNG Fuel Costs ($/year)	Average Operating Savings ($/year)
24T_Dump_Cl6-7_U	$451	$7,905	1,715	265,388	$4,838	$3,518
25T_Fire_Cl8_MP	$414	$7,257	1,389	214,976	$3,919	$3,752
26T_Fire_Cl8_U	$514	$9,007	1,724	266,810	$4,864	$4,657
27T_Flat_Cl6-7_MP	$247	$4,326	1,104	170,872	$3,115	$1,458
28T_Flat_Cl6-7_R	$240	$4,208	1,074	166,194	$3,030	$1,418
29T_Flat_Cl6-7_U	$272	$4,766	1,216	188,228	$3,431	$1,607
30Tractor_DC_Cl8_MP	$618	$10,839	2,767	428,301	$7,808	$3,649
31Tractor_DC_Cl6-7_MP	$542	$9,501	2,426	375,458	$6,845	$3,198
32Tractor_SC_Cl8_U	$2,452	$42,985	10,969	1,697,692	$30,949	$14,488
33Tractor_DC_Cl8_U	$1,374	$24,102	6,153	952,419	$17,363	$8,113
34T_Ref_Cl8_MP	$803	$14,067	2,332	361,012	$6,581	$8,289
35T_Ref_Cl6-7_MP	$911	$15,972	2,648	409,894	$7,472	$9,411
36T_Ref_Cl8_U	$803	$14,067	2,332	361,012	$6,581	$8,289
37T_Ref_Cl6-7_U	$1,004	$17,594	2,917	451,528	$8,231	$10,367
38RV_Cl8_R	$70	$1,227	313	48,393	$882	$415
39RV_Cl6-7_R	$72	$1,251	319	49,338	$899	$424
40RV_Cl4-5_R	$48	$848	216	33,428	$609	$287
41Tractor_DC_Cl7_R	$1,204	$21,119	5,392	834,549	$15,214	$7,109
42RV_Cl8_MP	$70	$1,227	313	48,393	$882	$415
43RV_Cl6-7_MP	$74	$1,286	328	50,727	$925	$435
44RV_Cl4-5_MP	$52	$906	231	35,744	$652	$306
45Tractor_DC_Cl8_R	$1,373	$24,097	6,152	952,224	$17,359	$8,111
46B_School_Cl8_MP	$365	$6,389	1,630	252,294	$4,599	$2,155
47B_School_Cl6-7_MP	$345	$6,042	1,541	238,577	$4,349	$2,038
48B_School_Cl4-5_MP	$205	$3,592	917	141,861	$2,586	$1,211

Vehicle ID	Diesel ICE Vehicle Average Annual DEF Cost ($/year)	Diesel ICE Vehicle Average Annual Diesel Cost ($/year)	Diesel ICE Vehicle Annual Diesel Consumption (gallons)	CNG Vehicle Annual CNG Consumpt. (scf)	CNG Vehicle Annual CNG Fuel Costs ($/year)	Average Operating Savings ($/year)
49B_School_Cl2b-3_MP	$205	$3,592	917	141,861	$2,586	$1,211
50B_School_Cl8_U	$453	$7,929	2,023	313,125	$5,708	$2,674
51B_School_Cl6-7_U	$345	$6,042	1,541	238,577	$4,349	$2,038
52B_School_Cl4-5_U	$228	$3,985	1,017	157,368	$2,869	$1,344
53B_School_Cl2b-3_U	$228	$3,985	1,017	157,368	$2,869	$1,344
54Tractor_SC_Cl8_R	$2,452	$42,985	10,969	1,697,692	$30,949	$14,488
55B_Shuttle_Cl2b-3_MP	$503	$8,810	2,248	347,904	$6,342	$2,971
56B_Shuttle_Cl4-5_U	$558	$9,773	2,493	385,934	$7,036	$3,295
57B_Shuttle_Cl2b-3_U	$558	$9,773	2,493	385,934	$7,036	$3,295
58B_Shuttle_Cl6-7_MP	$714	$12,503	3,190	493,732	$9,001	$4,216
59B_Shuttle_Cl6-7_U	$786	$13,773	3,514	543,882	$9,915	$4,644
60S_Plow_Cl6-7_MP	$290	$5,091	1,104	170,911	$3,116	$2,265
61S_Plow_Cl8_MP	$404	$7,083	1,536	237,771	$4,335	$3,152
62S_Plow_Cl6-7_U	$320	$5,608	1,216	188,270	$3,432	$2,496
63S_Plow_Cl8_U	$501	$8,790	1,907	295,100	$5,380	$3,911
64V_Step_Cl6-7_MP	$377	$6,612	1,687	261,156	$4,761	$2,228
65V_Step_Cl4-5_MP	$166	$2,915	744	115,145	$2,099	$982
66V_Step_Cl2b-3_MP	$254	$4,451	1,136	175,837	$3,206	$1,499
67V_Step_Cl6-7_U	$415	$7,284	1,859	287,682	$5,244	$2,455
68V_Step_Cl4-5_U	$184	$3,234	825	127,732	$2,329	$1,089
69V_Step_Cl2b-3_U	$281	$4,937	1,260	195,058	$3,556	$1,662
70S_Sweep_Cl6-7_U	$430	$7,536	1,538	238,102	$4,341	$3,625
71T_Tanker_Cl8_R	$416	$7,287	1,581	244,642	$4,460	$3,243
72T_Tanker_Cl8_MP	$471	$8,261	1,792	277,319	$5,056	$3,676

Vehicle ID	Diesel ICE Vehicle Average Annual DEF Cost ($/year)	Diesel ICE Vehicle Average Annual Diesel Cost ($/year)	Diesel ICE Vehicle Annual Diesel Consumption (gallons)	CNG Vehicle Annual CNG Consumpt. (scf)	CNG Vehicle Annual CNG Fuel Costs ($/year)	Average Operating Savings ($/year)
73T_Tanker_Cl8_U	$585	$10,252	2,224	344,184	$6,274	$4,563
74T_Tow_Cl8_R	$519	$9,095	1,973	305,328	$5,566	$4,048
75T_Tow_Cl6-7_R	$397	$6,968	1,511	233,920	$4,264	$3,101
76T_Tow_Cl8_U	$730	$12,796	2,775	429,564	$7,831	$5,695
77T_Tow_Cl6-7_U	$450	$7,892	1,712	264,934	$4,830	$3,512
78Tractor_SC_Cl8_MP	$1,751	$30,704	7,835	1,212,637	$22,106	$10,349
79Tractor_SC_Cl8_R	$2,452	$42,985	10,969	1,697,692	$30,949	$14,488
80Tractor_DC_Cl8_HH	$984	$17,256	4,403	681,518	$12,424	$5,816
81Tractor_DC_Cl7_R	$1,204	$21,119	5,392	834,549	$15,214	$7,109
82Tractor_DC_Cl8_R	$1,373	$24,097	6,152	952,224	$17,359	$8,111
83Tractor_DC_Cl7_U	$672	$11,783	3,008	465,614	$8,488	$3,967
84Tractor_DC_Cl8_U	$764	$13,408	3,423	529,857	$9,659	$4,513
85B_Transit_Cl8_MP	$1,279	$22,400	5,715	884,542	$16,125	$7,554
86B_Transit_Cl6-7_MP	$486	$8,507	2,170	335,916	$6,124	$2,869
87B_Transit_Cl8_U	$1,279	$22,400	5,715	884,542	$16,125	$7,554
88B_Transit_Cl6-7_U	$535	$9,371	2,391	370,036	$6,746	$3,160
89T_Utility_Cl8_MP	$244	$4,273	927	143,444	$2,615	$1,902
90T_Utility_Cl8_R	$215	$3,769	818	126,541	$2,307	$1,677
91T_Utility_Cl6-7_MP	$359	$6,285	1,363	211,001	$3,847	$2,797
92T_Utility_Cl6-7_R	$349	$6,113	1,326	205,224	$3,741	$2,721
93T_Utility_Cl4-5_MP	$253	$4,429	961	148,680	$2,710	$1,972
94T_Utility_Cl2b-3_MP	$116	$2,027	440	68,037	$1,240	$903
95T_Utility_Cl4-5_R	$231	$4,060	881	136,337	$2,485	$1,806
96T_Utility_Cl2b-3_R	$231	$4,060	881	136,337	$2,485	$1,806

Vehicle ID	Diesel ICE Vehicle Average Annual DEF Cost ($/year)	Diesel ICE Vehicle Average Annual Diesel Cost ($/year)	Diesel ICE Vehicle Annual Diesel Consumption (gallons)	CNG Vehicle Annual CNG Consumpt. (scf)	CNG Vehicle Annual CNG Fuel Costs ($/year)	Average Operating Savings ($/year)
97T_Utility_Cl8_U	$302	$5,303	1,150	178,030	$3,245	$2,360
98T_Utility_Cl6-7_U	$395	$6,924	1,502	232,433	$4,237	$3,082
99T_Utility_Cl4-5_U	$280	$4,913	1,066	164,932	$3,007	$2,186
100T_Utility_Cl2b-3_U	$128	$2,248	488	75,475	$1,376	$1,000
101Tractor_DC_Cl8_U	$385	$6,747	1,723	266,614	$4,860	$2,272

2.11.5.3 H2-ICE Vehicles

The operating costs of H2-ICE vehicles include H2 consumption to power the engine and DEF consumption to control the NOx emissions. These costs are compared to the operating DEF and diesel fuel costs for each of the baseline diesel-fueled ICE vehicle applications in HD TRUCS, as discussed in RIA Chapter 2.3.4.

H2-ICE vehicles operate on H2 gas instead of diesel fuel. We calculated the H2-ICE hydrogen fuel costs relative to our assessment of the hydrogen costs for FCEVs for each of the vehicle applications in HD TRUCS, as discussed in RIA Chapter 2.5.3.1.When comparing efficiencies between FCEV and H2-ICE vehicles, the FCEVs have an average efficiency of 53 percent, as discussed in RIA Chapter 2.5.1.2.1, while H2-ICEV has an efficiency of 42 percent.[1301] Therefore, we calculated the H2 fueling costs for H2-ICE relative to the FCEV fueling costs by applying a ratio of 0.53/0.42.

The H2-ICE vehicles also require a SCR system to control NOx, but the system will be smaller than a comparable diesel ICE vehicle because the engine-out NOx emissions are lower. We calculated the annual DEF costs for H2-ICE vehicles as 10 percent of the DEF costs for a comparable baseline diesel ICE vehicle.[1302] The average DEF costs for each of the baseline diesel-fueled ICE vehicle applications in HD TRUCS were developed as discussed in RIA Chapter 2.3.4. The net annual operating savings for each of the HD TRUCS vehicle applications by vehicle ID is shown in Table 2-154. The upfront H2-ICE powertrain technology costs, as shown in Section II.F.4.ii.c, on average would pay back in 2 years for LHD vocational vehicles, 6 years for MHD vocational vehicles, 9 years for HHD vocational vehicles. The operating costs for H2-ICE tractors exceed the operating costs of ICE tractors, but there may be other reasons that purchasers would consider this technology such as the vehicles emit nearly zero CO_2 emissions at the tailpipe, the low engine-out exhaust emissions from H2-ICE vehicles provide

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[1301] FEV, "Hydrogen ICE", The Aachen Colloquium Sustainable Mobility, October 5th – 7th, 2020.

[1302] Srna, Ales. Sandia National Laboratory. "The future of H2 internal combustion engines in California?" Slide 4. December 2023. Available online: https://ww2.arb.ca.gov/sites/default/files/2023-12/231128sandiapres.pdf the opportunity for efficient and durable after-treatment systems, and the efficiency of H2-ICE vehicles may continue to improve with time.

Table 2-154 Annual Operating Savings of H2-ICE Heavy-Duty Vehicles (2022$)

Vehicle ID	Diesel Vehicle Average Annual DEF Cost ($/year)	Diesel Vehicle Average Annual Diesel Cost ($/year)	FCEV Average Annual H2 Cost ($/year)	H2-ICE Average Annual H2 and DEF Cost ($/year)	H2-ICE Average Operating Savings ($/year)
01V_Amb_Cl4-5_MP	$148	$2,481	$1,540	$1,958	$671
02V_Amb_Cl2b-3_MP	$216	$3,781	$2,181	$2,774	$1,223
03V_Amb_Cl4-5_U	$189	$3,317	$1,629	$2,074	$1,432
04V_Amb_Cl2b-3_U	$193	$3,375	$1,618	$2,061	$1,507
05T_Box_Cl8_MP	$512	$8,981	$6,520	$8,278	$1,215
06T_Box_Cl8_R	$443	$7,766	$6,628	$8,408	$(199)
07T_Box_Cl6-7_MP	$247	$4,326	$2,704	$3,437	$1,136
08T_Box_Cl6-7_R	$235	$4,125	$2,897	$3,680	$680
09T_Box_Cl8_U	$636	$11,147	$6,297	$8,010	$3,773
10T_Box_Cl6-7_U	$265	$4,650	$2,424	$3,085	$1,830
11T_Box_Cl2b-3_U	$287	$5,037	$2,361	$3,008	$2,316
12T_Box_Cl2b-3_R	$242	$4,246	$2,811	$3,572	$916
13T_Box_Cl2b-3_MP	$259	$4,541	$2,577	$3,277	$1,523
14T_Box_Cl4-5_U	$184	$3,234	$1,528	$1,946	$1,472
15T_Box_Cl4-5_R	$156	$2,726	$1,817	$2,308	$574
16T_Box_Cl4-5_MP	$166	$2,915	$1,666	$2,119	$962
17B_Coach_Cl8_R	$1,109	$19,420	$14,660	$18,610	$1,919
18B_Coach_Cl8_MP	$1,109	$19,420	$14,593	$18,526	$2,003
19C_Mix_Cl8_MP	$1,523	$26,700	$15,693	$19,956	$8,267
20T_Dump_Cl8_U	$453	$7,948	$4,141	$5,271	$3,130
21T_Dump_Cl8_MP	$365	$6,404	$4,203	$5,341	$1,428
22T_Dump_Cl6-7_MP	$409	$7,176	$4,065	$5,170	$2,415
23T_Dump_Cl8_U	$453	$7,948	$4,141	$5,271	$3,130
24T_Dump_Cl6-7_U	$451	$7,905	$3,795	$4,834	$3,522
25T_Fire_Cl8_MP	$414	$7,257	$4,419	$5,617	$2,054
26T_Fire_Cl8_U	$514	$9,007	$4,421	$5,630	$3,891
27T_Flat_Cl6-7_MP	$247	$4,326	$2,704	$3,437	$1,136
28T_Flat_Cl6-7_R	$240	$4,208	$2,951	$3,748	$700
29T_Flat_Cl6-7_U	$272	$4,766	$2,485	$3,163	$1,875
30Tractor_DC_Cl8_MP	$618	$10,839	$9,896	$12,550	$(1,093)
31Tractor_DC_Cl6-7_MP	$542	$9,501	$8,256	$10,472	$(429)
32Tractor_SC_Cl8_U	$2,452	$42,985	$34,601	$43,908	$1,529
33Tractor_DC_Cl8_U	$1,374	$24,102	$18,296	$23,225	$2,251
34T_Ref_Cl8_MP	$803	$14,067	$6,499	$8,281	$6,589
35T_Ref_Cl6-7_MP	$911	$15,972	$9,536	$12,125	$4,758
36T_Ref_Cl8_U	$803	$14,067	$6,499	$8,281	$6,589
37T_Ref_Cl6-7_U	$1,004	$17,594	$9,405	$11,968	$6,630
38RV_Cl8_R	$70	$1,227	$808	$1,026	$271
39RV_Cl6-7_R	$72	$1,251	$859	$1,091	$232
40RV_Cl4-5_R	$48	$848	$545	$692	$204
41Tractor_DC_Cl7_R	$1,204	$21,119	$18,252	$23,153	$(830)
42RV_Cl8_MP	$70	$1,227	$808	$1,026	$271
43RV_Cl6-7_MP	$74	$1,286	$785	$999	$361
44RV_Cl4-5_MP	$52	$906	$498	$634	$324

Vehicle ID	Diesel Vehicle Average Annual DEF Cost ($/year)	Diesel Vehicle Average Annual Diesel Cost ($/year)	FCEV Average Annual H2 Cost ($/year)	H2-ICE Average Annual H2 and DEF Cost ($/year)	H2-ICE Average Operating Savings ($/year)
45Tractor_DC_Cl8_R	$1,373	$24,097	$21,865	$27,729	$(2,259)
46B_School_Cl8_MP	$365	$6,389	$4,797	$6,090	$664
47B_School_Cl6-7_MP	$345	$6,042	$3,019	$3,845	$2,542
48B_School_Cl4-5_MP	$205	$3,592	$2,118	$2,693	$1,104
49B_School_Cl2b-3_MP	$205	$3,592	$2,073	$2,637	$1,160
50B_School_Cl8_U	$453	$7,929	$4,596	$5,845	$2,537
51B_School_Cl6-7_U	$345	$6,042	$3,019	$3,845	$2,542
52B_School_Cl4-5_U	$228	$3,985	$1,950	$2,483	$1,730
53B_School_Cl2b-3_U	$228	$3,985	$1,904	$2,425	$1,788
54Tractor_SC_Cl8_R	$2,452	$42,985	$41,425	$52,520	$(7,083)
55B_Shuttle_Cl2b-3_MP	$503	$8,810	$4,982	$6,338	$2,975
56B_Shuttle_Cl4-5_U	$558	$9,773	$4,640	$5,911	$4,420
57B_Shuttle_Cl2b-3_U	$558	$9,773	$4,564	$5,816	$4,515
58B_Shuttle_Cl6-7_MP	$714	$12,503	$7,897	$10,037	$3,180
59B_Shuttle_Cl6-7_U	$786	$13,773	$7,269	$9,252	$5,307
60S_Plow_Cl6-7_MP	$290	$5,091	$2,898	$3,685	$1,696
61S_Plow_Cl8_MP	$404	$7,083	$4,579	$5,819	$1,668
62S_Plow_Cl6-7_U	$320	$5,608	$2,706	$3,447	$2,481
63S_Plow_Cl8_U	$501	$8,790	$4,493	$5,720	$3,571
64V_Step_Cl6-7_MP	$377	$6,612	$4,121	$5,238	$1,751
65V_Step_Cl4-5_MP	$166	$2,915	$1,666	$2,119	$962
66V_Step_Cl2b-3_MP	$254	$4,451	$2,530	$3,218	$1,487
67V_Step_Cl6-7_U	$415	$7,284	$3,787	$4,820	$2,879
68V_Step_Cl4-5_U	$184	$3,234	$1,528	$1,946	$1,472
69V_Step_Cl2b-3_U	$281	$4,937	$2,318	$2,953	$2,265
70S_Sweep_Cl6-7_U	$430	$7,536	$3,702	$4,715	$3,251
71T_Tanker_Cl8_R	$416	$7,287	$5,667	$7,193	$510
72T_Tanker_Cl8_MP	$471	$8,261	$5,552	$7,054	$1,678
73T_Tanker_Cl8_U	$585	$10,252	$5,513	$7,015	$3,822
74T_Tow_Cl8_R	$519	$9,095	$6,949	$8,821	$793
75T_Tow_Cl6-7_R	$397	$6,968	$4,388	$5,577	$1,788
76T_Tow_Cl8_U	$730	$12,796	$6,705	$8,534	$4,992
77T_Tow_Cl6-7_U	$450	$7,892	$3,786	$4,823	$3,519
78Tractor_SC_Cl8_MP	$1,751	$30,704	$29,632	$37,568	$(5,113)
79Tractor_SC_Cl8_R	$2,452	$42,985	$41,425	$52,520	$(7,083)
80Tractor_DC_Cl8_HH	$984	$17,256	$15,577	$19,755	$(1,515)
81Tractor_DC_Cl7_R	$1,204	$21,119	$18,276	$23,183	$(860)
82Tractor_DC_Cl8_R	$1,373	$24,097	$21,892	$27,763	$(2,293)
83Tractor_DC_Cl7_U	$672	$11,783	$10,211	$12,952	$(497)
84Tractor_DC_Cl8_U	$764	$13,408	$12,240	$15,522	$(1,350)
85B_Transit_Cl8_MP	$1,279	$22,400	$12,253	$15,590	$8,089
86B_Transit_Cl6-7_MP	$486	$8,507	$5,278	$6,709	$2,284
87B_Transit_Cl8_U	$1,279	$22,400	$12,253	$15,590	$8,089
88B_Transit_Cl6-7_U	$535	$9,371	$4,804	$6,116	$3,790
89T_Utility_Cl8_MP	$244	$4,273	$2,776	$3,528	$989
90T_Utility_Cl8_R	$215	$3,769	$2,852	$3,620	$364
91T_Utility_Cl6-7_MP	$359	$6,285	$3,667	$4,663	$1,981
92T_Utility_Cl6-7_R	$349	$6,113	$3,952	$5,022	$1,440
93T_Utility_Cl4-5_MP	$253	$4,429	$2,376	$3,024	$1,658

Vehicle ID	Diesel Vehicle Average Annual DEF Cost ($/year)	Diesel Vehicle Average Annual Diesel Cost ($/year)	FCEV Average Annual H2 Cost ($/year)	H2-ICE Average Annual H2 and DEF Cost ($/year)	H2-ICE Average Operating Savings ($/year)
94T_Utility_Cl2b-3_MP	$116	$2,027	$1,047	$1,333	$810
95T_Utility_Cl4-5_R	$231	$4,060	$2,502	$3,180	$1,111
96T_Utility_Cl2b-3_R	$231	$4,060	$2,502	$3,180	$1,111
97T_Utility_Cl8_U	$302	$5,303	$2,722	$3,465	$2,140
98T_Utility_Cl6-7_U	$395	$6,924	$3,443	$4,385	$2,934
99T_Utility_Cl4-5_U	$280	$4,913	$2,232	$2,845	$2,348
100T_Utility_Cl2b-3_U	$128	$2,248	$972	$1,240	$1,136
101Tractor_DC_Cl8_U	$385	$6,747	$6,183	$7,841	$(709)

2.11.5.4 Hybrid and Plug-in Hybrid Vehicles

Hybrid vehicles, similar to other ICE vehicle improvements, will have lower operating costs than a comparable ICE vehicle due to reduced diesel fuel consumption and DEF consumption. These HEV costs are compared to the operating DEF and diesel fuel costs for each of the baseline diesel-fueled ICE vehicle applications in HD TRUCS, as discussed in RIA Chapter 2.3.4. As discussed above, we used an effectiveness level for vocational vehicle hybrid powertrains of 15 percent and for tractor hybrid powertrains of 10 percent.

The annual operating savings for HEVs was calculated for each of the HD TRUCS vehicle applications, as shown in Table 2-155 by reducing the diesel ICE DEF and fuel costs by 15 percent for vocational vehicles and 10 percent for tractors. The annual operating savings were then compared to the upfront technology costs, as shown in Chapter 2.11.2.4. The hybrid powertrain technology will pay back in 10-11 years for vocational vehicles, but in a shorter period of time for some applications such as refuse haulers, step vans, and transit buses. The average payback period for this technology in day cab tractors is 7.5 years and 4 years in sleeper cab tractors.

Table 2-155 Annual Operating Savings of Hybrid Heavy-Duty Vehicles (2022$)

Vehicle ID	Diesel ICE Average Annual DEF Cost ($/year)	Diesel ICE Average Annual Diesel Cost ($/year)	HEV Average Operating Cost Savings ($/year)
01V_Amb_Cl4-5_MP	$148	$2,481	$394
02V_Amb_Cl2b-3_MP	$216	$3,781	$600
03V_Amb_Cl4-5_U	$189	$3,317	$526
04V_Amb_Cl2b-3_U	$193	$3,375	$535
05T_Box_Cl8_MP	$512	$8,981	$1,424
06T_Box_Cl8_R	$443	$7,766	$1,231
07T_Box_Cl6-7_MP	$247	$4,326	$686
08T_Box_Cl6-7_R	$235	$4,125	$654
09T_Box_Cl8_U	$636	$11,147	$1,767
10T_Box_Cl6-7_U	$265	$4,650	$737
11T_Box_Cl2b-3_U	$287	$5,037	$799
12T_Box_Cl2b-3_R	$242	$4,246	$673
13T_Box_Cl2b-3_MP	$259	$4,541	$720
14T_Box_Cl4-5_U	$184	$3,234	$513

Vehicle ID	Diesel ICE Average Annual DEF Cost ($/year)	Diesel ICE Average Annual Diesel Cost ($/year)	HEV Average Operating Cost Savings ($/year)
15T_Box_Cl4-5_R	$156	$2,726	$432
16T_Box_Cl4-5_MP	$166	$2,915	$462
17B_Coach_Cl8_R	$1,109	$19,420	$3,079
18B_Coach_Cl8_MP	$1,109	$19,420	$3,079
19C_Mix_Cl8_MP	$1,523	$26,700	$4,233
20T_Dump_Cl8_U	$453	$7,948	$1,260
21T_Dump_Cl8_MP	$365	$6,404	$1,015
22T_Dump_Cl6-7_MP	$409	$7,176	$1,138
23T_Dump_Cl8_U	$453	$7,948	$1,260
24T_Dump_Cl6-7_U	$451	$7,905	$1,253
25T_Fire_Cl8_MP	$414	$7,257	$1,151
26T_Fire_Cl8_U	$514	$9,007	$1,428
27T_Flat_Cl6-7_MP	$247	$4,326	$686
28T_Flat_Cl6-7_R	$240	$4,208	$667
29T_Flat_Cl6-7_U	$272	$4,766	$756
30Tractor_DC_Cl8_MP	$618	$10,839	$1,146
31Tractor_DC_Cl6-7_MP	$542	$9,501	$1,004
32Tractor_SC_Cl8_U	$2,452	$42,985	$4,544
33Tractor_DC_Cl8_U	$1,374	$24,102	$2,548
34T_Ref_Cl8_MP	$803	$14,067	$2,231
35T_Ref_Cl6-7_MP	$911	$15,972	$2,532
36T_Ref_Cl8_U	$803	$14,067	$2,231
37T_Ref_Cl6-7_U	$1,004	$17,594	$2,790
38RV_Cl8_R	$70	$1,227	$195
39RV_Cl6-7_R	$72	$1,251	$198
40RV_Cl4-5_R	$48	$848	$134
41Tractor_DC_Cl7_R	$1,204	$21,119	$2,232
42RV_Cl8_MP	$70	$1,227	$195
43RV_Cl6-7_MP	$74	$1,286	$204
44RV_Cl4-5_MP	$52	$906	$144
45Tractor_DC_Cl8_R	$1,373	$24,097	$2,547
46B_School_Cl8_MP	$365	$6,389	$1,013
47B_School_Cl6-7_MP	$345	$6,042	$958
48B_School_Cl4-5_MP	$205	$3,592	$570
49B_School_Cl2b-3_MP	$205	$3,592	$570
50B_School_Cl8_U	$453	$7,929	$1,257
51B_School_Cl6-7_U	$345	$6,042	$958
52B_School_Cl4-5_U	$228	$3,985	$632
53B_School_Cl2b-3_U	$228	$3,985	$632
54Tractor_SC_Cl8_R	$2,452	$42,985	$4,544
55B_Shuttle_Cl2b-3_MP	$503	$8,810	$1,397
56B_Shuttle_Cl4-5_U	$558	$9,773	$1,550
57B_Shuttle_Cl2b-3_U	$558	$9,773	$1,550
58B_Shuttle_Cl6-7_MP	$714	$12,503	$1,983
59B_Shuttle_Cl6-7_U	$786	$13,773	$2,184
60S_Plow_Cl6-7_MP	$290	$5,091	$807
61S_Plow_Cl8_MP	$404	$7,083	$1,123
62S_Plow_Cl6-7_U	$320	$5,608	$889
63S_Plow_Cl8_U	$501	$8,790	$1,394
64V_Step_Cl6-7_MP	$377	$6,612	$1,048

Vehicle ID	Diesel ICE Average Annual DEF Cost ($/year)	Diesel ICE Average Annual Diesel Cost ($/year)	HEV Average Operating Cost Savings ($/year)
65V_Step_Cl4-5_MP	$166	$2,915	$462
66V_Step_Cl2b-3_MP	$254	$4,451	$706
67V_Step_Cl6-7_U	$415	$7,284	$1,155
68V_Step_Cl4-5_U	$184	$3,234	$513
69V_Step_Cl2b-3_U	$281	$4,937	$783
70S_Sweep_Cl6-7_U	$430	$7,536	$1,195
71T_Tanker_Cl8_R	$416	$7,287	$1,155
72T_Tanker_Cl8_MP	$471	$8,261	$1,310
73T_Tanker_Cl8_U	$585	$10,252	$1,626
74T_Tow_Cl8_R	$519	$9,095	$1,442
75T_Tow_Cl6-7_R	$397	$6,968	$1,105
76T_Tow_Cl8_U	$730	$12,796	$2,029
77T_Tow_Cl6-7_U	$450	$7,892	$1,251
78Tractor_SC_Cl8_MP	$1,751	$30,704	$3,246
79Tractor_SC_Cl8_R	$2,452	$42,985	$4,544
80Tractor_DC_Cl8_HH	$984	$17,256	$1,824
81Tractor_DC_Cl7_R	$1,204	$21,119	$2,232
82Tractor_DC_Cl8_R	$1,373	$24,097	$2,547
83Tractor_DC_Cl7_U	$672	$11,783	$1,246
84Tractor_DC_Cl8_U	$764	$13,408	$1,417
85B_Transit_Cl8_MP	$1,279	$22,400	$3,552
86B_Transit_Cl6-7_MP	$486	$8,507	$1,349
87B_Transit_Cl8_U	$1,279	$22,400	$3,552
88B_Transit_Cl6-7_U	$535	$9,371	$1,486
89T_Utility_Cl8_MP	$244	$4,273	$678
90T_Utility_Cl8_R	$215	$3,769	$598
91T_Utility_Cl6-7_MP	$359	$6,285	$997
92T_Utility_Cl6-7_R	$349	$6,113	$969
93T_Utility_Cl4-5_MP	$253	$4,429	$702
94T_Utility_Cl2b-3_MP	$116	$2,027	$321
95T_Utility_Cl4-5_R	$231	$4,060	$644
96T_Utility_Cl2b-3_R	$231	$4,060	$644
97T_Utility_Cl8_U	$302	$5,303	$841
98T_Utility_Cl6-7_U	$395	$6,924	$1,098
99T_Utility_Cl4-5_U	$280	$4,913	$779
100T_Utility_Cl2b-3_U	$128	$2,248	$356
101Tractor_DC_Cl8_U	$385	$6,747	$713

Similar to our discussion for ZEVs under the modeled potential compliance pathways, the IRA provides powerful incentives in reducing the cost to manufacture and purchase PHEVs, as well as reducing the cost of charging infrastructure as applicable (see further discussion just below), that facilitates market penetration of PHEV technology in the time frame considered in this rulemaking. The upfront costs to purchasers of PHEVs would be less than the cost to manufacturers due to the IRA purchaser tax credit. IRA section 13403, “Qualified Commercial Clean Vehicles,” creates a tax credit of up to $40,000 per Class 4 through 8 HD vehicle (up to $7,500 per Class 2b or 3 vehicle) for the purchase or lease of a qualified commercial clean vehicle. This tax credit is available from CY 2023 through CY 2032 and is based on the lesser of the incremental cost of the clean vehicle over a comparable ICE vehicle or the specified percentage of the basis of the clean vehicle, up to the maximum $40,000 limitation. Among other specifications, these vehicles must be on-road vehicles (or mobile machinery) that are propelled to a significant extent by a battery-powered electric motor or are qualified fuel cell motor vehicles. For the former, the battery must have a capacity of at least 15 kWh (or 7 kWh if it has a gross vehicle weight rating of less than 14,000 pounds (Class 3 or below)) and must be rechargeable from an external source of electricity. For PHEVs, the per-vehicle tax credit cap limitation is 15 percent of the vehicle cost, which is the limiting factor for many of the applications. Since this tax credit overlaps with the model years for which we are finalizing standards (MYs 2027 through 2032), we included it in our calculations for each of those years in our analysis, as shown in Table 2-156.

Table 2-156 Upfront Incremental Technology Costs for Plug-in Hybrid Vehicle Purchasers – MY 2030 and Later

Vehicle Type	PHEV Costs before Tax Credit	PHEV Costs After Tax Credit
Light Heavy-Duty Vocational	$21,774	$5,465
Medium Heavy-Duty Vocational	$28,552	$7,652
Heavy Heavy-Duty Vocational	$40,627	$8,962
Day Cab Tractors	$37,224	$11,024
Sleeper Cab Tractors	$53,514	$17,043

The purchaser of a HD PHEV would need to consider the recharging needs of the vehicle. Because the battery sizes in HD PHEVs are significantly smaller than a comparable BEV and only discharge 60 percent of their battery in-use, the recharging demand is also lower than a comparable BEV. Therefore, for this analysis, the vehicles use depot charging and recharge with a 240 V/50 amp outlet that we project are available at no additional cost. There may be situations where the operator would need to create access to such an outlet, but those costs would be low. Furthermore, as discussed in RIA Chapter 1.3.2, the IRA can also help reduce the costs for deploying EVSE infrastructure. The IRA extends the Alternative Fuel Refueling Property Tax Credit (Section 13404) through 2032, with modifications. Under the new provisions, businesses would be eligible for up to 30 percent of the costs associated with purchasing and installing charging equipment in these areas (subject to a $100,000 cap per item) if prevailing wage and apprenticeship requirements are met.

Plug-in hybrid vehicle operating costs consist of a combination of ICE operation and battery electric operation. These PHEV costs are calculated relative to the operating costs for each of the baseline diesel-fueled ICE vehicle applications in HD TRUCS, as discussed in RIA Chapter 2.3.4 and the comparable BEV operating costs, as discussed in RIA Chapter 2.4.4. As discussed above, we used a utility factor for vocational vehicle PHEV powertrains of 41 percent and for tractor PHEV powertrains of 22 percent in MY 2030 and later. The annual operating savings was evaluated for each of the HD TRUCS vehicle applications compared to the comparable baseline diesel ICE vehicle, as shown in Table 2-157. The incremental cost of the PHEV powertrain technology after accounting for the IRA tax credit as shown in Table 2-156 for vocational vehicles will be offset by the operating savings with a payback period of 3 years. The day cab and sleeper cab tractor upfront costs would be offset with operational savings over an 8- and 9-year period, respectively.

Table 2-157 Annual Operating Savings of Plug-in Hybrid Heavy-Duty Vehicles (2022$)

Vehicle ID	Average Annual Operating Cost ($/year)			Average PHEV Operating Savings Relative to Diesel ICE ($/year)
	Diesel ICE	BEV	PHEV	
01V_Amb_Cl4-5_MP	$5,896	$3,537	$4,928	$967
02V_Amb_Cl2b-3_MP	$8,105	$4,565	$6,653	$1,451
03V_Amb_Cl4-5_U	$7,069	$3,804	$5,730	$1,338
04V_Amb_Cl2b-3_U	$7,112	$3,756	$5,736	$1,376
05T_Box_Cl8_MP	$15,759	$8,708	$12,868	$2,891
06T_Box_Cl8_R	$14,378	$8,713	$12,056	$2,323
07T_Box_Cl6-7_MP	$8,265	$4,714	$6,809	$1,456
08T_Box_Cl6-7_R	$7,989	$4,835	$6,696	$1,293
09T_Box_Cl8_U	$17,743	$8,550	$13,974	$3,769
10T_Box_Cl6-7_U	$8,547	$4,474	$6,877	$1,670
11T_Box_Cl2b-3_U	$9,986	$5,036	$7,957	$2,030
12T_Box_Cl2b-3_R	$9,157	$5,376	$7,607	$1,550
13T_Box_Cl2b-3_MP	$9,466	$5,198	$7,716	$1,750
14T_Box_Cl4-5_U	$6,850	$3,582	$5,510	$1,340
15T_Box_Cl4-5_R	$6,318	$3,822	$5,295	$1,023
16T_Box_Cl4-5_MP	$6,516	$3,697	$5,360	$1,156
17B_Coach_Cl8_R	$31,495	$25,342	$28,972	$2,523
18B_Coach_Cl8_MP	$31,495	$26,295	$29,363	$2,132
19C_Mix_Cl8_MP	$35,420	$16,129	$27,510	$7,909
20T_Dump_Cl8_U	$13,145	$6,188	$10,293	$2,853
21T_Dump_Cl8_MP	$11,527	$6,235	$9,357	$2,170
22T_Dump_Cl6-7_MP	$12,206	$6,631	$9,920	$2,286
23T_Dump_Cl8_U	$12,860	$6,188	$10,124	$2,735
24T_Dump_Cl6-7_U	$12,970	$6,403	$10,278	$2,693
25T_Fire_Cl8_MP	$12,422	$6,418	$9,960	$2,462
26T_Fire_Cl8_U	$13,970	$6,426	$10,877	$3,093
27T_Flat_Cl6-7_MP	$8,258	$4,710	$6,803	$1,454
28T_Flat_Cl6-7_R	$8,133	$4,914	$6,814	$1,320
29T_Flat_Cl6-7_U	$8,718	$4,530	$7,001	$1,717
30Tractor_DC_Cl8_MP	$19,409	$12,555	$17,901	$1,508
31Tractor_DC_Cl6-7_MP	$17,455	$11,198	$16,078	$1,377
32Tractor_SC_Cl8_U	$72,536	$58,080	$69,355	$3,180
33Tractor_DC_Cl8_U	$39,459	$30,528	$37,494	$1,965
34T_Ref_Cl8_MP	$19,942	$8,472	$15,240	$4,703
35T_Ref_Cl6-7_MP	$23,791	$11,886	$18,910	$4,881
36T_Ref_Cl8_U	$19,942	$8,472	$15,240	$4,703
37T_Ref_Cl6-7_U	$25,492	$11,792	$19,875	$5,617
38RV_Cl8_R	$3,448	$3,752	$3,573	-$125
39RV_Cl6-7_R	$3,415	$3,803	$3,574	-$159
40RV_Cl4-5_R	$2,802	$2,795	$2,800	$3
41Tractor_DC_Cl7_R	$36,306	$31,016	$35,142	$1,164
42RV_Cl8_MP	$3,448	$3,752	$3,573	-$125
43RV_Cl6-7_MP	$3,452	$3,588	$3,508	-$56
44RV_Cl4-5_MP	$2,864	$2,658	$2,780	$84
45Tractor_DC_Cl8_R	$40,077	$35,466	$39,063	$1,014
46B_School_Cl8_MP	$10,931	$6,994	$9,317	$1,614
47B_School_Cl6-7_MP	$10,690	$5,486	$8,556	$2,134
48B_School_Cl4-5_MP	$7,753	$4,517	$6,426	$1,327

Vehicle ID	Average Annual Operating Cost ($/year)			Average PHEV Operating Savings Relative to Diesel ICE ($/year)
	Diesel ICE	BEV	PHEV	
49B_School_Cl2b-3_MP	$7,810	$4,415	$6,418	$1,392
50B_School_Cl8_U	$12,546	$6,773	$10,179	$2,367
51B_School_Cl6-7_U	$10,690	$5,486	$8,556	$2,134
52B_School_Cl4-5_U	$8,164	$4,389	$6,616	$1,548
53B_School_Cl2b-3_U	$8,221	$4,283	$6,607	$1,615
55B_Shuttle_Cl2b-3_MP	$17,339	$9,413	$14,090	$3,250
56B_Shuttle_Cl4-5_U	$18,291	$9,272	$14,594	$3,698
57B_Shuttle_Cl2b-3_U	$18,349	$9,112	$14,562	$3,787
58B_Shuttle_Cl6-7_MP	$21,342	$11,824	$17,440	$3,902
59B_Shuttle_Cl6-7_U	$22,673	$11,375	$18,041	$4,632
60S_Plow_Cl6-7_MP	$9,059	$4,933	$7,367	$1,692
61S_Plow_Cl8_MP	$12,488	$7,012	$10,243	$2,245
62S_Plow_Cl6-7_U	$9,601	$4,771	$7,621	$1,980
63S_Plow_Cl8_U	$13,993	$6,940	$11,101	$2,892
64V_Step_Cl6-7_MP	$11,890	$6,529	$9,692	$2,198
65V_Step_Cl4-5_MP	$6,490	$3,697	$5,345	$1,145
66V_Step_Cl2b-3_MP	$9,295	$5,096	$7,574	$1,722
67V_Step_Cl6-7_U	$12,594	$6,277	$10,004	$2,590
68V_Step_Cl4-5_U	$6,825	$3,582	$5,495	$1,329
69V_Step_Cl2b-3_U	$9,805	$4,936	$7,809	$1,996
70S_Sweep_Cl6-7_U	$12,243	$5,850	$9,622	$2,621
71T_Tanker_Cl8_R	$13,136	$7,613	$10,872	$2,264
72T_Tanker_Cl8_MP	$13,871	$7,529	$11,271	$2,600
73T_Tanker_Cl8_U	$15,958	$7,505	$12,493	$3,466
74T_Tow_Cl8_R	$15,861	$9,449	$13,232	$2,629
75T_Tow_Cl6-7_R	$11,982	$6,908	$9,902	$2,080
76T_Tow_Cl8_U	$19,378	$9,262	$15,230	$4,148
77T_Tow_Cl6-7_U	$12,950	$6,397	$10,263	$2,687
78Tractor_SC_Cl8_MP	$52,579	$47,390	$51,438	$1,142
79Tractor_SC_Cl8_R	$72,536	$65,783	$71,050	$1,486
80Tractor_DC_Cl8_HH	$27,046	$17,727	$24,996	$2,050
81Tractor_DC_Cl7_R	$36,306	$30,385	$35,003	$1,303
82Tractor_DC_Cl8_R	$40,077	$34,692	$38,893	$1,185
83Tractor_DC_Cl7_U	$21,157	$13,857	$19,551	$1,606
84Tractor_DC_Cl8_U	$23,328	$19,861	$22,565	$763
85B_Transit_Cl8_MP	$33,319	$16,163	$26,285	$7,034
86B_Transit_Cl6-7_MP	$14,962	$8,800	$12,435	$2,526
87B_Transit_Cl8_U	$33,296	$16,163	$26,272	$7,024
88B_Transit_Cl6-7_U	$15,867	$8,401	$12,806	$3,061
89T_Utility_Cl8_MP	$8,510	$4,643	$6,925	$1,585
90T_Utility_Cl8_R	$7,982	$4,710	$6,641	$1,342
91T_Utility_Cl6-7_MP	$10,862	$5,781	$8,779	$2,083
92T_Utility_Cl6-7_R	$10,681	$6,006	$8,764	$1,917
93T_Utility_Cl4-5_MP	$8,830	$4,667	$7,123	$1,707
94T_Utility_Cl2b-3_MP	$4,683	$2,642	$3,846	$837
95T_Utility_Cl4-5_R	$8,364	$4,713	$6,867	$1,497
96T_Utility_Cl2b-3_R	$8,305	$4,711	$6,832	$1,474
97T_Utility_Cl8_U	$9,304	$4,598	$7,375	$1,930
98T_Utility_Cl6-7_U	$11,531	$5,607	$9,102	$2,429
99T_Utility_Cl4-5_U	$9,338	$4,555	$7,377	$1,961

Vehicle ID	Average Annual Operating Cost ($/year)			Average PHEV Operating Savings Relative to Diesel ICE ($/year)
	Diesel ICE	BEV	PHEV	
100T_Utility_Cl2b-3_U	$4,915	$2,570	$3,953	$962
101Tractor_DC_Cl8_U	$12,992	$8,414	$11,985	$1,007

2.12 Total Cost of Ownership (TCO) Analysis

EPA conducted a TCO analysis for the final rule. This analysis complements the payback analysis in HD TRUCS that is discussed in the sections above. The TCO analysis relies on the same upfront and operating costs that are used in HD TRUCS, plus financing costs and residual value, and can be calculated over several different time horizons.

2.12.1 TCO Analysis Time Horizon

We analyzed a financial time horizon of 5 years.

2.12.2 TCO Analysis Residual Value

A factor that is frequently captured in vehicle TCO analyses is the residual value of a vehicle, which is calculated at the end of the time horizon of the TCO analysis. To estimate the residual value for each vehicle, we relied on equations[1303] and coefficients that are used in the BEAN TCO analysis.[1304] Equation 2-88 below is used to calculate the residual value fraction of a vehicle at age k, that can then be multiplied by the upfront cost of the vehicle to estimate the residual value of a vehicle at age k.

Equation 2-88 Residual Value Fraction

$$\text{Residual Value Fraction} = e^{i*k_a+k_b*\frac{COR_{veh}(Y_i)}{1000}}$$

Where,

i = year of evaluation, starting with year 0,

$COR_{veh}(Y_i)$ = Cumulative VMT over Year i

k_a = Depreciation Coefficient A

k_b = Depreciation Coefficient B

Coefficients:

[1303] See the TCO tab in ANL's 2022 BEAN Tool MD HD Vehicle Techno-Economic Analysis.xlsm.

[1304] Argonne National Laboratory. VTO HFTO Analysis Reports – 2022. "ANL – ESD-2206 Report – BEAN Tool – MD HD Vehicle Techno-Economic Analysis.xlsm". Available online: https://anl.app.box.com/s/an4nx0v2xpudxtpsnkhd5peimzu4j1hk/folder/242640145714.

Coefficient	Tractors	Vocational Vehicles[1305]
A	-0.09753	-0.10455
B	-0.000956	-0.000947

There is limited data on residual values for HD ZEVs,[1306] therefore, the depreciation equations do not differ by powertrain type.

2.12.3 TCO Analysis Financing Costs

In response to comments received on the proposal, we included financing costs as part of our TCO analysis to reflect that not all vehicles are purchased outright. We performed this calculation by first finding the amount of interest paid per year. This can be seen in Equation 2-89.

Equation 2-89 Interest Paid per Year per Powertrain Type

$$I|_{PT} = \frac{\left(\left(\frac{C_{upfront}|_{PT} * (1-DP) * \left(\frac{i}{12}\right)}{\left(1-\left(1-\frac{i}{12}\right)^{-t*12}\right)}\right) * t * 12\right) - \left(C_{upfront}|_{PT} * (1-DP)\right)}{t}$$

Where,

$C_{upfront}$ = Upfront cost for each powertrain type ($)

DP = Down payment (%)

i = Interest rate (%)

t = Term of loan (years)

We than summed the interest per year values based on the time horizon selected for the TCO analysis in Equation 2-90.

Equation 2-90 Total Interest per Year

$$I_{cum}|_{PT} = \sum_{0}^{t_{TCO}} I|_{PT}$$

Where,

[1305] We used the BEAN "BoxMedium 4" coefficients for all vocational vehicles in HD TRUCS.

[1306] Burnham, A., Gohlke, D., Rush, L., Stephens, T., Zhou, Y., Delucchi, M. A., Birky, A., Hunter, C., Lin, Z., Ou, S., Xie, F., Proctor, C., Wiryadinata, S., Liu, N., Boloor, M. "Comprehensive Total Cost of Ownership Quantification for Vehicles with Different Size Classes and Powertrains". Argonne National Laboratory. April 1, 2021. Available online: https://publications.anl.gov/anlpubs/2021/05/167399.pdf. See page 58.

t_{TCO} = Time horizon of TCO analysis (years)

2.12.4 TCO Analysis Results

Table 2-158 shows the TCO results for each of the HD TRUCS vehicle types for MY 2032, using a 5-year time horizon and financing over a 5-year term with an interest rate of 5% and with a 20% down payment. The results show that costs for owning and operating a ZEV will be lower than a comparable ICE vehicle for all MY 2032 BEVs and FCEVs in our technology packages to support the modeled potential compliance pathway. In fact, all vehicles show several thousands of dollars in net TCO savings at the five-year point.

Table 2-158 TCO Results for MY 2032 Vehicles (2022$)

Vehicle ID	**ICE TCO**	**BEV TCO**	**FCEV TCO**	**Incremental BEV TCO**	**Incremental FCEV TCO**
01V_Amb_Cl4-5_MP	$65,786	$54,702	$58,392	-$11,084	--
02V_Amb_Cl2b-3_MP	$76,393	$56,381	$63,821	-$20,012	--
03V_Amb_Cl4-5_U	$72,043	$55,585	$60,327	-$16,459	--
04V_Amb_Cl2b-3_U	$71,263	$54,814	$58,362	-$16,450	--
05T_Box_Cl8_MP	$178,503	$136,788	$161,327	-$41,715	--
06T_Box_Cl8_R	$172,221	$151,245	$162,482	-$20,976	--
07T_Box_Cl6-7_MP	$83,275	$68,540	$68,200	-$14,734	--
08T_Box_Cl6-7_R	$82,520	$70,633	$69,317	-$11,886	--
09T_Box_Cl8_U	$183,240	$148,169	$149,704	-$35,071	--
10T_Box_Cl6-7_U	$84,868	$66,794	$66,433	-$18,075	--
11T_Box_Cl2b-3_U	$86,089	$57,957	$65,953	-$28,132	--
12T_Box_Cl2b-3_R	$81,488	$64,514	$68,253	-$16,974	--
13T_Box_Cl2b-3_MP	$83,200	$59,453	$67,054	-$23,748	--
14T_Box_Cl4-5_U	$69,607	$53,598	$56,081	-$16,010	--
15T_Box_Cl4-5_R	$66,653	$56,135	$57,425	-$10,518	--
16T_Box_Cl4-5_MP	$67,753	$51,492	$57,919	-$16,261	--
17B_Coach_Cl8_R	$248,018	$211,242	$208,181	-$36,775	--
18B_Coach_Cl8_MP	$248,018	$248,483	$214,806	--	-$33,212
19C_Mix_Cl8_MP	$281,519	$201,559	$209,307	-$79,960	--
20T_Dump_Cl8_U	$163,604	$137,438	$139,244	-$26,166	--
21T_Dump_Cl8_MP	$154,618	$125,582	$139,553	-$29,036	--
22T_Dump_Cl6-7_MP	$104,497	$83,335	$78,074	-$21,162	--
23T_Dump_Cl8_U	$155,915	$137,438	$128,823	-$18,477	--
24T_Dump_Cl6-7_U	$108,739	$96,045	$76,829	-$12,694	--
25T_Fire_Cl8_MP	$159,587	$140,223	$140,626	-$19,364	--
26T_Fire_Cl8_U	$162,083	$140,321	$130,217	-$21,762	--
27T_Flat_Cl6-7_MP	$83,099	$68,464	$67,964	-$14,636	--
28T_Flat_Cl6-7_R	$82,410	$76,360	$69,126	-$6,050	--
29T_Flat_Cl6-7_U	$85,657	$66,589	$66,935	-$19,068	--
30Tractor_DC_Cl8	$195,009	$173,204	$174,861	-$21,805	--
31Tractor_DC_Cl7	$171,653	$153,076	$150,768	-$18,577	--
32Tractor_SC_Cl8	$493,378	$436,686	$423,455	-$56,693	--
33Tractor_DC_Cl8	$297,265	$242,383	$251,833	-$54,882	--
34T_Ref_Cl8_MP	$190,480	$155,262	$140,250	-$35,218	--
35T_Ref_Cl6-7_MP	$164,834	$124,437	$118,435	-$40,397	--

Vehicle ID	**ICE TCO**	**BEV TCO**	**FCEV TCO**	**Incremental BEV TCO**	**Incremental FCEV TCO**
36T_Ref_Cl8_U	$190,480	$155,262	$140,250	-$35,218	--
37T_Ref_Cl6-7_U	$174,089	$124,178	$117,745	-$49,912	--
38RV_Cl8_R	$87,062	$81,364	$78,285	-$5,698	--
39RV_Cl6-7_R	$56,073	$46,480	$40,832	-$9,592	--
40RV_Cl4-5_R	$46,892	$38,928	$37,717	-$7,964	--
41Tractor_DC_Cl7	$278,628	$249,435	$246,185	--	-$32,442
42RV_Cl8_MP	$87,062	$81,364	$78,285	-$5,698	--
43RV_Cl6-7_MP	$56,260	$42,092	$41,446	-$14,168	--
44RV_Cl4-5_MP	$47,204	$40,556	$38,109	-$6,648	--
45Tractor_DC_Cl8	$316,196	$294,475	$299,893	--	-$16,303
46B_School_Cl8_MP	$127,512	$116,829	$107,604	-$10,683	--
47B_School_Cl6-7_MP	$94,478	$71,400	$71,834	-$23,078	--
48B_School_Cl4-5_MP	$72,473	$55,881	$60,531	-$16,591	--
49B_School_Cl2b-3_MP	$73,769	$54,927	$62,364	-$18,843	--
50B_School_Cl8_U	$136,193	$110,581	$106,592	-$25,612	--
51B_School_Cl6-7_U	$94,478	$71,400	$71,834	-$23,078	--
52B_School_Cl4-5_U	$74,686	$54,631	$59,737	-$20,054	--
53B_School_Cl2b-3_U	$75,982	$53,639	$61,562	-$22,343	--
54Tractor_SC_Cl8*	$493,378	$500,722	$480,646	$7,344	--
55B_Shuttle_Cl2b-3_MP	$121,904	$87,788	$93,821	-$34,116	--
56B_Shuttle_Cl4-5_U	$125,946	$86,533	$90,002	-$39,413	--
57B_Shuttle_Cl2b-3_U	$127,331	$85,212	$91,660	-$42,119	--
58B_Shuttle_Cl6-7_MP	$149,226	$111,662	$113,656	-$37,563	--
59B_Shuttle_Cl6-7_U	$156,382	$124,214	$110,410	-$32,168	--
60S_Plow_Cl6-7_MP	$87,552	$71,790	$68,508	-$15,763	--
61S_Plow_Cl8_MP	$160,024	$151,702	$141,635	-$8,322	--
62S_Plow_Cl6-7_U	$90,562	$75,810	$67,633	-$14,752	--
63S_Plow_Cl8_U	$162,246	$149,311	$130,804	-$12,935	--
64V_Step_Cl6-7_MP	$102,532	$78,583	$81,501	-$23,949	--
65V_Step_Cl4-5_MP	$67,174	$51,492	$56,565	-$15,682	--
66V_Step_Cl2b-3_MP	$83,582	$59,375	$68,506	-$24,207	--
67V_Step_Cl6-7_U	$106,441	$76,274	$79,788	-$30,167	--
68V_Step_Cl4-5_U	$69,029	$53,598	$55,922	-$15,431	--
69V_Step_Cl2b-3_U	$86,466	$61,306	$67,407	-$25,159	--
70S_Sweep_Cl6-7_U	$104,890	$75,723	$76,233	-$29,167	--
71T_Tanker_Cl8_R	$163,735	$144,979	$151,771	-$18,756	--
72T_Tanker_Cl8_MP	$161,631	$131,440	$140,747	-$30,192	--
73T_Tanker_Cl8_U	$173,224	$143,837	$140,540	-$29,387	--
74T_Tow_Cl8_R	$180,737	$168,314	$164,113	-$12,424	--
75T_Tow_Cl6-7_R	$103,255	$95,961	$79,505	-$7,295	--
76T_Tow_Cl8_U	$192,305	$163,005	$149,629	-$29,300	--
77T_Tow_Cl6-7_U	$108,632	$95,928	$76,732	-$12,704	--
78Tractor_SC_Cl8	$384,286	$357,570	$363,745	-$26,716	--
79Tractor_SC_Cl8	$493,378	$500,722	$480,646	--	-$12,732
80Tractor_DC_Cl8	$237,222	$204,681	$248,029	-$32,541	--
81Tractor_DC_Cl7	$278,628	$242,278	$246,662	-$36,349	--
82Tractor_DC_Cl8	$316,196	$283,546	$292,381	-$32,650	--
83Tractor_DC_Cl7	$192,765	$170,052	$170,060	-$22,714	--
84Tractor_DC_Cl8	$216,115	$194,500	$194,294	-$21,616	--
85B_Transit_Cl8_MP	$258,078	$197,445	$190,020	-$60,633	--
86B_Transit_Cl6-7_MP	$116,379	$100,764	$87,824	-$15,615	--
87B_Transit_Cl8_U	$257,405	$196,598	$189,173	-$60,807	--

Vehicle ID	ICE TCO	BEV TCO	FCEV TCO	Incremental BEV TCO	Incremental FCEV TCO
88B_Transit_Cl6-7_U	$121,248	$100,739	$85,699	-$20,508	--
89T_Utility_Cl8_MP	$137,636	$113,496	$127,651	-$24,141	--
90T_Utility_Cl8_R	$134,706	$126,570	$128,003	-$8,135	--
91T_Utility_Cl6-7_MP	$97,258	$75,506	$75,671	-$21,752	--
92T_Utility_Cl6-7_R	$96,256	$83,546	$77,079	-$12,711	--
93T_Utility_Cl4-5_MP	$81,436	$60,834	$66,837	-$20,602	--
94T_Utility_Cl2b-3_MP	$58,450	$49,446	$50,601	-$9,004	--
95T_Utility_Cl4-5_R	$79,696	$62,110	$67,641	-$17,586	--
96T_Utility_Cl2b-3_R	$78,365	$62,075	$65,530	-$16,290	--
97T_Utility_Cl8_U	$136,037	$125,047	$116,981	-$10,989	--
98T_Utility_Cl6-7_U	$100,974	$73,804	$74,569	-$27,170	--
99T_Utility_Cl4-5_U	$84,254	$59,744	$66,127	-$24,510	--
100T_Utility_Cl2b-3_U	$59,739	$48,533	$50,322	-$11,206	--
101Tractor_DC_Cl8	$156,361	$135,818	$139,350	-$20,544	--

* 54Tractor_SC_Cl8 is not included in our technology package in the modeled potential compliance pathway

Chapter 3 Program Costs

In this chapter, EPA presents the costs we estimate will be incurred by manufacturers and purchasers of HD vehicles impacted by the final standards, based upon the potential compliance pathway modeled for the final rule. We also present the social costs of the final standards. Our analyses characterize the costs of the potential compliance pathway's technology packages described in Section II.E of the preamble; however, as we note there, manufacturers may elect to comply using a different combination of HD vehicle and engine technologies than what we have modeled. We present these costs not only in terms of the upfront incremental technology cost differences between an HD BEV or FCEV powertrain and a comparable HD ICE powertrain[1307] as presented in Chapter 2 of this RIA, but also how those costs will change in years following implementation due to learning-by-doing effects as described in Chapter 3.2.1 below. These technology costs are presented in terms of direct manufacturing costs (DMC) and associated indirect costs (i.e., research and development (R&D), administrative costs, marketing, and other costs of running a company). These direct and indirect costs when summed are referred to as "technology package costs" in this section, and when summed and multiplied by vehicle sales estimated relative to the reference case[1308] represent the estimated costs incurred by manufacturers (i.e., regulated entities) to comply with the final standards should a manufacturer choose to comply using the compliance pathway EPA modeled as one means of showing the standards' feasibility.[1309]

The analysis also includes estimates of the operating costs associated with HD ICE vehicles, BEVs, and FCEVs. These operating costs do not represent compliance costs for manufacturers, but rather estimated costs incurred by users of MY 2027 and later HD vehicles.[1310] All costs are presented in 2022 dollars unless noted otherwise.

We break the costs into the following categories and subcategories:

1. Technology Package Costs, which are the sum of DMC and indirect costs. This may also be called the package retail price equivalent (package RPE). This includes:
    a. DMC, which include the costs of materials and labor to produce a product or piece of technology.

[1307] Baseline vehicles are ICE vehicles meeting the MY 2027 Phase 2 standards discussed in RIA Chapter 2.2.2 and the HD2027 Low NO_X standards discussed in RIA Chapter 2.3.2.

[1308] As discussed in RIA Chapter 4.2.2, the reference case is a no-action scenario that represents emissions in the U.S. without the final rulemaking. Note, reference case cost estimates also include costs associated with replacing a comparable ICE powertrain baseline vehicle with a BEV or FCEV powertrain for ZEV adoption rates in the reference case.

[1309] More accurately, these technology costs represent costs that manufacturers are expected to attempt to recapture via new vehicle sales. For example, profits are included in the indirect cost calculation. Clearly, profits are not a cost of compliance—EPA is not imposing new regulations to force manufacturers to make a profit (or dictate pricing strategies). However, we expect that manufacturers will want to make profits. As such, we expect that manufacturers will make a profit on the vehicles they sell and we consider those profits as part of the estimated technology costs.

[1310] Importantly, the final GHG standards will apply only to new, MY 2027 and later HD vehicles. The legacy fleet is not subject to the new requirements and, therefore, users of prior model year vehicles will not incur the operating costs we estimate.

    b. Indirect costs, which include research and development (R&D), warranty, corporate operations (such as salaries, pensions, health care costs, dealer support, and marketing), and profits. As described below, we estimate indirect costs using RPE markups.

2. Manufacturer Costs, or "manufacturer RPE," which is the package RPE less any applicable battery tax credits. This includes:
    a. Package RPE, as described above. Traditionally, the package RPE is the manufacturer RPE in EPA cost analyses for HD standards.
    b. Battery tax credits from IRA section 13502, "Advanced Manufacturing Production Credit," which serve to reduce manufacturer costs. The battery tax credit is described further in preamble Sections I and II and Chapters 1 and 2 of the RIA.
3. Purchaser Costs, which are the sum of purchaser 1) upfront costs (which include the upfront vehicle costs (manufacturer (also referred to as purchaser) RPE plus applicable federal excise and state sales taxes less any applicable vehicle tax credit) plus applicable EVSE costs), 2) and operating costs. This includes:
    a. Manufacturer RPE. In other words, the purchaser incurs the manufacturer's package costs less any applicable battery tax credits. As described above, we refer to this as the "manufacturer RPE" in relation to the manufacturer and, at times, the "purchaser RPE" in relation to the purchaser. These two terms are equivalent in this analysis.
    b. Vehicle tax credit from IRA section 13403, "Qualified Commercial Clean Vehicles," which serve to reduce purchaser costs. The vehicle tax credit is described further in preamble Sections I and II and Chapters 1 and 2 of the RIA.
    c. Electric Vehicle Supply Equipment (EVSE) costs, which are the costs associated with charging equipment and its installation at depots. Our EVSE cost estimates include indirect costs so are sometimes referred to as "EVSE RPE."
    d. EVSE tax credit from IRA section 13404, "Alternative Fuel Refueling Property Credit," which serve to reduce purchaser costs. The EVSE tax credit is described further in Sections I and II of this preamble and Chapters 1 and 2 of the RIA.
    e. Federal excise tax and state sales tax, which are upfront costs incurred for select vehicles for excise tax and for all heavy-duty vehicles for sales tax.
    f. Purchaser upfront vehicle costs, which include the manufacturer (also referred to as purchaser) RPE plus EVSE costs plus applicable federal excise and state sales taxes less any applicable vehicle tax credits.
    g. Operating costs, which include fuel costs (including costs for diesel, gasoline, CNG, electricity [which varies depending on whether the vehicle is charged at

a depot or at a public charging facility], and hydrogen), costs for diesel exhaust fluid (DEF), maintenance and repair costs, insurance, battery replacement costs, ICE vehicle engine rebuild costs, and EVSE replacement costs.

4. Social Costs, which are the sum of package RPE, EVSE RPE, and operating costs and computed on at a fleet level on an annual basis. Note that fuel taxes, federal excise tax, state sales tax and battery, and vehicle and EVSE tax credits as well as state registration fees on ZEVs are not included in the social costs. Taxes, registration fees, and tax credits are transfers as opposed to social costs. Social costs includes:
    a. Package RPE which, as described above, excludes applicable tax credits.
    b. EVSE RPE (which excludes applicable tax credits).
    c. Operating costs which include pre-tax fuel costs, charging costs (including those associated with electrification infrastructure and a public charging network), DEF costs, insurance, maintenance and repair costs, BEV battery replacement costs, ICE vehicle engine rebuild costs, and EVSE replacement costs.

We describe these costs and present our cost estimates in the text that follows, after we discuss the relevant IRA tax credits and how we have considered them in our estimates. All costs are presented in 2022 dollars, unless noted otherwise. Table 3-1 shows the gross domestic product price deflators used to adjust to 2022 dollars. We used the MOVES scenarios discussed in RIA Chapter 4, the reference, final standards and alternative cases,[1311] to compute technology costs and operating costs as well as social costs on an annual basis. Our costs and tax credits estimated on a per vehicle basis and do not change between the reference and final standards cases, but the estimated vehicle populations that will be ICE vehicles, BEVs or FCEVs do change between the reference and final standards cases. Under our modeled potential compliance pathway, we project an increase in BEV and FCEVs sales and a decrease of ICE vehicle sales in the final standards case compared to the reference case, and these changes in vehicle populations are the determining factor for total cost differences between the reference and final standards cases. Similarly for the alternative case, we project an increase in BEV and FCEVs sales and a decrease of ICE vehicle sales compared to the reference case but less than in the final standard case. Like the final standards case, the changes in vehicle populations are the determining factor for total cost differences between the reference and alternative cases.

Note that the analysis that follows sometimes presents undiscounted costs and sometimes presents discounted costs. We discount future costs and benefits to properly characterize their value in the present or, as directed by the Office of Management and Budget in Advisory Circular A-4, in the year costs and benefits begin.[1312] OMB Circular A-4 guidance (2003) directs Agencies to use a constant 3-percent and 7-pecent discount rate to calculate present and annualized values, which we have done here with some exceptions described below. While we were conducting the analysis for this rule, OMB finalized an update to Circular A-4 (2023), in

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[1311] As discussed in RIA Chapter 4.2.2, the reference case is a no-action scenario that represents emissions in the U.S. without the final rulemaking. The final standards and alternative cases represented emissions in the U.S. for each potential set of GHG standards.

[1312] See Advisory Circular A-4, Office of Management and Budget, September 17, 2003.

which it recommended the general application of a 2-percent discount rate to costs and benefits. Although the effective date of the updated Circular A-4 does not apply to this rulemaking, we have also included 2 percent discount rates in our analysis. Present and annualized values are abbreviated as PV and AV throughout the document tables in this chapter.

Table 3-1 GDP Price Deflators* Used to Adjust Costs to 2022 Dollars

Cost Basis Year	Conversion Factor
2012	1.272
2013	1.250
2014	1.227
2015	1.215
2016	1.203
2017	1.181
2018	1.153
2019	1.133
2020	1.118
2021	1.070
2022	1.000

* Based on the National Income and Product Accounts, Table 1.1.9 Implicit Price Deflators for Gross Domestic Product, Bureau of Economic Analysis, U.S. Department of Commerce, April 27, 2023.

The cost analysis is done using a tool written in Python and may be found in the docket for this action. The Python tool, along with some supporting documentation, may be found in the docket for this action and on our website.[1313]

Any applicable changes to costs discussed in the final rule preamble Section II, RIA Chapter 2, and RTC Sections 2 and 3 from proposal are reflected in the sections below. We have adjusted our analysis so that battery learning is on the flatter portion of the learning curve used in the proposal and is discussed in Chapter 3.2.1 of this RIA.

We also received comment about inclusion of dealer costs and we estimate them as a portion of RPE in the indirect manufacturing costs of technology package costs in the final rule, as discussed in Chapter 3.2.2 of this RIA.

3.1 IRA Tax Credits

Our cost analysis quantitatively includes consideration of three IRA tax credits, specifically the “Advanced Manufacturing Production Credit,”, “Qualified Commercial Clean Vehicles,”, and “Alternative Fuel Refueling Property Credit” applied to battery cost, vehicle purchase cost, and EVSE purchase cost respectively (Sections II.E.1, II.E.2, II.E.3, and II.E.4 of the preamble and Chapters 1.3.2 and 2.4.3 of the RIA). We note that a detailed discussion of how these tax credits were considered in our analysis of costs in our technology packages may be found in Section II.E of the preamble and Chapter 2.4.3 of the RIA. The battery tax credits is expected to reduce manufacturer costs, and in turn purchaser costs, as discussed in Chapter 3.3.2. The

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[1313] Sherwood, Todd. “Heavy-Duty Cost Tool,” memorandum to docket EPA-HQ-OAR-2022-0985. March 2024 vehicle tax credit and EVSE tax credit are also expected to reduce purchaser costs, as discussed in Chapter 3.4.2 and Chapter 3.4.4. For the cost analysis discussed in this chapter, the battery tax credit, vehicle tax credit, and EVSE tax credit were estimated for MYs 2027 through 2032 and then aggregated for each MOVES source type and regulatory class.

3.2 Technology Package Costs

Technology package costs include estimated technology costs associated with compliance with the final MY 2027 and later CO2 emission standards based on the projected technology packages modeled for the potential compliance pathway. Individual technology piece costs are presented in Chapter 2 of the RIA and the costs presented there represent costs in the first year that a new standard is implemented. For each of the model years following the first year of implementation, we have applied a learning effect to the technology costs for vehicles we expect to be sold in that model year which represent the cost reductions expected to occur via the "learning by doing" phenomenon.[1314] However, for the final rule, we shifted the battery learning onto the flatter portion of the learning curve used in the proposal. The "learning by doing" phenomenon is the process by which doing something over and over results in learning how to do that thing more efficiently which, in turn, leads to reduced resource usage, i.e., cost savings. This provides a year-over-year cost for each technology as applied to new vehicle production, which is then used to calculate total technology package costs of the final standards.

This technology package cost calculation approach presumes that the projected technologies (i.e., those in the particular technology package developed by EPA as a potential compliance pathway to support the feasibility of the final standards) will be purchased by the vehicle original equipment manufacturers (OEMs) from their suppliers. So, while the DMC estimates for the vehicle manufacturer in Chapter 3.2.1 include the indirect costs and profits incurred by the supplier, the indirect cost markups we apply in Chapter 3.2.2 cover the indirect costs incurred by vehicle manufacturers to incorporate the new technologies into their vehicles and profit margins for the vehicle manufacturers typical of the heavy-duty vehicle industry. To address these vehicle manufacturer indirect costs, we applied industry standard RPE markup factors to the DMC to estimate vehicle manufacturer indirect costs associated with the new technology. These factors represent an average price, or RPE, for products assuming all products recapture costs in the same way. We recognize that this is rarely the actual case since manufacturers typically have different pricing strategies for different products. For that reason, the RPE should not be considered a price but instead should be considered more like the average cross-subsidy needed to recapture both costs and profits to support ongoing business operations. Both the learning effects applied to direct costs and the application of markup factors to estimate indirect costs are consistent previous HD GHG rules with the cost estimation approaches used in EPA's past transportation-related regulatory programs.[1315] The sum of the DMC and indirect costs represents our estimate of technology "package costs" or "package RPE" per vehicle year-over-year. These per vehicle technology package costs multiplied by estimated sales for the final standards and reference scenarios. Then the total technology package-related costs for manufacturers (total

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[1314] "Cost Reduction through Learning in Manufacturing Industries and in the Manufacture of Mobile Sources, Final Report and Peer Review Report," EPA-420-R-16-018, November 2016.

[1315] See the Phase 1 heavy-duty greenhouse gas rule (76 FR 57106, 57319, September 15, 2011); the Phase 2 heavy-duty greenhouse gas rule (81 FR at 73863, October 25, 2016).

package costs or total package RPE) associated with the final HD GHG Phase 3 standards is the difference between the final standards and reference scenarios.

3.2.1 Direct Manufacturing Costs

To produce a unit of output, manufacturers incur direct and indirect manufacturing costs. DMC includes cost of materials and labor costs. Indirect manufacturing costs are discussed in the following section, Chapter 3.2.2. The DMCs presented here include the incremental technology piece costs associated with compliance with the final standards as compared to the technology piece costs[1316] associated with the comparable baseline vehicle.1317 In our analysis, the ICE vehicles include a suite of technologies that represent a vehicle that meets the previous MY 2027 Phase 2 CO_2 emission standards. Therefore, our direct manufacturing costs for the ICE vehicles are considered to be $0 because our projected technology package did not add additional CO2-reducing technologies to the ICE vehicles beyond those in the baseline vehicle (we note that even though such improvements were not included in the modeled potential compliance pathway, additional ICE vehicle technologies are feasible and manufacturers could utilize such technologies under a different compliance pathway to meet the final standards; see preamble Section II.F.6 for one example of such an alternative compliance pathway). The DMC of the BEVs or FCEVs could be thought of as the technology piece costs of replacing an ICE powertrain with a BEV or FCEV powertrain.

Throughout this discussion, when we refer to reference case costs we are referring to our cost estimate of the no-action case (impacts absent this final rule) which include costs associated with replacing a comparable ICE powertrain baseline vehicle with a BEV or FCEV powertrain for ZEV adoption rates in the reference case.

We have estimated the DMC by starting with the baseline vehicle, removing the cost of a comparable ICE powertrain, and adding the cost of a BEV or FCEV powertrain. We calculated the DMC per vehicle aggregated by MOVES source type and regulatory class via a technology-sales-weighted average using the DMC and adoption rates for the modeled potential compliance pathway presented in RIA Chapter 2. This calculation depended on the DMC for each of the 101 Vehicle IDs in HD TRUCS and the mix (i.e., the relative proportions) of those Vehicle IDs in each combination of source type and regulatory class, which is dependent on overall sales and technology adoption rates (i.e. the rates projected for our modeled potential compliance pathway) for each Vehicle ID. DMCs for MY 2027 for each of the 101 Vehicle IDs in HD TRUCS are shown in RIA Chapter 2.9.2 and the learning effect described later in this section was used to project costs to future MYs. Sales for each of the 101 Vehicle IDs in HD TRUCS are shown in Chapter 2.2.3. Technology adoption rates for MYs 2027, 2030, and 2032 for each of the 101 Vehicle IDs in HD TRUCS are shown in Chapter 2.9.3. For the purposes of this cost analysis, we interpolated these adoption rates similar to the phase-in of the standards described in Chapter 2.10.1 to calculate the adoption rates of Vehicle IDs in each combination of source type and regulatory class for MYs 2028, 2029, and 2031.

[1316] We sometimes use the term "piece cost" simply to refer to the cost associated with a piece of technology. That could be a turbocharger, it could be an EGR valve, it could also be a BEV powertrain in place of an ICE powertrain.

[1317] Baseline vehicles are ICE vehicles meeting the previous MY 2027 Phase 2 GHG standards as discussed in RIA Chapter 2.2.2 and the HD2027 criteria pollutant standards as discussed in RIA Chapter 2.3.2.

Net incremental costs reflect adding the total costs of components added to the powertrain to make it a BEV or FCEV, as well as removing the total costs of components removed from a comparable ICE baseline vehicle to make it a BEV or FCEV.

Chapter 4 of the RIA contains a description of the MOVES vehicle source types and regulatory classes. In short, we estimate costs in MOVES for vehicle source types that have both regulatory class populations and associated emission inventories. Also, throughout this section, LHD refers to light heavy-duty vehicles, MHD refers to medium heavy-duty vehicles, and HHD refers to heavy heavy-duty vehicles.

For some of the BEV, FCEV and ICE vehicle technologies considered in this analysis, manufacturer learning effects are expected to play a role in the actual end costs. The "learning curve" or "experience curve" describes the reduction in unit production costs as a function of accumulated production volume. We have traditionally applied learning impacts using learning factors applied to a given cost estimate as a means of reflecting learning-by-doing effects on future costs. [1318] In theory, the cost behavior the learning curve describes applies to cumulative production volume measured at the level of an individual manufacturer, although it is often assumed—as EPA has done in past regulatory analyses—to apply at the industry-wide level, particularly in industries that utilize many common technologies and component supply sources. We believe there are indeed many factors that cause costs to decrease over time. Research in the costs of manufacturing has consistently shown that, as manufacturers gain experience in production, they are able to apply innovations to simplify machining and assembly operations, use lower cost materials, and reduce the number or complexity of component parts. All of these factors allow manufacturers to lower the per-unit cost of production (i.e., "learning by doing" the manufacturing learning curve).[1319]

Learning effects are applied to all technologies, but at different rates because some of the expected technologies are already used rather widely in the industry and, presumably, much of the learning impacts have already occurred. We used this approach in the analysis to support the HD Phase 2 standards where we applied a steeper learning curve to emerging technologies such as strong hybrids and waste heat recovery.[1320] The steep-portion of learning was applied to technologies in this Phase 3 rulemaking that are considered to be new or emerging technologies - BEVs and FCEVs. The learning algorithms applied to each scenario for BEV or FCEV powertrain costs are summarized in Table 3-2. The final standards, alternative and reference case all used the same learning factors presented in Table 3-2.

The direct manufacturing costs for BEV, FCEV and ICE powertrains were adjusted to account for learning effects going forward from the first year of implementation (MY 2027), in

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[1318] See the 2010 light-duty greenhouse gas rule (75 FR 25324, May 7, 2010); the 2012 light-duty greenhouse gas rule (77 FR 62624, October 15, 2012); the 2011 heavy-duty greenhouse gas rule (76 FR 57106, September 15, 2011); the 2016 heavy-duty greenhouse gas rule (81 FR 73478, October 25, 2016); the 2014 light-duty Tier 3 rule (79 FR 23414, April 28, 2014); the heavy-duty NOx rule (88 FR 4296, January 24, 2023).

[1319] See "Learning Curves in Manufacturing," L. Argote and D. Epple, Science, Volume 247; "Toward Cost Buy down Via Learning-by-Doing for Environmental Energy Technologies, R. Williams, Princeton University, Workshop on Learning-by-Doing in Energy Technologies, June 2003; "Industry Learning Environmental and the Heterogeneity of Firm Performance, N. Balasubramanian and M. Lieberman, UCLA Anderson School of Management, December 2006, Discussion Papers, Center for Economic Studies, Washington DC

[1320] U.S. EPA. Regulatory Impact Analysis: Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles – Phase 2. Chapter 2.11.1. August 2016. EPA-420-R-16-900.

an approach similar to the one taken for the HD GHG Phase 2 final rule. The same learning factors were applied to BEV and FCEV powertrain add costs as well as ICE powertrain delete costs[1321] for the reference, final standards, and alternative scenarios and for each model year as shown in Table 3-2. These learning factors were generated with the expectation that learning on ICE technologies will slow, relative to their traditional rates, in favor of a focus on BEV and FCEV technologies. More specifically, overall, under the modeled potential compliance pathway we anticipate the number of ICE powertrains (including engines and transmissions) manufactured each year will decrease as more ZEVs enter the market. Due to decreasing production of ICE powertrains, this scenario may lead to slower cost reductions going forward than would typically occur from learning-by-doing in the context of component costs for ICE powertrains. On the other hand, with the inclusion of new hardware costs projected in our HD2027 final rule's modeled potential compliance pathway to meet the HD2027 emission standards, we expect learning effects will reduce the incremental cost of these technologies.

The learning algorithms were applied to the BEV, FCEV and ICE powertrains for the 101 Vehicle IDs in the HD TRUCS tool for model years 2027 through 2032 for the values shown in Table 3-2. The values were then aggregated by MOVES source type and regulatory class via a technology sales-weighted average using the DMC and adoption rates for the modeled potential compliance pathway presented in RIA Chapter 2. Then the DMC costs aggregated by MOVES source type and regulatory class from HD TRUCS for model year 2032 had the learning algorithm applied from model year 2033 to 2055 shown in Table 3-2. The resultant direct manufacturing costs and how those costs are expected to reduce over time are presented in Chapter 3.3.3 on a total cost basis.

Table 3-2 Learning Curve applied to BEV, FCEV and ICE Powertrain Costs in the Reference, Final Standards and Alternative Scenarios

Model Year	BEV and FCEV Powertrain Learning Scalar	ICE Powertrain Learning Scalar
2027	1.00	1.00
2028	0.94	0.99
2029	0.89	0.99
2030	0.86	0.99
2031	0.83	0.98
2032	0.80	0.98
2033	0.78	0.98
2034	0.76	0.97
2035	0.75	0.97
2036	0.73	0.97
2037	0.72	0.96
2038	0.71	0.96
2039	0.69	0.96
2040	0.68	0.95
2041	0.67	0.95
2042	0.66	0.95
2043	0.66	0.95

[1321] Powertrain add costs are the total costs of all components added to a powertrain to make it a BEV or FCEV. ICE powertrain delete costs are the total costs savings realized from removing all of the ICE powertrain components from a baseline vehicle.

Model Year	BEV and FCEV Powertrain Learning Scalar	ICE Powertrain Learning Scalar
2044	0.65	0.94
2045	0.64	0.94
2046	0.63	0.94
2047	0.63	0.94
2048	0.62	0.93
2049	0.61	0.93
2050	0.61	0.93
2051	0.60	0.92
2052	0.60	0.92
2053	0.59	0.92
2054	0.59	0.92
2055	0.59	0.92

3.2.2 Indirect Manufacturing Costs

Indirect manufacturing costs are all the costs associated with producing the unit of output that are not direct manufacturing costs – for example, they may be related to research and development (R&D), warranty, corporate operations (such as salaries, pensions, health care costs, dealer support, and marketing) and profits. An example of a R&D cost for this final rulemaking includes the engineering resources required to develop a battery state of health monitor as described in preamble Section III.B.1. An example of a warranty cost is the future cost covered by the manufacturer to repair defective BEV or FCEV components and meet the warranty requirements in Section III.B.2 of the preamble. Indirect costs are generally recovered by allocating a share of the indirect costs to each unit of goods sold. Although direct costs can be allocated to each unit of goods sold, it is more challenging to account for indirect costs allocated to a unit of goods sold. To ensure that regulatory analyses capture the changes in indirect costs, markup factors (which relate total indirect costs to total direct costs) have been developed and used by EPA and other stakeholders. These factors are often referred to as RPE multipliers and are typically applied to direct costs to estimate indirect costs. RPE multipliers provide, at an aggregate level, the proportionate share of revenues relative shares of revenue where:

Revenue = Direct Costs + Indirect Costs

so that:

Revenue/Direct Costs = 1 + Indirect Costs/Direct Costs = RPE multiplier

and,

Indirect Costs = Direct Costs x (RPE - 1).

If the relationship between revenues and direct costs (i.e., RPE multiplier) can be shown to equal an average value over time, then an estimate of direct costs can be multiplied by that average value to estimate revenues, or total costs. Further, that difference between estimated revenues, or total costs, and estimated direct costs can be taken as the indirect costs. Cost analysts and regulatory agencies have frequently used these multipliers[1322] to predict the

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[1322] See 75 FR 25324 (May 7, 2010); 76 FR 57106 (September 15, 2011); 77 FR 62624 (October 15, 2012); 79 FR 23414 (April 28, 2014); 81 FR 73478 (October 26, 2016); 86 FR 74434 (December 30, 2021).

resultant impact on costs associated with manufacturers' responses to regulatory requirements and we are using cost multipliers in this analysis.

The markup factors are based on company filings with the Securities and Exchange Commission for several engine and engine/truck manufacturers in the HD industry, as detailed in a study by RTI International that was commissioned by EPA.[1323] The RPE factors developed by RTI for HD engine manufacturers, HD truck manufacturers, and for the HD truck industry as a whole are shown in Table 3-3.[1324] Also shown in Table 3-3 are the RPE factors developed by RTI for light-duty vehicle manufacturers.[1325]

Table 3-3 Retail Price Equivalent Factors in the Heavy-Duty and Light-Duty Industries

Cost Contributor	**HD Engine Manufacturer**	**HD Truck Manufacturer**	**HD Truck Industry**	**LD Vehicle Industry**
Direct manufacturing cost	1.00	1.00	1.00	1.00
Warranty	0.02	0.04	0.03	0.03
R&D	0.04	0.05	0.05	0.05
Other (admin, retirement, health, dealer, etc.)	0.17	0.22	0.29	0.36
Profit (cost of capital)	0.05	0.05	0.05	0.06
RPE	1.28	1.36	1.42	1.50

For this analysis, EPA based indirect cost estimates for the replacement of HD CI engines (diesel and compressed natural gas (CNG) MOVES fuel types) on the HD Truck Industry RPE value shown in Table 3-3. We are using an RPE of 1.42 to compute the indirect costs associated with the replacement of a diesel-fueled or CNG-fueled powertrain with a BEV or FCEV powertrain in HD vehicles. For this analysis, EPA based indirect cost estimates for the replacement of HD SI engines (gasoline MOVES fuel types) on the LD Truck Vehicle RPE value shown in Table 3-3 because the engines and vehicles more closely match those built by LD vehicle manufacturers. We are using an RPE of 1.5 to compute the indirect costs associated with the replacement of a gasoline-fueled powertrain in HD vehicles with a BEV or FCEV powertrain. The heavy-duty vehicle industry is becoming more vertically integrated and the direct and indirect manufacturing costs we are analyzing are those that reflect the technology packages costs OEMs will try to recover at the purchaser level. For that reason, we believe the two respective vehicle industry RPE values represent the most appropriate factors for this analysis, and that our approach here is based on robust data and analysis.

EPA received comment that dealers may encounter new costs when new products are introduced (which we refer to in this rulemaking as "dealer new vehicle selling costs"), such as

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[1323] Heavy Duty Truck Retail Price Equivalent and Indirect Cost Multipliers, Draft Report, RTI International, RTI Project Number 021 1577.003.002, July 2010.

[1324] The engine manufacturers included were Hino and Cummins; the truck manufacturers included were PACCAR, Navistar, Daimler and Volvo. Where gaps existed such as specific line items not reported by these companies due to differing accounting practices, data from the Heavy Duty Truck Manufacturers Industry Report by Supplier Relations LLC (2009) and Census (2009) data for Other Engine Equipment Manufacturing Industry (NAICS 333618) and Heavy Duty Truck Manufacturing Industry (NAICS 336120) were used to fill the gaps. This is detailed in the study report at Appendix A.1.

[1325] Rogozhin, Alex, Michael Gallaher, Gloria Helfand, and Walter McManus. "Using Indirect Cost Multipliers to Estimate the Total Cost of Adding New Technology in the Automobile Industry." International Journal of Production Economics 124 (2010): 360-368.

technician training to repair ZEVs. We accounted for these costs in the retail price equivalent (RPE) multipliers. The heavy-duty RPE in Table 3-3 is based on values from the report, "Heavy Duty Truck Retail Price Equivalent and Indirect Cost Multipliers,"[1326] which contains detailed cost contributor subcategories, including costs associated with dealer support. Within the dealer support costs in the study, the contribution of new dealer selling costs in the RPE mark-up includes a 6 percent markup over manufacturing cost for dealer new vehicle selling costs, from the "Other" cost contributor shown in Table 3-3. On a related note, we included a change in the final rule to delay when the reduced maintenance and repair cost savings for ZEVs begin to accrue to account for the need for initial technician training).[1327]

Dealer new vehicle selling costs for CY 2027 through 2032 are shown in Table 3-4. We calculated the dealer new vehicle selling costs as 6 percent of the total direct cost calculated for the final standards. Table 3-4 also shows the undiscounted sum of dealer new vehicle selling costs from CY 2027 to 2032.

Table 3-4 Dealer new vehicle selling costs for final standards, undiscounted in Millions of 2022 Dollars*

Calendar Year	Dealer new vehicle selling costs for final standards
2027	$20
2028	$21
2029	$17
2030	$26
2031	$30
2032	$35
Sum of 2027 to 2032	$150

*Values rounded to two significant digits

3.2.3 Vehicle Technology Package RPE

Table 3-5 presents the fleet-wide incremental technology costs estimated for both the final standards and alternative relative to the reference case for the projected adoption of ZEVs in our technology package on an annual basis. The costs shown in Table 3-5 reflect incremental costs of the technology package for the final standards as compared to the baseline vehicle and, therefore, include removal of the ICE-specific components and associated savings and then addition of the BEV or FCEV components and associated costs.

It is important to note that these are costs and not prices. We do not attempt to estimate how manufacturers will price their products in the technology package used to develop a potential compliance pathway. Manufacturers may pass costs along to purchasers via price increases that reflect actual incremental costs to manufacture a ZEV when compared to a comparable ICE vehicle. However, manufacturers may also price products higher or lower than what will be necessary to account for the incremental cost difference. EPA is not attempting to mirror,

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[1326] Heavy Duty Truck Retail Price Equivalent and Indirect Cost Multipliers, Draft Report, RTI International, RTI Project Number 021 1577.003.002, July 2010.

[1327] See preamble Section II.E.5.

predict, or otherwise approximate individual companies' marketing strategies in estimating costs for the modeled potential compliance pathway.

Table 3-5 Fleet-Wide Incremental Technology Costs for ZEVs, Millions of 2022 dollars*

Calendar Year	Vehicle Package RPE for the Final Standards Relative to the Reference Case	Vehicle Package RPE for the Alternative Option Relative to the Reference Case
2027	$30	$1.8
2028	-$14	-$32
2029	-$85	-$69
2030	$160	$110
2031	$270	$210
2032	$480	$280
2033	$310	$250
2034	$260	$270
2035	$160	$280
2036	$23	$240
2037	-$25	$230
2038	-$140	$210
2039	-$230	$190
2040	-$260	$190
2041	-$330	$180
2042	-$400	$160
2043	-$390	$160
2044	-$450	$140
2045	-$510	$120
2046	-$490	$110
2047	-$530	$100
2048	-$560	$87
2049	-$590	$75
2050	-$570	$76
2051	-$590	$67
2052	-$620	$58
2053	-$640	$50
2054	-$610	$54
2055	-$590	$55
PV, 2%	-$4,200	$3,000
PV, 3%	-$3,200	$2,600
PV, 7%	-$1,000	$1,700
AV, 2%	-$190	$140
AV, 3%	-$170	$140
AV, 7%	-$83	$140

*Values rounded to two significant digits; negative values denote lower costs, i.e., savings in expenditures.

3.3 Manufacturer Costs

3.3.1 Relationship to Technology Package RPE

The manufacturer costs in EPA's past HD GHG rulemaking cost analysis on an average per vehicle basis was only the average per vehicle technology package RPE described in Chapter 3.2.3. However, in the cost analysis for this final rulemaking, we are also taking into account the IRA battery tax credit in our estimates of manufacturer costs (also referred to in this section as manufacturer's RPE), as we expect the battery tax credit to reduce manufacturer costs, and in turn purchaser costs.

3.3.2 Battery Tax Credits

Table 3-6 shows the annual estimated fleet-wide battery tax credits from IRA section 13502, "Advanced Manufacturing Production Credit," for the final standards relative to the reference case in 2022 dollars under the potential compliance pathway. These estimates were based on the detailed discussion in RIA Chapter 2 of how we considered battery tax credits. Both BEVs and FCEVs include a battery in the powertrain system that may meet the IRA battery tax credit requirements if the applicable criteria are met. The battery tax credits begin to phase down starting in CY 2030 and expire after CY 2032.

Table 3-6 Battery Tax Credit in Millions of 2022 dollars *

Calendar Year	Battery Tax Credits Final Standards Relative to the Reference Case	Battery Tax Credits Alternative Option Relative to the Reference Case
2027	$67	$39
2028	$130	$63
2029	$200	$110
2030	$290	$180
2031	$440	$200
2032	$380	$140
2033 and later	$0	$0
PV, 2%	$1,400	$670
PV, 3%	$1,300	$650
PV, 7%	$1,100	$550
AV, 2%	$63	$31
AV, 3%	$69	$34
AV, 7%	$92	$45

*Values rounded to two significant digits.

3.3.3 Manufacturer RPE

The manufacturer RPE is calculated by subtracting the applicable battery tax credit in Table 3-6 from the corresponding technology package RPE from Table 3-5 and the resultant manufacturer RPE is shown in Table 3-7 and Table 3-8 for the final standards and alternative, respectively. Table 3-7 and Table 3-8 reflects learning effects on vehicle package RPE and battery tax credits from CY 2027 through 2055. The sum of the vehicle package RPE and battery tax credits for each year is shown in the manufacturer RPE column. The difference in manufacturer RPE between the final standards and reference case is presented in Table 3-7. The difference in manufacturer RPE under the potential compliance pathway between the alternative and reference case is presented in Table 3-8.

Table 3-7 Total Vehicle Package RPE, Battery Tax Credits, and Manufacturer RPE (including Battery Tax Credits) for the Final Standards Relative to the Reference Case, All Regulatory Classes and All Fuels, Millions of 2022 dollars*

Calendar Year	Package RPE	Battery Tax Credits	Manufacturer RPE
2027	$30	-$67	-$37
2028	-$14	-$130	-$140
2029	-$85	-$200	-$290
2030	$160	-$290	-$130
2031	$270	-$440	-$170
2032	$480	-$380	$100
2033	$310	$0	$310
2034	$260	$0	$260
2035	$160	$0	$160
2036	$23	$0	$23
2037	-$25	$0	-$25
2038	-$140	$0	-$140
2039	-$230	$0	-$230
2040	-$260	$0	-$260
2041	-$330	$0	-$330
2042	-$400	$0	-$400
2043	-$390	$0	-$390
2044	-$450	$0	-$450
2045	-$510	$0	-$510
2046	-$490	$0	-$490
2047	-$530	$0	-$530
2048	-$560	$0	-$560
2049	-$590	$0	-$590
2050	-$570	$0	-$570
2051	-$590	$0	-$590
2052	-$620	$0	-$620
2053	-$640	$0	-$640
2054	-$610	$0	-$610
2055	-$590	$0	-$590
PV, 2%	-$4,200	-$1,400	-$5,500
PV, 3%	-$3,200	-$1,300	-$4,500
PV, 7%	-$1,000	-$1,100	-$2,100
AV, 2%	-$190	-$63	-$250
AV, 3%	-$170	-$69	-$240
AV, 7%	-$83	-$92	-$170

* Negative values denote lower costs, i.e., savings in expenditures.

Table 3-8 Total Package RPE, Battery Tax Credits, and Manufacturer RPE (including Battery Tax Credits) for the Alternative Option Relative to the Reference Case, All Regulatory Classes and All Fuels, Millions of 2022 dollars*

Calendar Year	Package RPE	Battery Tax Credits	Manufacturer RPE
2027	$1.8	-$39	-$37
2028	-$32	-$63	-$95
2029	-$69	-$110	-$180
2030	$110	-$180	-$75
2031	$210	-$200	$13
2032	$280	-$140	$140
2033	$250	$0	$250
2034	$270	$0	$270
2035	$280	$0	$280
2036	$240	$0	$240
2037	$230	$0	$230
2038	$210	$0	$210
2039	$190	$0	$190
2040	$190	$0	$190
2041	$180	$0	$180
2042	$160	$0	$160
2043	$160	$0	$160
2044	$140	$0	$140
2045	$120	$0	$120
2046	$110	$0	$110
2047	$100	$0	$100
2048	$87	$0	$87
2049	$75	$0	$75
2050	$76	$0	$76
2051	$67	$0	$67
2052	$58	$0	$58
2053	$50	$0	$50
2054	$54	$0	$54
2055	$55	$0	$55
PV, 2%	$3,000	-$670	$2,300
PV, 3%	$2,600	-$650	$2,000
PV, 7%	$1,700	-$550	$1,100
AV, 2%	$140	-$31	$110
AV, 3%	$140	-$34	$100
AV, 7%	$140	-$45	$91

* Values rounded to two significant digits; Negative values denote lower costs, i.e., savings in expenditures.

3.4 Purchaser Costs

3.4.1 Purchaser RPE

The purchaser RPE is the estimated upfront vehicle cost paid by the purchaser prior to considering the IRA vehicle tax credit. Note, as explained above in Chapter 3.3.2, we do consider the IRA battery tax credit in estimating the manufacturer RPE, which in this analysis we then consider to be equivalent to the purchaser RPE because we assume pass through of the IRA battery tax credit from the manufacturer to the purchaser. In other words, in this analysis, the manufacturer RPE and purchaser RPE are equivalent terms. The purchaser RPEs reflect the same values as the corresponding manufacturer RPEs presented in Chapter 3.3.3.

3.4.2 Vehicle Purchase Tax Credits

Table 3-9 shows the annual estimated vehicle tax credit for BEV and FCEV vehicles from IRA section 13403, "Qualified Commercial Clean Vehicles," for the final standards and alternative relative to the reference case in 2022 dollars under the potential compliance pathway. These estimates were based on the detailed discussion in RIA Chapter 2.4.3.5 of how we considered vehicle tax credits. The vehicle tax credits carry through to MY 2032 with the value diminishing over time as vehicle costs decrease due to the learning effect as shown in above in Chapter 3.2.1. Beginning in CY 2033, the tax credit program expires.

Table 3-9 Vehicle Tax Credit in Millions 2022 dollars*

Calendar Year	Vehicle Tax Credit for the Final Standards Relative to the Reference Case	Vehicle Tax Credit for the Alternative Option Relative to the Reference Case
2027	$39	$15
2028	$23	$5.1
2029	$10	$2.3
2030	$180	$120
2031	$450	$240
2032	$940	$390
2033 and later	$0	$0
PV, 2%	$1,500	$700
PV, 3%	$1,400	$670
PV, 7%	$1,100	$550
AV, 2%	$67	$32
AV, 3%	$73	$35
AV, 7%	$93	$45

*Values rounded to two significant digits

3.4.3 Depot Electric Vehicle Supply Equipment Costs

EVSE and associated costs are described in Chapter 2.6. EVSE is needed for charging of BEVs and is not needed for FCEVs.[1328] As discussed in this RIA, under the potential compliance

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[1328] As discussed in RIA Chapter 2.5, rather than focusing on depot hydrogen fueling infrastructure costs that would be incurred upfront, we included FCEV infrastructure costs in our per-kilogram retail price of hydrogen. Retail price of hydrogen is the total price of hydrogen when it becomes available to the end user, including the costs of production, distribution, storage, and dispensing at a fueling station. This approach is consistent with the method we use in HD TRUCS for comparable ICE vehicles, where the equivalent diesel fuel costs are included in the diesel fuel price instead of accounting for the costs of fuel stations separately. We also used this approach for the final rule in accounting for the BEVs using public charging.

pathway we assume that EVSE costs for depot charging[1329] are incurred by purchasers, i.e., heavy-duty vehicle purchasers/owners. The depot EVSE cost estimates are assumed to include both direct and indirect costs and are sometimes referred to in this final rulemaking as EVSE RPE costs. For these EVSE cost estimates, we project that up to two vocational vehicles or up to four tractors can share one EVSE port if there is sufficient dwell time for all vehicles to meet their daily charging needs.[1330] We analyzed EVSE costs in 2022 dollars on a fleet-wide basis for this analysis. The fleet-wide annual costs associated with EVSE for each MOVES source type and regulatory class are shown in Table 3-10 for both the final standards and alternative options relative to the reference case.

[1329] As discussed in Chapters 2.4 and 2.6, we modeled EVSE costs for public charging as part of the operating costs. The purchasers of these vehicles would not incur an upfront cost to purchase and install EVSE. As discussed in RIA Chapter 2.4.4.2 for public charging and in Chapter 2.5.3 for FCEVs, we included the respective infrastructure cost in our retail electricity prices per kwh and retail prices per kg of hydrogen.

[1330] We note that for some of the vehicle types we evaluated, additional vehicles could share an EVSE port and still meet their daily electricity consumption needs. However, we are choosing to limit sharing to two to four vehicles per EVSE port to be conservative as the market develops.

Table 3-10 Depot EVSE Costs, Millions 2022 dollars *

Calendar Year	EVSE Costs for the Final Standards Relative to the Reference Case	EVSE Costs for the Alternative Option Relative to the Reference Case
2027	$440	$250
2028	$610	$290
2029	$730	$410
2030	$630	$360
2031	$1,300	$480
2032	$2,000	$620
2033	$1,900	$490
2034	$1,700	$380
2035	$1,600	$260
2036	$1,600	$240
2037	$1,500	$220
2038	$1,500	$200
2039	$1,500	$180
2040	$1,500	$160
2041	$1,500	$140
2042	$1,400	$130
2043	$1,400	$130
2044	$1,400	$120
2045	$1,400	$120
2046	$1,300	$110
2047	$1,300	$110
2048	$1,300	$100
2049	$1,300	$99
2050	$1,200	$95
2051	$1,200	$92
2052	$1,200	$89
2053	$1,200	$86
2054	$1,200	$82
2055	$1,100	$79
PV, 2%	$28,000	$5,000
PV, 3%	$25,000	$4,600
PV, 7%	$15,000	$3,400
AV, 2%	$1,300	$230
AV, 3%	$1,300	$240
AV, 7%	$1,300	$270

*Values rounded to two significant digits

3.4.4 Electric Vehicle Supply Equipment Tax Credits

Table 3-11 shows the annual estimated EVSE tax credit from IRA section 13404, “Alternative Fuel Refueling Property Credit,” for the final standards relative to the reference case, in 2022 dollars under the potential compliance pathway. These estimates were based on the detailed discussion in RIA Chapter 2 of how we considered EVSE tax credits. The EVSE tax credits carry through to MY 2032. Beginning in CY 2033, the tax credit program expires.

Table 3-11 Incremental EVSE Tax Credit for the Final Standards Relative to the Reference Case for in Millions 2022 Dollars*

Calendar Year	EVSE Tax Credit for the Final Standards Relative to the Reference Case	EVSE Tax Credit for the Alternative Option Relative to the Reference Case
2027	$79	$46
2028	$110	$52
2029	$130	$73
2030	$110	$65
2031	$240	$87
2032	$360	$110
2033 and later	$0	$0
PV, 2%	$950	$400
PV, 3%	$910	$380
PV, 7%	$770	$330
AV, 2%	$43	$18
AV, 3%	$47	$20
AV, 7%	$63	$27

*Values rounded to two significant digits

3.4.5 Federal Excise Tax and State Sales Tax

As discussed in Preamble II.E.5, in the NPRM we did not account for the upfront taxes paid by the purchaser of the vehicle. Several commenters raised concerns about additional costs that were not included in HD TRUCS for the proposal. The concern raised by the greatest number of commenters was the additional cost from Federal Excise Tax (FET) and State Sales Tax because higher BEV and FCEV upfront vehicle cost under the potential compliance pathway. We agree with the commenters with regards to FET and State Sales Tax. For the final rule, we added FET and state sale tax as a part of the purchaser upfront vehicle cost calculation. A FET of 12 percent was applied to the upfront powertrain technology retail price equivalent for Class 8 heavy-duty vehicles and all tractors in HD TRUCS. Similarly, a state tax of 5.02 percent, the average sales tax in the U.S. for heavy-duty vehicles discussed in RIA Chapter 2.4.3, was applied to the upfront powertrain technology retail price equivalent and was added to all vehicles for the final rule analysis.

Table 3-12 Incremental Federal Excise Tax and State Sales Tax for the Final Standards Relative to the Reference Case for in Millions 2022 Dollars*

Calendar Year	State Sales Taxes, Final standards relative to reference case	Federal Excise Taxes, Final standards relative to reference case	State Sales Taxes, Alternative standards relative to reference case	Federal Excise Taxes, Alternative standards relative to reference case
2027	-$1.9	$1.1	-$1.9	$0
2028	-$7.2	-$0.90	-$4.8	-$0.10
2029	-$14	-$7.6	-$9.1	-$3.9
2030	-$6.4	$16	-$3.8	$12
2031	-$8.7	$44	$0.65	$29
2032	$5	$110	$7.2	$50
2033	$15	$120	$13	$55
2034	$13	$110	$13	$51
2035	$8.0	$99	$14	$47
2036	$1.1	$88	$12	$42
2037	-$1.3	$82	$12	$39
2038	-$7	$73	$10	$35
2039	-$12	$64	$9.6	$32
2040	-$13	$61	$9.7	$30
2041	-$17	$54	$9.3	$27
2042	-$20	$47	$8.3	$24
2043	-$20	$45	$8.0	$24
2044	-$23	$39	$6.9	$21
2045	-$26	$33	$5.9	$19
2046	-$25	$32	$5.7	$18
2047	-$27	$28	$5.0	$16
2048	-$28	$24	$4.4	$15
2049	-$30	$19	$3.8	$13
2050	-$28	$20	$3.8	$13
2051	-$30	$17	$3.4	$12
2052	-$31	$13	$2.9	$11
2053	-$32	$10	$2.5	$9.8
2054	-$30	$11	$2.7	$9.9
2055	-$30	$11	$2.8	$9.8
PV, 2%	-$280	$990	$12	$510
PV, 3%	-$230	$890	$99	$450
PV, 7%	-$110	$580	$56	$290
AV, 2%	-$13	$45	$5.3	$23
AV, 3%	-$12	$46	$5.2	$24
AV, 7%	-$8.8	$47	$4.6	$24

* Values rounded to two significant digits; Negative values denote lower costs, i.e., savings in expenditures.

3.4.6 Purchaser Upfront Costs

The expected upfront incremental costs to the purchaser include the purchaser upfront vehicle costs plus the purchaser upfront EVSE costs as applicable, after tax credits and including FET and sales state tax, under the potential compliance pathway. In other words, the estimated purchaser upfront incremental costs include the purchaser RPE discussed in Chapter 3.4.1 less the vehicle tax credit discussed in Chapter 3.4.2 plus the EVSE RPE in Chapter 3.4.3 less the

EVSE tax credit discussed in 3.4.4 plus any applicable excise and sales tax discussed in Chapter 3.4.5. Table 3-13 shows the estimated incremental upfront purchaser costs for BEVs and FCEVs by calendar year for the final standards relative to the reference case.

Table 3-14 shows the estimated incremental upfront purchaser costs for BEVs and FCEVs by calendar year for the alternative option relative to the reference case. Note that EVSE costs are associated with BEVs using depot charging only; FCEVs and BEVs solely using public charging do not have any associated upfront EVSE costs because those costs are reflected in the public hydrogen refueling and charging electricity costs.

Table 3-13 Incremental Purchaser Upfront Costs for the Final Standards Relative to the Reference Case for in Millions 2022 dollars*

Calendar Year	Purchaser RPE	State Sales Taxes	Federal Excise Taxes	Vehicle Purchase Tax Credit	EVSE Costs for Depot Charging	EVSE Tax Credit	Total Upfront Purchaser Cost
2027	-$37	-$1.9	$1.1	-$39	$440	-$79	$280
2028	-$140	-$7.2	-$0.9	-$23	$610	-$110	$330
2029	-$290	-$14	-$7.6	-$10	$730	-$130	$280
2030	-$130	-$6.4	$16	-$180	$630	-$110	$210
2031	-$170	-$8.7	$44	-$450	$1,300	-$240	$500
2032	$100	$5.0	$110	-$940	$2,000	-$360	$920
2033	$310	$15	$120	$0	$1,900	$0	$2,300
2034	$260	$13	$110	$0	$1,700	$0	$2,100
2035	$160	$8.0	$99	$0	$1,600	$0	$1,800
2036	$23	$1.1	$88	$0	$1,600	$0	$1,700
2037	-$25	-$1.3	$82	$0	$1,500	$0	$1,600
2038	-$140	-$7	$73	$0	$1,500	$0	$1,500
2039	-$230	-$12	$64	$0	$1,500	$0	$1,300
2040	-$260	-$13	$61	$0	$1,500	$0	$1,300
2041	-$330	-$17	$54	$0	$1,500	$0	$1,200
2042	-$400	-$20	$47	$0	$1,400	$0	$1,100
2043	-$390	-$20	$45	$0	$1,400	$0	$1,100
2044	-$450	-$23	$39	$0	$1,400	$0	$960
2045	-$510	-$26	$33	$0	$1,400	$0	$860
2046	-$490	-$25	$32	$0	$1,300	$0	$850
2047	-$530	-$27	$28	$0	$1,300	$0	$780
2048	-$560	-$28	$24	$0	$1,300	$0	$710
2049	-$590	-$30	$19	$0	$1,300	$0	$650
2050	-$570	-$28	$20	$0	$1,200	$0	$650
2051	-$590	-$30	$17	$0	$1,200	$0	$610
2052	-$620	-$31	$13	$0	$1,200	$0	$560
2053	-$640	-$32	$10	$0	$1,200	$0	$510
2054	-$610	-$30	$11	$0	$1,200	$0	$530
2055	-$590	-$30	$11	$0	$1,100	$0	$530
PV, 2%	-$5,500	-$280	$990	-$1,500	$28,000	-$950	$21,000
PV, 3%	-$4,500	-$230	$890	-$1,400	$25,000	-$910	$19,000
PV, 7%	-$2,100	-$110	$580	-$1,100	$15,000	-$770	$12,000
AV, 2%	-$250	-$13	$45	-$67	$1,300	-$43	$970
AV, 3%	-$240	-$12	$46	-$73	$1,300	-$47	$970
AV, 7%	-$170	-$8.8	$47	-$93	$1,300	-$63	$960

*Values rounded to two significant digits; negative values denote lower costs, i.e., savings in expenditures.

Table 3-14 Incremental Purchaser Upfront Costs for the Alternative Option Relative to the Reference Case in Millions 2022 dollars*

Calendar Year	Purchaser RPE	State Sales Taxes	Federal Excise Taxes	Vehicle Purchase Tax Credit	EVSE Costs for Depot Charging	EVSE Tax Credit	Total Upfront Purchaser Cost
2027	-$37	-$1.9	$0	-$15	$250	-$46	$150
2028	-$95	-$4.8	-$0.10	-$5.1	$290	-$52	$130
2029	-$180	-$9.1	-$3.9	-$2.3	$410	-$73	$140
2030	-$75	-$3.8	$12	-$120	$360	-$65	$110
2031	$13	$0.65	$29	-$240	$480	-$87	$190
2032	$140	$7.2	$50	-$390	$620	-$110	$310
2033	$250	$13	$55	$0	$490	$0	$810
2034	$270	$13	$51	$0	$380	$0	$710
2035	$280	$14	$47	$0	$260	$0	$600
2036	$240	$12	$42	$0	$240	$0	$540
2037	$230	$12	$39	$0	$220	$0	$510
2038	$210	$10	$35	$0	$200	$0	$460
2039	$190	$9.6	$32	$0	$180	$0	$420
2040	$190	$9.7	$30	$0	$160	$0	$400
2041	$180	$9.3	$27	$0	$140	$0	$360
2042	$160	$8.3	$24	$0	$130	$0	$330
2043	$160	$8.0	$24	$0	$130	$0	$320
2044	$140	$6.9	$21	$0	$120	$0	$290
2045	$120	$5.9	$19	$0	$120	$0	$260
2046	$110	$5.7	$18	$0	$110	$0	$250
2047	$100	$5.0	$16	$0	$110	$0	$230
2048	$87	$4.4	$15	$0	$100	$0	$210
2049	$75	$3.8	$13	$0	$99	$0	$190
2050	$76	$3.8	$13	$0	$95	$0	$190
2051	$67	$3.4	$12	$0	$92	$0	$170
2052	$58	$2.9	$11	$0	$89	$0	$160
2053	$50	$2.5	$9.8	$0	$86	$0	$150
2054	$54	$2.7	$9.9	$0	$82	$0	$150
2055	$55	$2.8	$9.8	$0	$79	$0	$150
PV, 2%	$2,300	$120	$510	-$700	$5,000	-$400	$6,900
PV, 3%	$2,000	$99	$450	-$670	$4,600	-$380	$6,100
PV, 7%	$1,100	$56	$290	-$550	$3,400	-$330	$4,000
AV, 2%	$110	$5.3	$23	-$32	$230	-$18	$310
AV, 3%	$100	$5.2	$24	-$35	$240	-$20	$320
AV, 7%	$91	$4.6	$24	-$45	$270	-$27	$320

*Values rounded to two significant digits; negative values denote lower costs, i.e., savings in expenditures.

3.4.7 Operating Costs

We have estimated six types of operating costs associated with the final HD GHG Phase 3 emission standards and our potential projected compliance pathway’s technology packages that includes BEV or FCEV powertrains. These six types of operating costs include changes in fuel costs of BEVs and FCEVs compared to comparable ICE vehicles, avoided diesel exhaust fluid (DEF) consumption by BEVs and FCEV compared to comparable diesel-fueled ICE vehicles, reduced maintenance and repair costs of BEVs and FCEVs as compared to comparable ICE vehicles, costs associated with insurance of BEVs and FCEVs as compared to comparable ICE vehicles, and costs associated with battery replacement and engine rebuilding. To estimate fuel, DEF and maintenance and repair costs of ICE vehicles, EPA used the results of MOVES runs, as discussed in RIA Chapter 4, to estimate costs associated with fuel consumption, DEF consumption, and VMT. Similarly, the electricity, hydrogen fuel, and maintenance and repair costs of BEVs and FCEVs were calculated based on the MOVES outputs for fuel/electricity consumption and VMT. Battery replacement and engine rebuild costs are based on the years in operation of the vehicle. Insurance costs are based on the incremental upfront cost of the vehicle and calculated for each year a vehicle is operating. We have estimated the net effect on fuel costs, DEF costs, maintenance and repair costs, insurance, and battery replacement. We describe our approach below.

3.4.7.1 Costs Associated with Fuel Usage and Energy Consumption

To determine the total costs associated with fuel usage for MY 2027, 2030 and 2032 ICE vehicles, EPA multiplied the fuel consumption for each MOVES source type/regulatory class/fuel type combination by the applicable fuel price from the AEO 2023 reference case for diesel, gasoline, or CNG prices over the lifetime of the vehicle.[1331] We used retail fuel prices since we expect that retail fuel prices are the prices paid by owners of these ICE vehicles. For electric vehicle costs, the electricity prices used estimates of the cost per kWh of charging at depot and public charge points. How these costs per kWh were generated is presented in Chapter 2.4.4.2 and the values used to estimate program costs are shown in Table 3-15. For hydrogen vehicle fuel costs, we used the hydrogen prices presented in Chapter 2.5.3.1 and presented in Table 3-16. To calculate the average cost per mile of fuel usage for each scenario, MOVES source type/ regulatory class/fuel type combination, the fuel cost was divided by the VMT for each of the MY 2027 vehicles from calendar year 2027 to 2055. The estimates of fuel cost per mile by MOVES source type, regulatory class and fuel combination for MY 2027 vehicles under the final standards are shown in Table 3-37, Table 3-38 and Table 3-39 for with 2, 3 and 7 percent discounting, respectively. Fuel costs per mile calculations by MOVES source type, regulatory class and fuel combination for MY 2030 at discount rates of 2, 3 and 7 percent in are shown in Table 3-40, Table 3-41 and Table 3-42, respectively. For MY 2030, the fuel costs per mile are from the sum of the total fuel costs and VMT from calendar year 2030 to 2055. MY 2032 fuel costs per mile by MOVES source type, regulatory class and fuel combination at discount rates of 2, 3 and 7 percent are shown in Table 3-43, Table 3-44 and Table 3-45, respectively. For MY 2032, the fuel costs per mile are from the sum of the total fuel costs and VMT from calendar year 2032 to 2055. Blank values (denoted by a "-") in Table 3-37 through Table 3-45 represent cases where a given MOVES source type and regulatory class did not use a specific fuel type for a given MY.[1332]

[1331] Reference Case Projection Tables, U.S. Energy Information Administration. Annual Energy Outlook 2023.

[1332] For example, there were no vehicles in our MOVES runs for the transit bus source type in the MOVES LHD45 regulatory class that are diesel-fueled, so the value in the table is left blank for MY 2032.

Table 3-15 Charging Prices by Type of Charge Point (2022 dollars per kWh)*

Calendar Year	Depot Charging	Public Charging
2027	$0.1236	$0.1960
2028	$0.1236	$0.1960
2029	$0.1209	$0.1933
2030	$0.1183	$0.1907
2031	$0.1181	$0.1905
2032	$0.1179	$0.1903
2033	$0.1177	$0.1902
2034	$0.1176	$0.1900
2035	$0.1174	$0.1898
2036	$0.1172	$0.1897
2037	$0.1171	$0.1895
2038	$0.1170	$0.1894
2039	$0.1168	$0.1892
2040	$0.1167	$0.1891
2041	$0.1161	$0.1885
2042	$0.1155	$0.1879
2043	$0.1149	$0.1873
2044	$0.1143	$0.1867
2045	$0.1137	$0.1861
2046	$0.1128	$0.1852
2047	$0.1119	$0.1843
2048	$0.1110	$0.1834
2049	$0.1101	$0.1826
2050	$0.1093	$0.1817
2051	$0.1093	$0.1817
2052	$0.1093	$0.1817
2053	$0.1093	$0.1817
2054	$0.1093	$0.1817
2055	$0.1093	$0.1817

* Values shown to 4 significant digits

Table 3-16 Hydrogen Price (2022 dollars per kg)

Calendar Year	Price
2030	$6.00
2031	$5.60
2032	$5.20
2033	$4.80
2034	$4.40
2035 and later	$4.00

The retail fuel cost per mile for MY 2027 from calendar year 2027 to 2025 across all vehicle fuel types, as well as the change in cost relative to the reference case for the final standards and alternative cases, are shown in Table 3-26, Table 3-27, and Table 3-28 for the 2-percent, 3-percent and 7-percent discounting cases, respectively. The retail fuel cost per mile for MY 2030 from calendar year 2030 to 2025 across all vehicle fuel types, as well as the change in cost relative to the reference case for the final standards and alternative cases, are shown in Table 3-29, Table 3-30, and Table 3-31 for the 2-percent, 3-percent and 7-percent discounting cases, respectively. The retail fuel cost per mile for MY 2032 from calendar year 2032 to 2025 across all vehicle fuel types, as well as the change in cost relative to the reference case for the final standards and alternative cases, are shown in Table 3-32, Table 3-33, and Table 3-34 for the 2-percent, 3-percent and 7-percent discounting cases, respectively. When considering the retail fuel costs per vehicle between scenarios, the impacts show no impact or a cost savings for both the final standards and alternative cases for nearly every MOVES source type and regulatory class.

Table 3-17 Retail Fuel Cost Per Mile for Model Year 2027 Vehicles from Calendar Year 2027 to 2055 for each MOVES Source Type and Regulatory Class by Fuel Type for the Final Standards* (cents/mile in 2022 dollars, 2% discounting)

MOVES Source Type	Regulatory Class	Diesel	Gasoline	Electricity	CNG
Other Buses	LHD45	-	44.7	10.9	-
	MHD67	39.0	-	16.3	-
	HHD8	41.4	-	25.0	48.2
Transit Bus	LHD45	-	44.4	13.0	-
	MHD67	39.1	-	17.6	-
	Urban Bus	41.8	-	11.7	48.0
School Bus	LHD45	-	32.6	9.2	-
	MHD67	30.5	35.7	11.9	-
	HHD8	32.7	-	11.2	38.9
Refuse Truck	MHD67	42.0	50.1	17.5	-
	HHD8	43.5	-	21.1	51.1
Single Unit Short-haul Truck	LHD45	20.5	29.7	8.5	-
	MHD67	31.0	37.5	14.5	-
	HHD8	37.4	-	18.4	44.6
Single Unit Long-haul Truck	LHD45	19.2	28.2	8.6	-
	MHD67	29.0	35.0	16.0	-
	HHD8	34.9	-	21.8	42.1
Combination Short-haul Truck	MHD67	41.5	-	46.1	-
	HHD8	43.0	-	65.4	48.3
Combination Long-haul Truck	MHD67	40.6	-	77.5	-
	HHD8	41.4	-	86.6	45.7

* Values rounded to the nearest tenth of a cent; blank values represent cases where a given MOVES source type and regulatory class did not use a specific fuel type.

Table 3-18 Retail Fuel Cost Per Mile for Model Year 2027 Vehicles from Calendar Year 2027 to 2055 for each MOVES Source Type and Regulatory Class by Fuel Type for the Final Standards* (cents/mile in 2022 dollars, 3% discounting)

MOVES Source Type	Regulatory Class	Diesel	Gasoline	Electricity	CNG
Other Buses	LHD45	-	40.5	9.9	-
	MHD67	35.4	-	14.8	-
	HHD8	37.5	-	22.7	43.7
Transit Bus	LHD45	-	40.4	11.8	-
	MHD67	35.6	-	16.0	-
	Urban Bus	38.1	-	10.6	43.7
School Bus	LHD45	-	29.6	8.3	-
	MHD67	27.7	32.4	10.8	-

MOVES Source Type	Regulatory Class	Diesel	Gasoline	Electricity	CNG
	HHD8	29.6	-	10.2	35.2
Refuse Truck	MHD67	38.5	46.0	16.0	-
	HHD8	40.0	-	19.3	46.9
Single Unit Short-haul Truck	LHD45	19.1	27.6	7.9	-
	MHD67	28.8	34.9	13.5	-
	HHD8	34.8	-	17.1	41.4
Single Unit Long-haul Truck	LHD45	17.9	26.3	8.1	-
	MHD67	27.0	32.7	14.9	-
	HHD8	32.6	-	20.3	39.2
Combination Short-haul Truck	MHD67	38.8	-	42.9	-
	HHD8	40.2	-	60.7	45.2
Combination Long-haul Truck	MHD67	37.5	-	71.6	-
	HHD8	38.3	-	80.0	42.2

* Values rounded to the nearest tenth of a cent; blank values represent cases where a given MOVES source type and regulatory class did not use a specific fuel type.

Table 3-19 Retail Fuel Cost Per Mile for Model Year 2027 Vehicles from Calendar Year 2027 to 2055 for each MOVES Source Type and Regulatory Class by Fuel Type for the Final Standards* (cents/mile in 2022 dollars, 7% discounting)

MOVES Source Type	Regulatory Class	Diesel	Gasoline	Electricity	CNG
Other Buses	LHD45	-	28.9	7.0	-
	MHD67	25.2	-	10.6	-
	HHD8	26.8	-	16.1	31.1
Transit Bus	LHD45	-	29.1	8.5	-
	MHD67	25.7	-	11.5	-
	Urban Bus	27.5	-	7.7	31.5
School Bus	LHD45	-	21.0	5.9	-
	MHD67	19.7	23.1	7.7	-
	HHD8	21.1	-	7.3	25.1
Refuse Truck	MHD67	28.5	33.9	11.8	-
	HHD8	29.5	-	14.2	34.6
Single Unit Short-haul Truck	LHD45	14.7	21.2	6.1	-
	MHD67	22.2	26.8	10.3	-
	HHD8	26.8	-	13.1	31.9
Single Unit Long-haul Truck	LHD45	14.0	20.5	6.3	-
	MHD67	21.1	25.5	11.6	-
	HHD8	25.5	-	15.9	30.7
Combination Short-haul Truck	MHD67	30.6	-	33.0	-
	HHD8	31.7	-	46.6	35.6
Combination Long-haul Truck	MHD67	28.5	-	54.1	-
	HHD8	29.0	-	60.5	32.0

* Values rounded to the nearest tenth of a cent; blank values represent cases where a given MOVES source type and regulatory class did not use a specific fuel type.

Table 3-20 Retail Fuel Cost Per Mile for Model Year 2030 Vehicles from Calendar Year 2030 to 2055 for each MOVES Source Type and Regulatory Class by Fuel Type for the Final Standards* (cents/mile in 2022 dollars, 2% discounting)

MOVES Source Type	Regulatory Class	Diesel	Gasoline	Electricity	CNG	Hydrogen
Other Buses	LHD45	-	47.4	8.5	-	-
	MHD67	37.1	-	15.7	-	-
	HHD8	41.1	-	23.4	48.0	20.5
Transit Bus	LHD45	-	47.0	10.2	-	-
	MHD67	37.1	-	16.8	-	-
	Urban Bus	40.9	-	13.8	47.0	-
School Bus	LHD45	-	32.9	7.9	-	-
	MHD67	28.9	34.0	11.4	-	-
	HHD8	31.6	-	13.7	37.6	-
Refuse Truck	MHD67	40.0	47.8	16.2	-	-
	HHD8	41.4	-	18.0	48.7	-
Single Unit Short-haul Truck	LHD45	19.6	28.4	7.9	-	-
	MHD67	29.3	35.4	13.8	-	-
	HHD8	35.7	-	17.5	42.6	-
Single Unit Long-haul Truck	LHD45	18.3	26.9	8.0	-	-
	MHD67	27.4	33.1	15.2	-	-
	HHD8	33.4	-	20.8	40.2	-
Combination Short-haul Truck	MHD67	38.9	-	46.3	-	46.6
	HHD8	40.4	-	54.1	45.5	50.4
Combination Long-haul Truck	MHD67	38.5	-	56.1	-	39.8
	HHD8	39.2	-	57.8	43.4	41.1

* Values rounded to the nearest tenth of a cent; blank values represent cases where a given MOVES source type and regulatory class did not use a specific fuel type.

Table 3-21 Retail Fuel Cost Per Mile for Model Year 2030 Vehicles from Calendar Year 2030 to 2055 for each MOVES Source Type and Regulatory Class by Fuel Type for the Final Standards* (cents/mile in 2022 dollars, 3% discounting)

MOVES Source Type	Regulatory Class	Diesel	Gasoline	Electricity	CNG	Hydrogen
Other Buses	LHD45	-	41.9	7.5	-	-
	MHD67	32.8	-	13.9	-	-
	HHD8	36.3	-	20.7	42.4	18.2
Transit Bus	LHD45	-	41.7	9.0	-	-
	MHD67	32.9	-	14.9	-	-
	Urban Bus	36.2	-	12.2	41.7	-
School Bus	LHD45	-	29.1	7.0	-	-
	MHD67	25.6	30.0	10.0	-	-
	HHD8	27.9	-	12.1	33.3	-
Refuse Truck	MHD67	35.7	42.6	14.5	-	-
	HHD8	36.9	-	16.1	43.4	-
Single Unit Short-haul Truck	LHD45	17.7	25.6	7.1	-	-
	MHD67	26.4	32.0	12.4	-	-
	HHD8	32.2	-	15.8	38.4	-
Single Unit Long-haul Truck	LHD45	16.6	24.4	7.3	-	-
	MHD67	24.8	30.0	13.8	-	-

MOVES Source Type	Regulatory Class	Diesel	Gasoline	Electricity	CNG	Hydrogen
	HHD8	30.3	-	18.8	36.5	-
Combination Short-haul Truck	MHD67	35.4	-	42.0	-	42.6
	HHD8	36.7	-	49.1	41.3	46.0
Combination Long-haul Truck	MHD67	34.6	-	50.4	-	36.0
	HHD8	35.3	-	51.9	39.0	37.1

* Values rounded to the nearest tenth of a cent; blank values represent cases where a given MOVES source type and regulatory class did not use a specific fuel type.

Table 3-22 Retail Fuel Cost Per Mile for Model Year 2030 Vehicles from Calendar Year 2030 to 2055 for each MOVES Source Type and Regulatory Class by Fuel Type for the Final Standards* (cents/mile in 2022 dollars, 7% discounting)

MOVES Source Type	Regulatory Class	Diesel	Gasoline	Electricity	CNG	Hydrogen
Other Buses	LHD45	-	26.9	4.8	-	-
	MHD67	21.0	-	8.9	-	-
	HHD8	23.3	-	13.2	27.2	11.9
Transit Bus	LHD45	-	27.0	5.8	-	-
	MHD67	21.4	-	9.6	-	-
	Urban Bus	23.5	-	7.9	27.0	-
School Bus	LHD45	-	18.6	4.5	-	-
	MHD67	16.4	19.2	6.4	-	-
	HHD8	17.9	-	7.7	21.3	-
Refuse Truck	MHD67	23.6	28.1	9.5	-	-
	HHD8	24.4	-	10.6	28.6	-
Single Unit Short-haul Truck	LHD45	12.2	17.6	4.9	-	-
	MHD67	18.2	22.0	8.5	-	-
	HHD8	22.2	-	10.8	26.4	-
Single Unit Long-haul Truck	LHD45	11.6	17.1	5.1	-	-
	MHD67	17.3	21.0	9.6	-	-
	HHD8	21.2	-	13.1	25.5	-
Combination Short-haul Truck	MHD67	24.9	-	29.3	-	30.4
	HHD8	25.8	-	34.3	29.0	32.8
Combination Long-haul Truck	MHD67	23.4	-	34.0	-	24.8
	HHD8	23.9	-	35.0	26.4	25.6

* Values rounded to the nearest tenth of a cent; blank values represent cases where a given MOVES source type and regulatory class did not use a specific fuel type.

Table 3-23 Retail Fuel Cost Per Mile for Model Year 2032 Vehicles from Calendar Year 2032 to 2055 for each MOVES Source Type and Regulatory Class by Fuel Type for the Final Standards* (cents/mile in 2022 dollars, 2% discounting)

MOVES Source Type	Regulatory Class	Diesel	Gasoline	Electricity	CNG	Hydrogen
Other Buses	LHD45	-	44.4	10.3	-	-
	MHD67	36.0	-	15.2	-	-
	HHD8	40.6	-	22.5	47.4	18.7
Transit Bus	LHD45	-	44.0	12.3	-	-
	MHD67	36.1	-	16.1	-	-

MOVES Source Type	Regulatory Class	Diesel	Gasoline	Electricity	CNG	Hydrogen
	Urban Bus	38.2	-	16.0	43.9	-
School Bus	LHD45	-	31.4	8.4	-	-
	MHD67	28.5	33.4	10.8	-	-
	HHD8	30.0	-	14.6	35.7	-
Refuse Truck	MHD67	38.9	46.5	15.6	-	-
	HHD8	40.5	-	16.9	47.7	-
Single Unit Short-haul Truck	LHD45	19.0	27.5	7.6	-	-
	MHD67	28.4	34.4	13.0	-	-
	HHD8	34.6	-	17.3	41.3	-
Single Unit Long-haul Truck	LHD45	17.8	26.1	7.8	-	-
	MHD67	26.6	32.1	14.3	-	-
	HHD8	32.2	-	20.8	38.8	-
Combination Short-haul Truck	MHD67	37.9	-	40.8	-	37.8
	HHD8	40.3	-	45.7	45.3	39.4
Combination Long-haul Truck	MHD67	37.5	-	50.0	-	33.4
	HHD8	38.3	-	51.1	42.4	34.1

* Values rounded to the nearest tenth of a cent; blank values represent cases where a given MOVES source type and regulatory class did not use a specific fuel type.

Table 3-24 Retail Fuel Cost Per Mile for Model Year 2032 Vehicles from Calendar Year 2032 to 2055 for each MOVES Source Type and Regulatory Class by Fuel Type for the Final Standards* (cents/mile in 2022 dollars, 3% discounting)

MOVES Source Type	Regulatory Class	Diesel	Gasoline	Electricity	CNG	Hydrogen
Other Buses	LHD45	-	38.6	8.9	-	-
	MHD67	31.4	-	13.2	-	-
	HHD8	35.3	-	19.5	41.2	16.3
Transit Bus	LHD45	-	38.4	10.7	-	-
	MHD67	31.5	-	14.0	-	-
	Urban Bus	33.3	-	14.0	38.3	-
School Bus	LHD45	-	27.3	7.3	-	-
	MHD67	24.8	29.1	9.4	-	-
	HHD8	26.1	-	12.7	31.1	-
Refuse Truck	MHD67	34.1	40.7	13.7	-	-
	HHD8	35.5	-	14.8	41.8	-
Single Unit Short-haul Truck	LHD45	16.8	24.4	6.8	-	-
	MHD67	25.2	30.5	11.5	-	-
	HHD8	30.7	-	15.3	36.6	-
Single Unit Long-haul Truck	LHD45	15.9	23.3	6.9	-	-
	MHD67	23.7	28.6	12.8	-	-
	HHD8	28.7	-	18.5	34.6	-
Combination Short-haul Truck	MHD67	33.8	-	36.3	-	33.7
	HHD8	36.0	-	40.7	40.4	35.2
Combination Long-haul Truck	MHD67	33.2	-	44.1	-	29.5
	HHD8	33.8	-	45.0	37.4	30.1

* Values rounded to the nearest tenth of a cent; blank values represent cases where a given MOVES source type and regulatory class did not use a specific fuel type.

Table 3-25 Retail Fuel Cost Per Mile for Model Year 2032 Vehicles from Calendar Year 2032 to 2055 for each MOVES Source Type and Regulatory Class by Fuel Type for the Final Standards* (cents/mile in 2022 dollars, 7% discounting)

MOVES Source Type	Regulatory Class	Diesel	Gasoline	Electricity	CNG	Hydrogen
Other Buses	LHD45	-	23.1	5.3	-	-
	MHD67	18.8	-	7.9	-	-
	HHD8	21.2	-	11.7	24.7	9.8
Transit Bus	LHD45	-	23.2	6.5	-	-
	MHD67	19.1	-	8.5	-	-
	Urban Bus	20.2	-	8.5	23.2	-
School Bus	LHD45	-	16.4	4.4	-	-
	MHD67	14.9	17.4	5.6	-	-
	HHD8	15.6	-	7.6	18.6	-
Refuse Truck	MHD67	21.0	25.0	8.4	-	-
	HHD8	21.8	-	9.1	25.7	-
Single Unit Short-haul Truck	LHD45	10.8	15.6	4.3	-	-
	MHD67	16.1	19.5	7.3	-	-
	HHD8	19.6	-	9.8	23.3	-
Single Unit Long-haul Truck	LHD45	10.3	15.1	4.5	-	-
	MHD67	15.4	18.6	8.3	-	-
	HHD8	18.6	-	12.0	22.4	-
Combination Short-haul Truck	MHD67	22.1	-	23.6	-	22.1
	HHD8	23.5	-	26.5	26.4	23.1
Combination Long-haul Truck	MHD67	20.9	-	27.7	-	18.7
	HHD8	21.3	-	28.3	23.6	19.1

* Values rounded to the nearest tenth of a cent; blank values represent cases where a given MOVES source type and regulatory class did not use a specific fuel type.

Table 3-26 Retail Fuel Cost Per Mile for Model Year 2027 Vehicles from Calendar Year 2027 to 2055 for each MOVES Source Type and Regulatory Class Across All Fuel Types* (cents/mile in 2022 dollars, 2% discounting)

MOVES Source Type	Regulatory Class	Cost in Reference	Cost in Final Standards	Cost in Alternative	Final Standards Change from Reference	Alternative Change from Reference
Other Buses	LHD45	40.6	37.9	39.3	-2.7	-1.4
	MHD67	37.4	35.8	36.6	-1.6	-0.8
	HHD8	41.1	41.1	41.1	0.0	0.0
Transit Bus	LHD45	40.6	38.1	39.4	-2.5	-1.2
	MHD67	37.6	37.0	37.5	-0.6	-0.1
	Urban Bus	40.7	40.7	40.7	0.0	0.0
School Bus	LHD45	30.1	27.9	28.8	-2.1	-1.3
	MHD67	29.6	27.2	28.1	-2.4	-1.6
	HHD8	32.0	32.0	32.0	0.0	0.0
Refuse Truck	MHD67	40.2	37.1	38.3	-3.1	-1.9
	HHD8	43.6	43.6	43.6	0.0	0.0
	LHD45	22.5	20.9	21.4	-1.6	-1.1
	MHD67	31.2	30.2	30.7	-0.9	-0.4

MOVES Source Type	Regulatory Class	Cost in Reference	Cost in Final Standards	Cost in Alternative	Final Standards Change from Reference	Alternative Change from Reference
Single Unit Short-haul Truck	HHD8	37.0	37.0	37.0	0.0	0.0
Single Unit Long-haul Truck	LHD45	21.2	21.2	21.2	0.0	0.0
	MHD67	29.2	28.3	28.7	-1.0	-0.5
	HHD8	34.8	34.8	34.8	0.0	0.0
Combination Short-haul Truck	MHD67	41.9	41.8	41.9	0.0	0.0
	HHD8	44.0	44.0	44.0	0.0	0.0
Combination Long-haul Truck	MHD67	40.7	40.7	40.7	0.0	0.0
	HHD8	41.5	41.5	41.5	0.0	0.0

* Values rounded to the nearest tenth of a cent; negative values denote lower costs, i.e., savings in expenditures.

Table 3-27 Retail Fuel Cost Per Mile for Model Year 2027 Vehicles from Calendar Year 2027 to 2055 for each MOVES Source Type and Regulatory Class Across All Fuel Types* (cents/mile in 2022 dollars, 3% discounting)

MOVES Source Type	Regulatory Class	Cost in Reference	Cost in Final Standards	Cost in Alternative	Final Standards Change from Reference	Alternative Change from Reference
Other Buses	LHD45	36.9	34.4	35.6	-2.5	-1.2
	MHD67	33.9	32.5	33.2	-1.4	-0.7
	HHD8	37.3	37.3	37.3	0.0	0.0
Transit Bus	LHD45	36.9	34.7	35.8	-2.3	-1.1
	MHD67	34.2	33.6	34.1	-0.6	-0.1
	Urban Bus	37.0	37.0	37.0	0.0	0.0
School Bus	LHD45	27.2	25.3	26.1	-2.0	-1.2
	MHD67	26.9	24.7	25.5	-2.2	-1.4
	HHD8	29.0	29.0	29.0	0.0	0.0
Refuse Truck	MHD67	36.9	34.1	35.1	-2.8	-1.8
	HHD8	40.0	40.0	40.0	0.0	0.0
Single Unit Short-haul Truck	LHD45	20.9	19.4	19.9	-1.5	-1.0
	MHD67	29.0	28.1	28.6	-0.9	-0.4
	HHD8	34.4	34.4	34.4	0.0	0.0
Single Unit Long-haul Truck	LHD45	19.8	19.8	19.8	0.0	0.0
	MHD67	27.3	26.4	26.8	-0.9	-0.5
	HHD8	32.4	32.4	32.4	0.0	0.0
Combination Short-haul Truck	MHD67	39.2	39.1	39.2	0.0	0.0
	HHD8	41.1	41.1	41.1	0.0	0.0
Combination Long-haul Truck	MHD67	37.6	37.6	37.6	0.0	0.0
	HHD8	38.4	38.4	38.4	0.0	0.0

* Values rounded to the nearest tenth of a cent; negative values denote lower costs, i.e., savings in expenditures.

Table 3-28 Retail Fuel Cost Per Mile for Model Year 2027 Vehicles from Calendar Year 2027 to 2055 for each MOVES Source Type and Regulatory Class Across All Fuel Types* (cents/mile in 2022 dollars, 7% discounting)

MOVES Source Type	Regulatory Class	Cost in Reference	Cost in Final Standards	Cost in Alternative	Final Standards Change from Reference	Alternative Change from Reference
Other Buses	LHD45	26.2	24.5	25.4	-1.8	-0.9
	MHD67	24.2	23.2	23.7	-1.0	-0.5
	HHD8	26.6	26.6	26.6	0.0	0.0
Transit Bus	LHD45	26.6	25.0	25.8	-1.6	-0.8
	MHD67	24.7	24.3	24.6	-0.4	-0.1
	Urban Bus	26.7	26.7	26.7	0.0	0.0
School Bus	LHD45	19.4	18.0	18.6	-1.4	-0.8
	MHD67	19.2	17.6	18.1	-1.6	-1.0
	HHD8	20.7	20.7	20.7	0.0	0.0
Refuse Truck	MHD67	27.2	25.1	25.9	-2.1	-1.3
	HHD8	29.5	29.5	29.5	0.0	0.0
Single Unit Short-haul Truck	LHD45	16.1	14.9	15.3	-1.1	-0.8
	MHD67	22.3	21.6	22.0	-0.7	-0.3
	HHD8	26.5	26.5	26.5	0.0	0.0
Single Unit Long-haul Truck	LHD45	15.4	15.4	15.4	0.0	0.0
	MHD67	21.3	20.6	21.0	-0.7	-0.4
	HHD8	25.4	25.4	25.4	0.0	0.0
Combination Short-haul Truck	MHD67	30.8	30.7	30.8	0.0	0.0
	HHD8	32.3	32.3	32.3	0.0	0.0
Combination Long-haul Truck	MHD67	28.6	28.6	28.6	0.0	0.0
	HHD8	29.2	29.2	29.2	0.0	0.0

* Values rounded to the nearest tenth of a cent; negative values denote lower costs, i.e., savings in expenditures.

Table 3-29 Retail Fuel Cost Per Mile for Model Year 2030 Vehicles from Calendar Year 2030 to 2055 for each MOVES Source Type and Regulatory Class Across All Fuel Types* (cents/mile in 2022 dollars, 2% discounting)

MOVES Source Type	Regulatory Class	Cost in Reference	Cost in Final Standards	Cost in Alternative	Final Standards Change from Reference	Alternative Change from Reference
Other Buses	LHD45	34.5	33.6	34.5	-0.9	0.0
	MHD67	33.3	33.3	33.3	0.0	0.0
	HHD8	39.0	39.0	39.0	0.0	0.0
Transit Bus	LHD45	34.7	33.9	34.7	-0.8	0.0
	MHD67	33.6	33.6	33.6	0.0	0.0
	Urban Bus	37.5	35.9	37.1	-1.6	-0.3
School Bus	LHD45	25.6	24.0	24.8	-1.6	-0.8
	MHD67	26.4	22.8	23.7	-3.5	-2.6

MOVES Source Type	Regulatory Class	Cost in Reference	Cost in Final Standards	Cost in Alternative	Final Standards Change from Reference	Alternative Change from Reference
	HHD8	29.6	27.9	28.8	-1.7	-0.8
Refuse Truck	MHD67	35.7	33.8	34.7	-1.9	-1.0
	HHD8	40.0	37.2	38.2	-2.7	-1.7
Single Unit Short-haul Truck	LHD45	19.2	17.5	18.0	-1.6	-1.2
	MHD67	27.7	27.3	27.7	-0.4	0.0
	HHD8	34.1	33.5	34.0	-0.7	-0.1
Single Unit Long-haul Truck	LHD45	18.2	18.2	18.2	0.0	0.0
	MHD67	26.3	25.6	26.0	-0.7	-0.3
	HHD8	32.3	32.0	32.3	-0.4	0.0
Combination Short-haul Truck	MHD67	40.0	40.0	40.0	0.0	0.0
	HHD8	42.4	42.8	42.6	0.4	0.3
Combination Long-haul Truck	MHD67	38.9	39.2	39.1	0.3	0.2
	HHD8	39.7	40.0	39.9	0.3	0.2

* Values rounded to the nearest tenth of a cent; negative values denote lower costs, i.e., savings in expenditures.

Table 3-30 Retail Fuel Cost Per Mile for Model Year 2030 Vehicles from Calendar Year 2030 to 2055 for each MOVES Source Type and Regulatory Class Across All Fuel Types* (cents/mile in 2022 dollars, 3% discounting)

MOVES Source Type	Regulatory Class	Cost in Reference	Cost in Final Standards	Cost in Alternative	Final Standards Change from Reference	Alternative Change from Reference
Other Buses	LHD45	30.5	29.7	30.5	-0.8	0.0
	MHD67	29.5	29.5	29.5	0.0	0.0
	HHD8	34.5	34.5	34.5	0.0	0.0
Transit Bus	LHD45	30.8	30.0	30.8	-0.7	0.0
	MHD67	29.8	29.8	29.8	0.0	0.0
	Urban Bus	33.2	31.8	32.9	-1.4	-0.3
School Bus	LHD45	22.7	21.2	21.9	-1.4	-0.7
	MHD67	23.3	20.1	21.0	-3.1	-2.3
	HHD8	26.2	24.7	25.5	-1.5	-0.7
Refuse Truck	MHD67	31.8	30.1	30.9	-1.7	-0.9
	HHD8	35.6	33.2	34.1	-2.4	-1.5
Single Unit Short-haul Truck	LHD45	17.3	15.8	16.2	-1.5	-1.0
	MHD67	25.0	24.6	25.0	-0.4	0.0
	HHD8	30.8	30.2	30.7	-0.6	-0.1
Single Unit Long-haul Truck	LHD45	16.5	16.5	16.5	0.0	0.0
	MHD67	23.8	23.2	23.6	-0.6	-0.2
	HHD8	29.3	29.0	29.3	-0.3	0.0
Combination Short-haul Truck	MHD67	36.3	36.3	36.3	0.0	0.0
	HHD8	38.5	38.9	38.8	0.4	0.3
	MHD67	35.0	35.2	35.2	0.3	0.2

MOVES Source Type	Regulatory Class	Cost in Reference	Cost in Final Standards	Cost in Alternative	Final Standards Change from Reference	Alternative Change from Reference
Combination Long-haul Truck	HHD8	35.7	36.0	35.9	0.3	0.2

* Values rounded to the nearest tenth of a cent; negative values denote lower costs, i.e., savings in expenditures.

Table 3-31 Retail Fuel Cost Per Mile for Model Year 2030 Vehicles from Calendar Year 2030 to 2055 for each MOVES Source Type and Regulatory Class Across All Fuel Types* (cents/mile in 2022 dollars, 7% discounting)

MOVES Source Type	Regulatory Class	Cost in Reference	Cost in Final Standards	Cost in Alternative	Final Standards Change from Reference	Alternative Change from Reference
Other Buses	LHD45	19.5	19.0	19.5	-0.5	0.0
	MHD67	18.9	18.9	18.9	0.0	0.0
	HHD8	22.1	22.1	22.1	0.0	0.0
Transit Bus	LHD45	20.0	19.5	20.0	-0.5	0.0
	MHD67	19.3	19.3	19.3	0.0	0.0
	Urban Bus	21.6	20.6	21.4	-0.9	-0.2
School Bus	LHD45	14.5	13.6	14.1	-0.9	-0.5
	MHD67	14.9	12.9	13.4	-2.0	-1.5
	HHD8	16.8	15.8	16.3	-1.0	-0.4
Refuse Truck	MHD67	21.0	19.9	20.4	-1.1	-0.6
	HHD8	23.5	21.9	22.5	-1.6	-1.0
Single Unit Short-haul Truck	LHD45	11.9	10.9	11.2	-1.0	-0.7
	MHD67	17.2	16.9	17.2	-0.3	0.0
	HHD8	21.2	20.8	21.1	-0.4	-0.1
Single Unit Long-haul Truck	LHD45	11.5	11.5	11.5	0.0	0.0
	MHD67	16.6	16.2	16.5	-0.4	-0.2
	HHD8	20.5	20.2	20.5	-0.2	0.0
Combination Short-haul Truck	MHD67	25.5	25.5	25.5	0.0	0.0
	HHD8	27.0	27.3	27.2	0.3	0.2
Combination Long-haul Truck	MHD67	23.7	23.9	23.8	0.2	0.1
	HHD8	24.2	24.4	24.3	0.2	0.1

* Values rounded to the nearest tenth of a cent; negative values denote lower costs, i.e., savings in expenditures.

Table 3-32 Retail Fuel Cost Per Mile for Model Year 2032 Vehicles from Calendar Year 2032 to 2055 for each MOVES Source Type and Regulatory Class Across All Fuel Types* (cents/mile in 2022 dollars, 2% discounting)

MOVES Source Type	Regulatory Class	Cost in Reference	Cost in Final Standards	Cost in Alternative	Final Standards Change from Reference	Alternative Change from Reference
Other Buses	LHD45	32.1	21.6	31.0	-10.5	-1.1
	MHD67	31.7	31.7	31.7	0.0	0.0
	HHD8	37.7	37.7	37.7	0.0	0.0
Transit Bus	LHD45	32.5	22.8	31.4	-9.6	-1.0
	MHD67	31.9	31.6	31.9	-0.3	0.0
	Urban Bus	36.1	29.9	34.8	-6.2	-1.2
School Bus	LHD45	24.0	16.1	22.0	-7.9	-2.0
	MHD67	25.0	16.2	20.9	-8.8	-4.1
	HHD8	28.5	24.2	27.4	-4.3	-1.1
Refuse Truck	MHD67	33.8	29.8	33.2	-4.0	-0.6
	HHD8	38.4	31.8	35.7	-6.6	-2.7
Single Unit Short-haul Truck	LHD45	17.9	12.5	15.9	-5.4	-1.9
	MHD67	26.2	23.9	26.1	-2.3	-0.2
	HHD8	32.8	30.0	32.2	-2.8	-0.6
Single Unit Long-haul Truck	LHD45	17.0	15.6	17.0	-1.4	0.0
	MHD67	25.0	22.5	24.5	-2.5	-0.5
	HHD8	31.1	28.0	30.0	-3.2	-1.2
Combination Short-haul Truck	MHD67	38.6	38.5	38.6	-0.1	0.0
	HHD8	41.1	42.6	41.7	1.5	0.6
Combination Long-haul Truck	MHD67	38.0	39.1	38.6	1.1	0.6
	HHD8	38.8	40.0	39.4	1.2	0.6

* Values rounded to the nearest tenth of a cent; negative values denote lower costs, i.e., savings in expenditures.

Table 3-33 Retail Fuel Cost Per Mile for Model Year 2032 Vehicles from Calendar Year 2032 to 2055 for each MOVES Source Type and Regulatory Class Across All Fuel Types* (cents/mile in 2022 dollars, 3% discounting)

MOVES Source Type	Regulatory Class	Cost in Reference	Cost in Final Standards	Cost in Alternative	Final Standards Change from Reference	Alternative Change from Reference
Other Buses	LHD45	28.0	18.8	27.0	-9.1	-0.9
	MHD67	27.6	27.6	27.6	0.0	0.0
	HHD8	32.8	32.8	32.8	0.0	0.0
Transit Bus	LHD45	28.3	19.9	27.4	-8.4	-0.9
	MHD67	27.9	27.6	27.9	-0.3	0.0
	Urban Bus	31.5	26.1	30.4	-5.4	-1.1
School Bus	LHD45	20.8	14.0	19.1	-6.8	-1.7
	MHD67	21.8	14.1	18.2	-7.6	-3.6
	HHD8	24.8	21.0	23.9	-3.7	-0.9
Refuse Truck	MHD67	29.6	26.1	29.1	-3.5	-0.5
	HHD8	33.6	27.8	31.3	-5.8	-2.4
Single Unit Short-haul Truck	LHD45	15.8	11.0	14.1	-4.8	-1.7
	MHD67	23.2	21.2	23.1	-2.1	-0.1
	HHD8	29.0	26.6	28.5	-2.4	-0.5
Single Unit Long-haul Truck	LHD45	15.2	13.9	15.2	-1.2	0.0
	MHD67	22.2	20.1	21.8	-2.2	-0.4
	HHD8	27.8	24.9	26.7	-2.9	-1.0
Combination Short-haul Truck	MHD67	34.5	34.4	34.4	-0.1	0.0
	HHD8	36.7	38.0	37.2	1.4	0.5
Combination Long-haul Truck	MHD67	33.5	34.5	34.0	1.0	0.5
	HHD8	34.2	35.3	34.8	1.0	0.5

* Values rounded to the nearest tenth of a cent; Negative values denote lower costs, i.e., savings in expenditures.

Table 3-34 Retail Fuel Cost Per Mile for Model Year 2032 Vehicles from Calendar Year 2032 to 2055 for each MOVES Source Type and Regulatory Class Across All Fuel Types* (cents/mile in 2022 dollars, 7% discounting)

MOVES Source Type	Regulatory Class	Cost in Reference	Cost in Final Standards	Cost in Alternative	Final Standards Change from Reference	Alternative Change from Reference
Other Buses	LHD45	16.8	11.3	16.2	-5.5	-0.6
	MHD67	16.6	16.6	16.6	0.0	0.0
	HHD8	19.7	19.7	19.7	0.0	0.0
Transit Bus	LHD45	17.1	12.1	16.6	-5.1	-0.5
	MHD67	16.9	16.7	16.9	-0.2	0.0
	Urban Bus	19.1	15.8	18.4	-3.3	-0.7
School Bus	LHD45	12.5	8.4	11.5	-4.1	-1.0
	MHD67	13.1	8.5	10.9	-4.6	-2.2
	HHD8	14.9	12.6	14.3	-2.2	-0.6
Refuse Truck	MHD67	18.2	16.1	17.9	-2.2	-0.3
	HHD8	20.7	17.1	19.2	-3.6	-1.4
Single Unit Short-haul Truck	LHD45	10.1	7.0	9.0	-3.1	-1.1
	MHD67	14.8	13.5	14.8	-1.3	-0.1
	HHD8	18.6	17.0	18.2	-1.6	-0.3
Single Unit Long-haul Truck	LHD45	9.8	9.0	9.8	-0.8	0.0
	MHD67	14.4	13.0	14.2	-1.4	-0.3
	HHD8	18.0	16.2	17.4	-1.9	-0.7
Combination Short-haul Truck	MHD67	22.5	22.4	22.4	-0.1	0.0
	HHD8	23.9	24.8	24.2	0.8	0.3
Combination Long-haul Truck	MHD67	21.1	21.8	21.5	0.6	0.3
	HHD8	21.6	22.2	21.9	0.6	0.3

* Values rounded to the nearest tenth of a cent; Negative values denote lower costs, i.e., savings in expenditures.

Table 3-35 and Table 3-36 present the annual undiscounted pre-tax fuel costs associated with the final standards and alternative, respectively. CNG fuel savings are calculated as gasoline gallon equivalents and, as such, are monetized using gasoline fuel prices.

Table 3-35 Annual Undiscounted Pre-Tax Fuel Costs for the Final Standards Relative to the Reference Case, Millions of 2022 dollars *

Calendar Year	Diesel	Gasoline	CNG	Electricity	Hydrogen	Sum
2027	-$100	-$59	$0	$76	$0	-$84
2028	-$260	-$110	-$2	$200	$0	-$170
2029	-$480	-$170	-$3	$370	$0	-$280
2030	-$930	-$220	-$6	$880	$100	-$170
2031	-$1,900	-$350	-$11	$1,900	$290	-$110
2032	-$3,800	-$560	-$20	$3,700	$650	$37
2033	-$5,600	-$760	-$29	$5,500	$970	$120
2034	-$7,400	-$930	-$38	$7,300	$1,200	$170
2035	-$9,200	-$1,100	-$47	$9,100	$1,400	$160
2036	-$11,000	-$1,200	-$57	$11,000	$1,700	$350
2037	-$12,000	-$1,300	-$66	$12,000	$2,000	$490
2038	-$14,000	-$1,400	-$76	$14,000	$2,300	$640
2039	-$15,000	-$1,500	-$85	$15,000	$2,500	$810
2040	-$16,000	-$1,600	-$95	$16,000	$2,700	$980
2041	-$17,000	-$1,700	-$100	$17,000	$2,900	$990
2042	-$18,000	-$1,800	-$110	$18,000	$3,100	$1,100
2043	-$19,000	-$1,800	-$120	$19,000	$3,300	$1,100
2044	-$19,000	-$1,800	-$130	$19,000	$3,400	$1,200
2045	-$20,000	-$1,900	-$140	$20,000	$3,500	$1,200
2046	-$20,000	-$1,900	-$150	$20,000	$3,600	$880
2047	-$21,000	-$1,900	-$160	$20,000	$3,700	$800
2048	-$21,000	-$2,000	-$170	$20,000	$3,700	$670
2049	-$21,000	-$2,000	-$180	$20,000	$3,800	$540
2050	-$21,000	-$2,000	-$190	$20,000	$3,800	$430
2051	-$21,000	-$2,000	-$210	$20,000	$3,900	$420
2052	-$21,000	-$2,000	-$220	$20,000	$3,900	$410
2053	-$22,000	-$2,100	-$230	$20,000	$4,000	$390
2054	-$22,000	-$2,100	-$240	$20,000	$4,000	$370
2055	-$22,000	-$2,100	-$260	$20,000	$4,000	$350

* Values rounded to two significant digits; Negative values denote lower costs, i.e., savings in expenditures.

Table 3-36 Annual Undiscounted Pre-Tax Fuel Costs for the Alternative Relative to the Reference Case, Millions of 2022 dollars *

Calendar Year	Diesel	Gasoline	CNG	Electricity	Hydrogen	Sum
2027	-$51	-$36	$0	$38	$0	-$50
2028	-$110	-$70	$0	$85	$0	-$97
2029	-$240	-$100	-$1	$180	$0	-$160
2030	-$520	-$130	-$2	$500	$67	-$94
2031	-$1,000	-$170	-$4	$1,000	$180	-$13
2032	-$1,700	-$230	-$7	$1,700	$350	$94
2033	-$2,500	-$270	-$10	$2,400	$480	$190
2034	-$3,100	-$300	-$12	$3,100	$600	$280
2035	-$3,800	-$310	-$15	$3,800	$680	$350
2036	-$4,300	-$320	-$17	$4,400	$810	$510
2037	-$4,900	-$310	-$19	$4,900	$930	$650
2038	-$5,300	-$310	-$22	$5,400	$1,000	$790
2039	-$5,700	-$290	-$24	$5,800	$1,100	$930
2040	-$6,100	-$280	-$26	$6,200	$1,200	$1,100
2041	-$6,400	-$260	-$28	$6,500	$1,300	$1,100
2042	-$6,600	-$240	-$30	$6,800	$1,400	$1,200
2043	-$6,800	-$210	-$32	$6,900	$1,500	$1,300
2044	-$6,900	-$190	-$34	$7,100	$1,500	$1,400
2045	-$7,000	-$170	-$36	$7,100	$1,500	$1,400
2046	-$7,100	-$160	-$38	$7,100	$1,600	$1,400
2047	-$7,200	-$140	-$40	$7,100	$1,600	$1,400
2048	-$7,100	-$120	-$43	$7,100	$1,600	$1,300
2049	-$7,100	-$110	-$45	$7,000	$1,600	$1,300
2050	-$7,100	-$100	-$47	$7,000	$1,600	$1,300
2051	-$7,100	-$93	-$50	$6,900	$1,600	$1,300
2052	-$7,100	-$85	-$52	$6,900	$1,600	$1,300
2053	-$7,000	-$78	-$55	$6,800	$1,600	$1,300
2054	-$7,000	-$71	-$58	$6,800	$1,600	$1,300
2055	-$6,900	-$66	-$60	$6,700	$1,600	$1,300

* Values rounded to two significant digits; Negative values denote lower costs, i.e., savings in expenditures.

3.4.7.2 Costs Associated with Diesel Exhaust Fluid

DEF consumption costs in heavy-duty vehicles were estimated by EPA in the HD2027 final rule.[1333] We are applying the same methodology in this analysis to estimate the total costs of DEF under the final HD GHG Phase 3 standards. Examples of total cost estimates of DEF for MY 2027, 2030 and 2032 vehicles are provided for 2-percent, 3-percent and 7 percent discounting in Table 3-37 through Table 3-45. To determine the total costs associated with DEF usage for a given model year, the DEF usage for each MOVES source type and regulatory class was multiplied by the DEF price over the from the first year of the vehicle until 2055.[1334] The total DEF cost was divided by the total VMT for a given model year vehicle for each MOVES

[1333] 88 FR 4413, January 24, 2023.

[1334] This analysis uses the DEF prices presented in the NCP Technical Support Document (see "Nonconformance Penalties for On-highway Heavy-duty Diesel Engines: Technical Support Document," EPA-420-R-12-014) with growth beyond 2042 projected at the same 1.3 percent rate as noted in the NCP TSD. Note that the DEF prices used update the NCP TSD's 2011 prices to 2022 dollars.

Source Type and regulatory class combination from the first year of the vehicle until 2055 to determine the average cost of DEF per mile. The DEF cost per mile was computed for the reference case, alternative case and final standard case under the potential compliance pathway for each fuel type. The estimates of DEF cost per mile for MY 2027 for the final standards cases are shown in Table 3-37, Table 3-38, and Table 3-39 for 2-percent, 3-percent, and 7-percnet discounting, respectively. The estimates of DEF cost per mile for MY 2030 for the final standards cases are shown in Table 3-40, Table 3-41, and Table 3-42 for 2-percent, 3-percent, and 7-percnet discounting, respectively. The estimates of DEF cost per mile for MY 2032 for the final standards cases are shown in Table 3-43, Table 3-44, and Table 3-45 for 2-percent, 3-percent, and 7-percnet discounting, respectively. Several source types and regulatory classes contain no diesel-fueled ICE vehicles and therefore no DEF consumption costs. Values shown as a dash "-" in Table 3-37 through Table 3-45 represent cases where a given MOVES source type and regulatory class did not use a specific fuel type. The values of 0 for gasoline, electricity, CNG and hydrogen as those vehicles do not consume any DEF and therefore do not incur any cost per mile.

Table 3-37 DEF Cost Per Mile for Model Year 2027 Vehicles from Calendar Year 2027 to 2055 for each MOVES Source Type and Regulatory Class by Fuel Type for the Final Standards* (cents/mile in 2022 dollars, 2% discounting)

MOVES Source Type	Regulatory Class	Diesel	Gasoline	Electricity	CNG
Other Buses	LHD45	-	0.00	0.00	-
	MHD67	2.33	-	0.00	-
	HHD8	2.47	-	0.00	0.00
Transit Bus	LHD45	-	0.00	0.00	-
	MHD67	2.33	-	0.00	-
	Urban Bus	2.49	-	0.00	0.00
School Bus	LHD45	-	0.00	0.00	-
	MHD67	1.82	0.00	0.00	-
	HHD8	1.95	-	0.00	0.00
Refuse Truck	MHD67	2.48	0.00	0.00	-
	HHD8	2.57	-	0.00	0.00
Single Unit Short-haul Truck	LHD45	1.20	0.00	0.00	-
	MHD67	1.81	0.00	0.00	-
	HHD8	2.18	-	0.00	0.00
Single Unit Long-haul Truck	LHD45	1.11	0.00	0.00	-
	MHD67	1.68	0.00	0.00	-
	HHD8	2.02	-	0.00	0.00
Combination Short-haul Truck	MHD67	2.40	-	0.00	-
	HHD8	2.48	-	0.00	0.00
Combination Long-haul Truck	MHD67	2.37	-	0.00	-
	HHD8	2.42	-	0.00	0.00

* Values rounded to the nearest hundredth of a cent; blank values represent cases where a given MOVES source type and regulatory class did not use a specific fuel type.

Table 3-38 DEF Cost Per Mile for Model Year 2027 Vehicles from Calendar Year 2027 to 2055 for each MOVES Source Type and Regulatory Class by Fuel Type for the Final Standards* (cents/mile in 2022 dollars, 3% discounting)

MOVES Source Type	Regulatory Class	Diesel	Gasoline	Electricity	CNG
Other Buses	LHD45	-	0.00	0.00	-
	MHD67	2.10	-	0.00	-
	HHD8	2.23	-	0.00	0.00
Transit Bus	LHD45	-	0.00	0.00	-
	MHD67	2.11	-	0.00	-
	Urban Bus	2.26	-	0.00	0.00
School Bus	LHD45	-	0.00	0.00	-
	MHD67	1.65	0.00	0.00	-
	HHD8	1.76	-	0.00	0.00
Refuse Truck	MHD67	2.27	0.00	0.00	-
	HHD8	2.35	-	0.00	0.00
Single Unit Short-haul Truck	LHD45	1.11	0.00	0.00	-
	MHD67	1.67	0.00	0.00	-
	HHD8	2.02	-	0.00	0.00
Single Unit Long-haul Truck	LHD45	1.04	0.00	0.00	-
	MHD67	1.56	0.00	0.00	-
	HHD8	1.88	-	0.00	0.00
Combination Short-haul Truck	MHD67	2.24	-	0.00	-
	HHD8	2.32	-	0.00	0.00
Combination Long-haul Truck	MHD67	2.19	-	0.00	-
	HHD8	2.23	-	0.00	0.00

* Values rounded to the nearest hundredth of a cent; blank values represent cases where a given MOVES source type and regulatory class did not use a specific fuel type.

Table 3-39 DEF Cost Per Mile for Model Year 2027 Vehicles from Calendar Year 2027 to 2055 for each MOVES Source Type and Regulatory Class by Fuel Type for the Final Standards* (cents/mile in 2022 dollars, 7% discounting)

MOVES Source Type	Regulatory Class	Diesel	Gasoline	Electricity	CNG
Other Buses	LHD45	-	0.00	0.00	-
	MHD67	1.47	-	0.00	-
	HHD8	1.56	-	0.00	0.00
Transit Bus	LHD45	-	0.00	0.00	-
	MHD67	1.50	-	0.00	-
	Urban Bus	1.60	-	0.00	0.00
School Bus	LHD45	-	0.00	0.00	-
	MHD67	1.15	0.00	0.00	-
	HHD8	1.23	-	0.00	0.00
Refuse Truck	MHD67	1.65	0.00	0.00	-
	HHD8	1.71	-	0.00	0.00
Single Unit Short-haul Truck	LHD45	0.84	0.00	0.00	-
	MHD67	1.28	0.00	0.00	-
	HHD8	1.54	-	0.00	0.00
Single Unit Long-haul Truck	LHD45	0.80	0.00	0.00	-
	MHD67	1.21	0.00	0.00	-

MOVES Source Type	Regulatory Class	Diesel	Gasoline	Electricity	CNG
	HHD8	1.46	-	0.00	0.00
Combination Short-haul Truck	MHD67	1.75	-	0.00	-
	HHD8	1.81	-	0.00	0.00
Combination Long-haul Truck	MHD67	1.64	-	0.00	-
	HHD8	1.67	-	0.00	0.00

* Values rounded to the nearest hundredth of a cent; blank values represent cases where a given MOVES source type and regulatory class did not use a specific fuel type.

Table 3-40 DEF Cost Per Mile for Model Year 2030 Vehicles from Calendar Year 2030 to 2055 for each MOVES Source Type and Regulatory Class by Fuel Type for the Final Standards* (cents/mile in 2022 dollars, 2% discounting)

MOVES Source Type	Regulatory Class	Diesel	Gasoline	Electricity	CNG	Hydrogen
Other Buses	LHD45	-	0.00	0.00	-	-
	MHD67	2.28	-	0.00	-	-
	HHD8	2.52	-	0.00	0.00	0.00
Transit Bus	LHD45	-	0.00	0.00	-	-
	MHD67	2.27	-	0.00	-	-
	Urban Bus	2.50	-	0.00	0.00	-
School Bus	LHD45	-	0.00	0.00	-	-
	MHD67	1.78	0.00	0.00	-	-
	HHD8	1.94	-	0.00	0.00	-
Refuse Truck	MHD67	2.43	0.00	0.00	-	-
	HHD8	2.51	-	0.00	0.00	-
Single Unit Short-haul Truck	LHD45	1.18	0.00	0.00	-	-
	MHD67	1.76	0.00	0.00	-	-
	HHD8	2.14	-	0.00	0.00	-
Single Unit Long-haul Truck	LHD45	1.09	0.00	0.00	-	-
	MHD67	1.63	0.00	0.00	-	-
	HHD8	1.99	-	0.00	0.00	-
Combination Short-haul Truck	MHD67	2.32	-	0.00	-	0.00
	HHD8	2.41	-	0.00	0.00	0.00
Combination Long-haul Truck	MHD67	2.32	-	0.00	-	0.00
	HHD8	2.36	-	0.00	0.00	0.00

* Values rounded to the nearest hundredth of a cent; blank values represent cases where a given MOVES source type and regulatory class did not use a specific fuel type.

Table 3-41 DEF Cost Per Mile for Model Year 2030 Vehicles from Calendar Year 2030 to 2055 for each MOVES Source Type and Regulatory Class by Fuel Type for the Final Standards* (cents/mile in 2022 dollars, 3% discounting)

MOVES Source Type	Regulatory Class	Diesel	Gasoline	Electricity	CNG	Hydrogen
Other Buses	LHD45	-	0.00	0.00	-	-
	MHD67	2.00	-	0.00	-	-
	HHD8	2.22	-	0.00	0.00	0.00
Transit Bus	LHD45	-	0.00	0.00	-	-
	MHD67	2.01	-	0.00	-	-

MOVES Source Type	Regulatory Class	Diesel	Gasoline	Electricity	CNG	Hydrogen
	Urban Bus	2.21	-	0.00	0.00	-
School Bus	LHD45	-	0.00	0.00	-	-
	MHD67	1.56	0.00	0.00	-	-
	HHD8	1.71	-	0.00	0.00	-
Refuse Truck	MHD67	2.16	0.00	0.00	-	-
	HHD8	2.23	-	0.00	0.00	-
Single Unit Short-haul Truck	LHD45	1.06	0.00	0.00	-	-
	MHD67	1.58	0.00	0.00	-	-
	HHD8	1.93	-	0.00	0.00	-
Single Unit Long-haul Truck	LHD45	0.99	0.00	0.00	-	-
	MHD67	1.48	0.00	0.00	-	-
	HHD8	1.80	-	0.00	0.00	-
Combination Short-haul Truck	MHD67	2.10	-	0.00	-	0.00
	HHD8	2.18	-	0.00	0.00	0.00
Combination Long-haul Truck	MHD67	2.08	-	0.00	-	0.00
	HHD8	2.12	-	0.00	0.00	0.00

* Values rounded to the nearest hundredth of a cent; blank values represent cases where a given MOVES source type and regulatory class did not use a specific fuel type.

Table 3-42 DEF Cost Per Mile for Model Year 2030 Vehicles from Calendar Year 2030 to 2055 for each MOVES Source Type and Regulatory Class by Fuel Type for the Final Standards* (cents/mile in 2022 dollars, 7% discounting)

MOVES Source Type	Regulatory Class	Diesel	Gasoline	Electricity	CNG	Hydrogen
Other Buses	LHD45	-	0.00	0.00	-	-
	MHD67	1.27	-	0.00	-	-
	HHD8	1.40	-	0.00	0.00	0.00
Transit Bus	LHD45	-	0.00	0.00	-	-
	MHD67	1.28	-	0.00	-	-
	Urban Bus	1.41	-	0.00	0.00	-
School Bus	LHD45	-	0.00	0.00	-	-
	MHD67	0.99	0.00	0.00	-	-
	HHD8	1.08	-	0.00	0.00	-
Refuse Truck	MHD67	1.41	0.00	0.00	-	-
	HHD8	1.46	-	0.00	0.00	-
Single Unit Short-haul Truck	LHD45	0.72	0.00	0.00	-	-
	MHD67	1.08	0.00	0.00	-	-
	HHD8	1.31	-	0.00	0.00	-
Single Unit Long-haul Truck	LHD45	0.69	0.00	0.00	-	-
	MHD67	1.02	0.00	0.00	-	-
	HHD8	1.25	-	0.00	0.00	-
Combination Short-haul Truck	MHD67	1.47	-	0.00	-	0.00
	HHD8	1.52	-	0.00	0.00	0.00
Combination Long-haul Truck	MHD67	1.39	-	0.00	-	0.00
	HHD8	1.42	-	0.00	0.00	0.00

* Values rounded to the nearest hundredth of a cent; blank values represent cases where a given MOVES source type and regulatory class did not use a specific fuel type.

Table 3-43 DEF Cost Per Mile for Model Year 2032 Vehicles from Calendar Year 2032 to 2055 for each MOVES Source Type and Regulatory Class by Fuel Type for the Final Standards* (cents/mile in 2022 dollars, 2% discounting)

MOVES Source Type	Regulatory Class	Diesel	Gasoline	Electricity	CNG	Hydrogen
Other Buses	LHD45	-	0.00	0.00	-	-
	MHD67	2.25	-	0.00	-	-
	HHD8	2.53	-	0.00	0.00	0.00
Transit Bus	LHD45	-	0.00	0.00	-	-
	MHD67	2.24	-	0.00	-	-
	Urban Bus	2.38	-	0.00	0.00	-
School Bus	LHD45	-	0.00	0.00	-	-
	MHD67	1.77	0.00	0.00	-	-
	HHD8	1.88	-	0.00	0.00	-
Refuse Truck	MHD67	2.40	0.00	0.00	-	-
	HHD8	2.50	-	0.00	0.00	-
Single Unit Short-haul Truck	LHD45	1.16	0.00	0.00	-	-
	MHD67	1.73	0.00	0.00	-	-
	HHD8	2.11	-	0.00	0.00	-
Single Unit Long-haul Truck	LHD45	1.08	0.00	0.00	-	-
	MHD67	1.61	0.00	0.00	-	-
	HHD8	1.96	-	0.00	0.00	-
Combination Short-haul Truck	MHD67	2.30	-	0.00	-	0.00
	HHD8	2.43	-	0.00	0.00	0.00
Combination Long-haul Truck	MHD67	2.30	-	0.00	-	0.00
	HHD8	2.34	-	0.00	0.00	0.00

* Values rounded to the nearest hundredth of a cent; blank values represent cases where a given MOVES source type and regulatory class did not use a specific fuel type.

Table 3-44 DEF Cost Per Mile for Model Year 2032 Vehicles from Calendar Year 2032 to 2055 for each MOVES Source Type and Regulatory Class by Fuel Type for the Final Standards* (cents/mile in 2022 dollars, 3% discounting)

MOVES Source Type	Regulatory Class	Diesel	Gasoline	Electricity	CNG	Hydrogen
Other Buses	LHD45	-	0.00	0.00	-	-
	MHD67	1.95	-	0.00	-	-
	HHD8	2.19	-	0.00	0.00	0.00
Transit Bus	LHD45	-	0.00	0.00	-	-
	MHD67	1.95	-	0.00	-	-
	Urban Bus	2.07	-	0.00	0.00	-
School Bus	LHD45	-	0.00	0.00	-	-
	MHD67	1.54	0.00	0.00	-	-
	HHD8	1.63	-	0.00	0.00	-
Refuse Truck	MHD67	2.10	0.00	0.00	-	-
	HHD8	2.18	-	0.00	0.00	-
Single Unit Short-haul Truck	LHD45	1.03	0.00	0.00	-	-
	MHD67	1.53	0.00	0.00	-	-
	HHD8	1.87	-	0.00	0.00	-
Single Unit Long-haul Truck	LHD45	0.96	0.00	0.00	-	-
	MHD67	1.43	0.00	0.00	-	-

MOVES Source Type	Regulatory Class	Diesel	Gasoline	Electricity	CNG	Hydrogen
	HHD8	1.74	-	0.00	0.00	-
Combination Short-haul Truck	MHD67	2.05	-	0.00	-	0.00
	HHD8	2.17	-	0.00	0.00	0.00
Combination Long-haul Truck	MHD67	2.03	-	0.00	-	0.00
	HHD8	2.06	-	0.00	0.00	0.00

* Values rounded to the nearest hundredth of a cent; blank values represent cases where a given MOVES source type and regulatory class did not use a specific fuel type.

Table 3-45 DEF Cost Per Mile for Model Year 2032 Vehicles from Calendar Year 2032 to 2055 for each MOVES Source Type and Regulatory Class by Fuel Type for the Final Standards* (cents/mile in 2022 dollars, 7% discounting)

MOVES Source Type	Regulatory Class	Diesel	Gasoline	Electricity	CNG	Hydrogen
Other Buses	LHD45	-	0.00	0.00	-	-
	MHD67	1.15	-	0.00	-	-
	HHD8	1.30	-	0.00	0.00	0.00
Transit Bus	LHD45	-	0.00	0.00	-	-
	MHD67	1.17	-	0.00	-	-
	Urban Bus	1.24	-	0.00	0.00	-
School Bus	LHD45	-	0.00	0.00	-	-
	MHD67	0.91	0.00	0.00	-	-
	HHD8	0.96	-	0.00	0.00	-
Refuse Truck	MHD67	1.28	0.00	0.00	-	-
	HHD8	1.33	-	0.00	0.00	-
Single Unit Short-haul Truck	LHD45	0.65	0.00	0.00	-	-
	MHD67	0.97	0.00	0.00	-	-
	HHD8	1.18	-	0.00	0.00	-
Single Unit Long-haul Truck	LHD45	0.62	0.00	0.00	-	-
	MHD67	0.93	0.00	0.00	-	-
	HHD8	1.12	-	0.00	0.00	-
Combination Short-haul Truck	MHD67	1.32	-	0.00	-	0.00
	HHD8	1.40	-	0.00	0.00	0.00
Combination Long-haul Truck	MHD67	1.26	-	0.00	-	0.00
	HHD8	1.29	-	0.00	0.00	0.00

* Values rounded to the nearest hundredth of a cent; blank values represent cases where a given MOVES source type and regulatory class did not use a specific fuel type.

The DEF cost per mile for MY 2027 from Calendar Year 2027 to 2055 across all vehicle fuel types, as well as the change in cost relative to the reference case for the final standards and alternative cases, are shown in Table 3-46, Table 3-47, and Table 3-48 for the 2-percent, 3-percent and 7-percent discounting cases, respectively. The retail fuel cost per mile for MY 2030 from Calendar Year 2030 to 2055 across all vehicle fuel types, as well as the change in cost relative to the reference case for the final standards and alternative cases, are shown in Table 3-49, Table 3-50, and Table 3-51for the 2-percent, 3-percent and 7-percent discounting cases, respectively. The retail fuel cost per mile for MY 2032 from Calendar Year 2032 to 2055 across all vehicle fuel types, as well as the change in cost relative to the reference case for the final standards and alternative cases, are shown in Table 3-52, Table 3-53, and Table 3-54 for the 2-percent, 3-percent and 7-percent discounting cases, respectively. When considering the DEF costs per vehicle between scenarios, the impacts show no impact or a cost savings for both the final standards and alternative cases for nearly every MOVES source type and regulatory class.

Table 3-46 DEF Cost Per Mile for Model Year 2027 Vehicles from Calendar Year 2027 to 2055 for each MOVES Source Type and Regulatory Class Across All Fuel Types* (cents/mile in 2022 dollars, 2% discounting)

MOVES Source Type	Regulatory Class	Cost in Reference	Cost in Final Standards	Cost in Alternative	Final Standards Change from Reference	Alternative Change from Reference
Other Buses	LHD45	0.0	0.0	0.0	0.0	0.0
	MHD67	2.2	2.0	2.1	-0.2	-0.1
	HHD8	2.0	2.0	2.0	0.0	0.0
Transit Bus	LHD45	0.0	0.0	0.0	0.0	0.0
	MHD67	2.2	2.1	2.1	-0.1	0.0
	Urban Bus	2.1	2.1	2.1	0.0	0.0
School Bus	LHD45	0.0	0.0	0.0	0.0	0.0
	MHD67	1.5	1.3	1.4	-0.2	-0.1
	HHD8	1.7	1.7	1.7	0.0	0.0
Refuse Truck	MHD67	2.3	2.0	2.1	-0.3	-0.2
	HHD8	2.2	2.2	2.2	0.0	0.0
Single Unit Short-haul Truck	LHD45	0.7	0.6	0.6	-0.1	0.0
	MHD67	1.3	1.2	1.3	-0.1	0.0
	HHD8	2.0	2.0	2.0	0.0	0.0
Single Unit Long-haul Truck	LHD45	0.6	0.6	0.6	0.0	0.0
	MHD67	1.2	1.1	1.2	-0.1	0.0
	HHD8	1.8	1.8	1.8	0.0	0.0
Combination Short-haul Truck	MHD67	2.3	2.2	2.3	0.0	0.0
	HHD8	2.4	2.4	2.4	0.0	0.0
Combination Long-haul Truck	MHD67	2.4	2.4	2.4	0.0	0.0
	HHD8	2.4	2.4	2.4	0.0	0.0

* Values rounded to the nearest tenth of a cent; negative values denote lower costs, i.e., savings in expenditures.

Table 3-47 DEF Cost Per Mile for Model Year 2027 Vehicles from Calendar Year 2027 to 2055 for each MOVES Source Type and Regulatory Class Across All Fuel Types* (cents/mile in 2022 dollars, 3% discounting)

MOVES Source Type	Regulatory Class	Cost in Reference	Cost in Final Standards	Cost in Alternative	Final Standards Change from Reference	Alternative Change from Reference
Other Buses	LHD45	0.0	0.0	0.0	0.0	0.0
	MHD67	2.0	1.8	1.9	-0.1	-0.1
	HHD8	1.9	1.9	1.9	0.0	0.0

MOVES Source Type	Regulatory Class	Cost in Reference	Cost in Final Standards	Cost in Alternative	Final Standards Change from Reference	Alternative Change from Reference
Transit Bus	LHD45	0.0	0.0	0.0	0.0	0.0
	MHD67	2.0	1.9	2.0	-0.1	0.0
	Urban Bus	1.9	1.9	1.9	0.0	0.0
School Bus	LHD45	0.0	0.0	0.0	0.0	0.0
	MHD67	1.4	1.2	1.3	-0.2	-0.1
	HHD8	1.5	1.5	1.5	0.0	0.0
Refuse Truck	MHD67	2.1	1.8	1.9	-0.3	-0.2
	HHD8	2.0	2.0	2.0	0.0	0.0
Single Unit Short-haul Truck	LHD45	0.6	0.6	0.6	-0.1	0.0
	MHD67	1.2	1.1	1.2	-0.1	0.0
	HHD8	1.8	1.8	1.8	0.0	0.0
Single Unit Long-haul Truck	LHD45	0.6	0.6	0.6	0.0	0.0
	MHD67	1.1	1.1	1.1	-0.1	0.0
	HHD8	1.7	1.7	1.7	0.0	0.0
Combination Short-haul Truck	MHD67	2.1	2.1	2.1	0.0	0.0
	HHD8	2.2	2.2	2.2	0.0	0.0
Combination Long-haul Truck	MHD67	2.2	2.2	2.2	0.0	0.0
	HHD8	2.2	2.2	2.2	0.0	0.0

* Values rounded to the nearest tenth of a cent; negative values denote lower costs, i.e., savings in expenditures.

Table 3-48 DEF Cost Per Mile for Model Year 2027 Vehicles from Calendar Year 2027 to 2055 for each MOVES Source Type and Regulatory Class Across All Fuel Types* (cents/mile in 2022 dollars, 7% discounting)

MOVES Source Type	Regulatory Class	Cost in Reference	Cost in Final Standards	Cost in Alternative	Final Standards Change from Reference	Alternative Change from Reference
Other Buses	LHD45	0.0	0.0	0.0	0.0	0.0
	MHD67	1.4	1.3	1.3	-0.1	0.0
	HHD8	1.3	1.3	1.3	0.0	0.0
Transit Bus	LHD45	0.0	0.0	0.0	0.0	0.0
	MHD67	1.4	1.4	1.4	0.0	0.0
	Urban Bus	1.3	1.3	1.3	0.0	0.0
School Bus	LHD45	0.0	0.0	0.0	0.0	0.0
	MHD67	1.0	0.8	0.9	-0.1	-0.1
	HHD8	1.1	1.1	1.1	0.0	0.0
Refuse Truck	MHD67	1.5	1.3	1.4	-0.2	-0.1
	HHD8	1.5	1.5	1.5	0.0	0.0
Single Unit Short-haul Truck	LHD45	0.5	0.4	0.4	0.0	0.0
	MHD67	0.9	0.9	0.9	0.0	0.0
	HHD8	1.4	1.4	1.4	0.0	0.0
	LHD45	0.4	0.4	0.4	0.0	0.0
	MHD67	0.9	0.8	0.8	-0.1	0.0

MOVES Source Type	Regulatory Class	Cost in Reference	Cost in Final Standards	Cost in Alternative	Final Standards Change from Reference	Alternative Change from Reference
Single Unit Long-haul Truck	HHD8	1.3	1.3	1.3	0.0	0.0
Combination Short-haul Truck	MHD67	1.7	1.6	1.7	0.0	0.0
	HHD8	1.7	1.7	1.7	0.0	0.0
Combination Long-haul Truck	MHD67	1.6	1.6	1.6	0.0	0.0
	HHD8	1.7	1.7	1.7	0.0	0.0

* Values rounded to the nearest tenth of a cent; negative values denote lower costs, i.e., savings in expenditures.

Table 3-49 DEF Cost Per Mile for Model Year 2030 Vehicles from Calendar Year 2030 to 2055 for each MOVES Source Type and Regulatory Class Across All Fuel Types* (cents/mile in 2022 dollars, 2% discounting)

MOVES Source Type	Regulatory Class	Cost in Reference	Cost in Final Standards	Cost in Alternative	Final Standards Change from Reference	Alternative Change from Reference
Other Buses	LHD45	0.0	0.0	0.0	0.0	0.0
	MHD67	1.9	1.9	1.9	0.0	0.0
	HHD8	1.9	1.9	1.9	0.0	0.0
Transit Bus	LHD45	0.0	0.0	0.0	0.0	0.0
	MHD67	1.9	1.9	1.9	0.0	0.0
	Urban Bus	1.9	1.8	1.9	-0.1	0.0
School Bus	LHD45	0.0	0.0	0.0	0.0	0.0
	MHD67	1.3	1.0	1.1	-0.3	-0.2
	HHD8	1.6	1.4	1.5	-0.2	-0.1
Refuse Truck	MHD67	2.0	1.8	1.9	-0.2	-0.1
	HHD8	2.1	1.8	1.9	-0.2	-0.2
Single Unit Short-haul Truck	LHD45	0.6	0.5	0.5	-0.1	-0.1
	MHD67	1.1	1.1	1.1	0.0	0.0
	HHD8	1.8	1.8	1.8	-0.1	0.0
Single Unit Long-haul Truck	LHD45	0.5	0.5	0.5	0.0	0.0
	MHD67	1.1	1.0	1.0	-0.1	0.0
	HHD8	1.7	1.6	1.7	-0.1	0.0
Combination Short-haul Truck	MHD67	2.1	2.0	2.0	-0.1	0.0
	HHD8	2.2	2.0	2.0	-0.2	-0.1
Combination Long-haul Truck	MHD67	2.3	2.2	2.2	-0.1	-0.1
	HHD8	2.3	2.2	2.2	-0.1	-0.1

* Values rounded to the nearest tenth of a cent; negative values denote lower costs, i.e., savings in expenditures.

Table 3-50 DEF Cost Per Mile for Model Year 2030 Vehicles from Calendar Year 2030 to 2055 for each MOVES Source Type and Regulatory Class Across All Fuel Types* (cents/mile in 2022 dollars, 3% discounting)

MOVES Source Type	Regulatory Class	Cost in Reference	Cost in Final Standards	Cost in Alternative	Final Standards Change from Reference	Alternative Change from Reference
Other Buses	LHD45	0.0	0.0	0.0	0.0	0.0
	MHD67	1.6	1.6	1.6	0.0	0.0
	HHD8	1.7	1.7	1.7	0.0	0.0
Transit Bus	LHD45	0.0	0.0	0.0	0.0	0.0
	MHD67	1.7	1.7	1.7	0.0	0.0
	Urban Bus	1.7	1.6	1.7	-0.1	0.0
School Bus	LHD45	0.0	0.0	0.0	0.0	0.0
	MHD67	1.2	0.9	1.0	-0.3	-0.2
	HHD8	1.4	1.2	1.3	-0.2	-0.1
Refuse Truck	MHD67	1.8	1.6	1.7	-0.2	-0.1
	HHD8	1.8	1.6	1.7	-0.2	-0.1
Single Unit Short-haul Truck	LHD45	0.5	0.4	0.4	-0.1	0.0
	MHD67	1.0	1.0	1.0	0.0	0.0
	HHD8	1.6	1.6	1.6	-0.1	0.0
Single Unit Long-haul Truck	LHD45	0.5	0.5	0.5	0.0	0.0
	MHD67	1.0	0.9	0.9	-0.1	0.0
	HHD8	1.5	1.5	1.5	-0.1	0.0
Combination Short-haul Truck	MHD67	1.9	1.8	1.9	-0.1	0.0
	HHD8	2.0	1.8	1.9	-0.2	-0.1
Combination Long-haul Truck	MHD67	2.0	2.0	2.0	-0.1	0.0
	HHD8	2.1	2.0	2.0	-0.1	-0.1

* Values rounded to the nearest tenth of a cent; negative values denote lower costs, i.e., savings in expenditures.

Table 3-51 DEF Cost Per Mile for Model Year 2030 Vehicles from Calendar Year 2030 to 2055 for each MOVES Source Type and Regulatory Class Across All Fuel Types* (cents/mile in 2022 dollars, 7% discounting)

MOVES Source Type	Regulatory Class	Cost in Reference	Cost in Final Standards	Cost in Alternative	Final Standards Change from Reference	Alternative Change from Reference
Other Buses	LHD45	0.0	0.0	0.0	0.0	0.0
	MHD67	1.0	1.0	1.0	0.0	0.0
	HHD8	1.1	1.1	1.1	0.0	0.0
Transit Bus	LHD45	0.0	0.0	0.0	0.0	0.0
	MHD67	1.1	1.1	1.1	0.0	0.0
	Urban Bus	1.1	1.0	1.1	-0.1	0.0
School Bus	LHD45	0.0	0.0	0.0	0.0	0.0
	MHD67	0.7	0.6	0.6	-0.2	-0.1
	HHD8	0.9	0.8	0.8	-0.1	0.0

MOVES Source Type	Regulatory Class	Cost in Reference	Cost in Final Standards	Cost in Alternative	Final Standards Change from Reference	Alternative Change from Reference
Refuse Truck	MHD67	1.1	1.0	1.1	-0.1	-0.1
	HHD8	1.2	1.0	1.1	-0.1	-0.1
Single Unit Short-haul Truck	LHD45	0.3	0.3	0.3	0.0	0.0
	MHD67	0.7	0.7	0.7	0.0	0.0
	HHD8	1.1	1.1	1.1	0.0	0.0
Single Unit Long-haul Truck	LHD45	0.3	0.3	0.3	0.0	0.0
	MHD67	0.7	0.6	0.7	0.0	0.0
	HHD8	1.1	1.0	1.1	0.0	0.0
Combination Short-haul Truck	MHD67	1.3	1.3	1.3	-0.1	0.0
	HHD8	1.4	1.2	1.3	-0.1	-0.1
Combination Long-haul Truck	MHD67	1.4	1.3	1.3	0.0	0.0
	HHD8	1.4	1.3	1.3	0.0	0.0

* Values rounded to the nearest tenth of a cent; negative values denote lower costs, i.e., savings in expenditures.

Table 3-52 DEF Cost Per Mile for Model Year 2032 Vehicles from Calendar Year 2032 to 2055 for each MOVES Source Type and Regulatory Class Across All Fuel Types* (cents/mile in 2022 dollars, 2% discounting)

MOVES Source Type	Regulatory Class	Cost in Reference	Cost in Final Standards	Cost in Alternative	Final Standards Change from Reference	Alternative Change from Reference
Other Buses	LHD45	0.0	0.0	0.0	0.0	0.0
	MHD67	1.8	1.8	1.8	0.0	0.0
	HHD8	1.9	1.9	1.9	0.0	0.0
Transit Bus	LHD45	0.0	0.0	0.0	0.0	0.0
	MHD67	1.8	1.7	1.8	0.0	0.0
	Urban Bus	1.9	1.3	1.8	-0.6	-0.1
School Bus	LHD45	0.0	0.0	0.0	0.0	0.0
	MHD67	1.3	0.5	0.9	-0.8	-0.4
	HHD8	1.5	1.1	1.4	-0.5	-0.1
Refuse Truck	MHD67	1.9	1.5	1.8	-0.4	-0.1
	HHD8	2.0	1.4	1.7	-0.6	-0.2
Single Unit Short-haul Truck	LHD45	0.5	0.2	0.4	-0.3	-0.1
	MHD67	1.1	0.9	1.1	-0.2	0.0
	HHD8	1.8	1.4	1.7	-0.3	-0.1
Single Unit Long-haul Truck	LHD45	0.5	0.4	0.5	-0.1	0.0
	MHD67	1.0	0.8	1.0	-0.2	0.0
	HHD8	1.6	1.1	1.5	-0.5	-0.2
Combination Short-haul Truck	MHD67	2.0	1.6	1.9	-0.4	-0.1
	HHD8	2.1	1.3	1.8	-0.8	-0.3
	MHD67	2.1	1.7	1.9	-0.4	-0.2

MOVES Source Type	Regulatory Class	Cost in Reference	Cost in Final Standards	Cost in Alternative	Final Standards Change from Reference	Alternative Change from Reference
Combination Long-haul Truck	HHD8	2.2	1.8	2.0	-0.4	-0.2

* Values rounded to the nearest tenth of a cent; negative values denote lower costs, i.e., savings in expenditures.

Table 3-53 DEF Cost Per Mile for Model Year 2032 Vehicles from Calendar Year 2032 to 2055 for each MOVES Source Type and Regulatory Class Across All Fuel Types* (cents/mile in 2022 dollars, 3% discounting)

MOVES Source Type	Regulatory Class	Cost in Reference	Cost in Final Standards	Cost in Alternative	Final Standards Change from Reference	Alternative Change from Reference
Other Buses	LHD45	0.0	0.0	0.0	0.0	0.0
	MHD67	1.5	1.5	1.5	0.0	0.0
	HHD8	1.6	1.6	1.6	0.0	0.0
Transit Bus	LHD45	0.0	0.0	0.0	0.0	0.0
	MHD67	1.5	1.5	1.5	0.0	0.0
	Urban Bus	1.6	1.1	1.5	-0.5	-0.1
School Bus	LHD45	0.0	0.0	0.0	0.0	0.0
	MHD67	1.1	0.4	0.8	-0.7	-0.3
	HHD8	1.3	0.9	1.2	-0.4	-0.1
Refuse Truck	MHD67	1.6	1.3	1.6	-0.4	0.0
	HHD8	1.7	1.2	1.5	-0.5	-0.2
Single Unit Short-haul Truck	LHD45	0.5	0.2	0.4	-0.2	-0.1
	MHD67	1.0	0.8	0.9	-0.2	0.0
	HHD8	1.6	1.3	1.5	-0.3	-0.1
Single Unit Long-haul Truck	LHD45	0.4	0.4	0.4	-0.1	0.0
	MHD67	0.9	0.7	0.8	-0.2	0.0
	HHD8	1.5	1.0	1.3	-0.4	-0.2
Combination Short-haul Truck	MHD67	1.8	1.5	1.7	-0.3	-0.1
	HHD8	1.9	1.2	1.6	-0.7	-0.3
Combination Long-haul Truck	MHD67	1.9	1.5	1.7	-0.3	-0.2
	HHD8	1.9	1.5	1.7	-0.4	-0.2

* Values rounded to the nearest tenth of a cent; negative values denote lower costs, i.e., savings in expenditures.

Table 3-54 DEF Cost Per Mile for Model Year 2032 Vehicles from Calendar Year 2032 to 2055 for each MOVES Source Type and Regulatory Class Across All Fuel Types* (cents/mile in 2022 dollars, 7% discounting)

MOVES Source Type	Regulatory Class	Cost in Reference	Cost in Final Standards	Cost in Alternative	Final Standards Change from Reference	Alternative Change from Reference
Other Buses	LHD45	0.0	0.0	0.0	0.0	0.0
	MHD67	0.9	0.9	0.9	0.0	0.0
	HHD8	0.9	0.9	0.9	0.0	0.0
Transit Bus	LHD45	0.0	0.0	0.0	0.0	0.0
	MHD67	0.9	0.9	0.9	0.0	0.0
	Urban Bus	1.0	0.7	0.9	-0.3	-0.1
School Bus	LHD45	0.0	0.0	0.0	0.0	0.0
	MHD67	0.7	0.2	0.5	-0.4	-0.2
	HHD8	0.8	0.6	0.7	-0.2	-0.1
Refuse Truck	MHD67	1.0	0.8	1.0	-0.2	0.0
	HHD8	1.0	0.7	0.9	-0.3	-0.1
Single Unit Short-haul Truck	LHD45	0.3	0.1	0.2	-0.1	-0.1
	MHD67	0.6	0.5	0.6	-0.1	0.0
	HHD8	1.0	0.8	0.9	-0.2	0.0
Single Unit Long-haul Truck	LHD45	0.3	0.2	0.3	0.0	0.0
	MHD67	0.6	0.4	0.6	-0.1	0.0
	HHD8	0.9	0.7	0.8	-0.3	-0.1
Combination Short-haul Truck	MHD67	1.2	0.9	1.1	-0.2	0.0
	HHD8	1.2	0.8	1.0	-0.4	-0.2
Combination Long-haul Truck	MHD67	1.2	0.9	1.1	-0.2	-0.1
	HHD8	1.2	1.0	1.1	-0.2	-0.1

* Values rounded to the nearest tenth of a cent; negative values denote lower costs, i.e., savings in expenditures.

The number of diesel vehicles decrease in the final standards case compared to the reference case therefore the total DEF costs for all vehicles are less in final standards case when computed on an annual basis. Similarly for the alternative, there number of diesel vehicles decrease in the alternative compared to the reference case, but to a lesser extent than in the final standards. Table 3-55 and Table 3-56 show the annual savings associated with less DEF consumption in the final standards and alternative relative to the reference case, respectively. Note that non-diesel vehicles are shown for completeness with no savings since those vehicles do not consume DEF.

Table 3-55 Annual Undiscounted DEF Costs for the Final Standards relative to the Reference Case, Millions of 2022 dollars*

Calendar Year	Diesel	Gasoline	CNG	Electricity	Hydrogen	Sum
2027	-$6	$0	$0	$0	$0	-$6
2028	-$17	$0	$0	$0	$0	-$17
2029	-$32	$0	$0	$0	$0	-$32
2030	-$61	$0	$0	$0	$0	-$61
2031	-$130	$0	$0	$0	$0	-$130
2032	-$250	$0	$0	$0	$0	-$250
2033	-$380	$0	$0	$0	$0	-$380
2034	-$500	$0	$0	$0	$0	-$500
2035	-$630	$0	$0	$0	$0	-$630
2036	-$740	$0	$0	$0	$0	-$740
2037	-$860	$0	$0	$0	$0	-$860
2038	-$960	$0	$0	$0	$0	-$960
2039	-$1,100	$0	$0	$0	$0	-$1,100
2040	-$1,200	$0	$0	$0	$0	-$1,200
2041	-$1,200	$0	$0	$0	$0	-$1,200
2042	-$1,300	$0	$0	$0	$0	-$1,300
2043	-$1,400	$0	$0	$0	$0	-$1,400
2044	-$1,400	$0	$0	$0	$0	-$1,400
2045	-$1,500	$0	$0	$0	$0	-$1,500
2046	-$1,500	$0	$0	$0	$0	-$1,500
2047	-$1,600	$0	$0	$0	$0	-$1,600
2048	-$1,600	$0	$0	$0	$0	-$1,600
2049	-$1,600	$0	$0	$0	$0	-$1,600
2050	-$1,700	$0	$0	$0	$0	-$1,700
2051	-$1,700	$0	$0	$0	$0	-$1,700
2052	-$1,700	$0	$0	$0	$0	-$1,700
2053	-$1,800	$0	$0	$0	$0	-$1,800
2054	-$1,800	$0	$0	$0	$0	-$1,800
2055	-$1,800	$0	$0	$0	$0	-$1,800

* Values rounded to two significant digits; Negative values denote lower costs, i.e., savings in expenditures.

Table 3-56 Annual Undiscounted DEF Costs for the Alternative relative to the Reference Case, Millions of 2022 dollars*

Calendar Year	Diesel	Gasoline	CNG	Electricity	Hydrogen	Sum
2027	-$3	$0	$0	$0	$0	-$3
2028	-$7	$0	$0	$0	$0	-$7
2029	-$15	$0	$0	$0	$0	-$15
2030	-$35	$0	$0	$0	$0	-$35
2031	-$68	$0	$0	$0	$0	-$68
2032	-$120	$0	$0	$0	$0	-$120
2033	-$170	$0	$0	$0	$0	-$170
2034	-$210	$0	$0	$0	$0	-$210
2035	-$260	$0	$0	$0	$0	-$260
2036	-$300	$0	$0	$0	$0	-$300
2037	-$340	$0	$0	$0	$0	-$340
2038	-$370	$0	$0	$0	$0	-$370
2039	-$410	$0	$0	$0	$0	-$410
2040	-$440	$0	$0	$0	$0	-$440
2041	-$460	$0	$0	$0	$0	-$460
2042	-$480	$0	$0	$0	$0	-$480
2043	-$500	$0	$0	$0	$0	-$500
2044	-$520	$0	$0	$0	$0	-$520
2045	-$530	$0	$0	$0	$0	-$530
2046	-$540	$0	$0	$0	$0	-$540
2047	-$550	$0	$0	$0	$0	-$550
2048	-$550	$0	$0	$0	$0	-$550
2049	-$560	$0	$0	$0	$0	-$560
2050	-$560	$0	$0	$0	$0	-$560
2051	-$570	$0	$0	$0	$0	-$570
2052	-$570	$0	$0	$0	$0	-$570
2053	-$570	$0	$0	$0	$0	-$570
2054	-$580	$0	$0	$0	$0	-$580
2055	-$580	$0	$0	$0	$0	-$580

* Values rounded to two significant digits; Negative values denote lower costs, i.e., savings in expenditures.

3.4.7.3 Costs Associated with Maintenance and Repair

We assessed the estimated maintenance and repair costs of all vehicles for the reference case, the alternative case and the final standards case under the potential compliance pathway, and compared these estimates with estimated maintenance and repair costs for all vehicles in the baseline on an annual basis. After consideration of comments, we have reduced the maintenance and repair costs for vocational ICE vehicles in the final rule. This change led to a decrease in the M&R costs of the BEVs and FCEVs accordingly, as explained below. Also explained below, we made further changes to M&R costs for BEVs and FCEVs in the early years of the Phase 3 program such that the M&R savings do not accrue as quickly as they did in our NPRM analysis. The results of our analysis show that maintenance and repair costs associated with HD BEVs and FCEVs are estimated to be lower than maintenance and repair costs associated with comparable ICE vehicles.

For the estimate of maintenance and repair costs for diesel-fueled ICE vehicles, we relied on the research compiled by Burnham et al. 2021, in Chapter 3.5.5 of "Comprehensive Total Cost of

Ownership Quantification for Vehicles with Different Size Classes and Powertrains" and used equations found in the BEAN model, as discussed in RIA Chapter 2.3.4.2.[1335,1336] Burnham et al. used data from Utilimarc and ATRI to estimate maintenance and repair costs per mile for multiple heavy-duty vehicle categories over time. Equation 3-1 is the curve Burnham et al. used to estimate cost per mile as a function of age and vehicle type. In the NPRM, we used two different curves, one for long-haul tractors and the other for vocational vehicles. As discussed in RIA Chapter 2.3.4.2, for the final rule we selected the semi-tractor curve to represent all HD vehicles used in Burnham et al., which leads to an overall reduction in M&R costs for all vocational vehicles (ICE vehicle, BEV, and FCEV). Table 3-57 shows the slope and intercept used in Equation 3-1 for each vehicle type. The slope and intercept values were converted to from 2019 to 2022 dollars in Table 3-57. We assumed that gasoline and CNG vehicles had the same maintenance and repair costs curves as diesel vehicles.

As discussed in RIA Chapter 2.4.4.1 and 2.5.3.2, several literature sources propose multiplying diesel vehicle maintenance costs by a factor to estimate BEV and FCEV maintenance costs. For the NPRM, we followed this approach and used scalars based on the research in Wang et al., 2022.[1337] In this final rule, EPA has phased in the BEV and FCEV scaling factors for maintenance and repair. Specifically, instead of applying a single scaling factor for every year commencing in 2027 as at proposal, EPA is starting with a higher scaling factor and gradually decreasing it (i.e., gradually increasing the projected cost savings) from calendar year 2027-2032. These changes are discussed in RIA Chapter 2.4.4.1 and 2.5.3.2. For the final rule, we used the scalars listed in Table 3-58 and slope and intercept listed in Table 3-57 in Equation 3-1 to compute the maintenance and repair costs on a per mile basis.

Equation 3-1 Maintenance and repair costs dollars per mile as a function of age and vehicle type

$$mr_{age} = scalar * (slope * age + intercept)$$

Where:

mr_{age} is the estimated maintenance and repair cost in dollars per mile at a given age

scalar is the value based on the vehicle type and calendar year

slope is from Table 3-57 (2022 dollars)

age is the current age of the vehicle

intercept is from Table 3-57 (2022 dollars)

[1335] Burnham, A., Gohlke, D., Rush, L., Stephens, T., Zhou, Y., Delucchi, M. A., Birky, A., Hunter, C., Lin, Z., Ou, S., Xie, F., Proctor, C., Wiryadinata, S., Liu, N., Boloor, M. "Comprehensive Total Cost of Ownership Quantification for Vehicles with Different Size Classes and Powertrains". Argonne National Laboratory. Chapter 3.5.5. April 1, 2021. Available at https://publications.anl.gov/anlpubs/2021/05/167399.pdf.

[1336] Argonne National Lab, Vehicle & Mobility Systems Group, BEAN, found at: https://vms.taps.anl.gov/tools/bean/ (accessed August 2022).

[1337] Wang, G., Miller, M., and Fulton, L." Estimating Maintenance and Repair Costs for Battery Electric and Fuel Cell Heavy Duty Trucks, 2022. Available online: https://escholarship.org/content/qt36c08395/qt36c08395_noSplash_589098e470b036b3010eae00f3b7b618.pdf?t=r6zwjb.

Table 3-57: Values for Determining Maintenance and Repair in Equation 3-1

Equation Parameter	2019 Dollars	2022 Dollars
Slope	0.03	0.033981
Intercept	0.11	0.124598

Table 3-58 Scalars of Maintenance and Repair based on Vehicle Fuel Type by Calendar Year

Vehicle Fuel Type	2027	2028	2029	2030	2031	2032	2033	2034	2035 and beyond
Diesel	1	1	1	1	1	1	1	1	1
Gasoline	1	1	1	1	1	1	1	1	1
CNG	1	1	1	1	1	1	1	1	1
Electricity	0.88	0.846	0.812	0.778	0.744	0.71	0.71	0.71	0.71
Hydrogen	1	1	1	1	0.95	0.9	0.85	0.8	0.75

For a given model year, Equation 3-1 was computed by from the for every year out to CY 2055 for each MOVES source type and fuel type to get an annual maintenance and repair cost per mile rate Each annual maintenance and repair cost by MOVES Source Type was computed for a single age (or calendar year) by multiplying that specific age's maintenance and repair cost per mile by VMT at that age. Then, we calculated the total maintenance and repair costs for each MOVES Source Type and regulatory class in by summing the cost for all years from the first calendar year of the vehicle to CY 2055. EPA divided the total maintenance and repair cost summed from the first calendar year of the vehicle to CY 2055 by the total VMT across from age 0 to CY 2055 for each MOVES Source Type.

Table 3-59, Table 3-60, and Table 3-61 show the computed maintenance and repair costs per mile for MY 2027 by MOVES source type for ICE vehicles compared to BEVs for the final standards for 2-percent, 3-percent and 7-percent discounting, respectively. Note that there are no FCEV modeled in MOVES until 2030, so there are no maintenance and repair costs for FCEV for MY2027 tables. Table 3-62, Table 3-63, and Table 3-64 show the computed maintenance and repair costs per mile for MY 2030 by MOVES source type for ICE vehicles compared to BEVs and FCEVs for the final standards at 2-percent, 3-percent and 7-percent discounting, respectively. Table 3-65, Table 3-66, and Table 3-67 show the computed maintenance and repair costs per mile for MY 2032 by MOVES source type for ICE vehicles compared to BEVs and FCEVs for the final standards at 2-percent, 3-percent and 7-percent discounting, respectively. For each MOVES source type, the cost of maintenance and repair per mile remained the same regardless of MOVES regulatory class and are reported by MOVES source type in Table 3-59 through Table 3-67.

A comparison of the maintenance and repair cost on a per mile basis for comparable ICE vehicles compared to BEVs are shown in Table 3-59 through Table 3-67 show the reduced cost of maintenance and repair for ZEVs compared to ICE vehicles.

The impacts of maintenance and repairs for MY 2027, 2030 and 2032 vehicles in each MOVES source type associated with reference, final standards, and alterative cases are shown for 2-percent, 3-percent and 7-percent discounting in Table 3-68 through Table 3-76. Both the final standards and alternative cases show either no change[1338] or reductions in maintenance and repair costs when compared to the reference case.

Table 3-59 Maintenance and Repair Per Mile for Model Year 2027 Vehicles from Calendar Year 2027 to 2055 for each MOVES Source Type and Regulatory Class by Fuel Type for the Final Standards* (cents/mile in 2022 dollars, 2% discounting)

MOVES Source Type	**ICE**	**BEV**
Other Buses	35.2	25.4
Transit Bus	34.4	24.9
School Bus	35.2	25.5
Refuse Truck	32.7	23.8
Single Unit Short-haul Truck	29.8	21.8
Single Unit Long-haul Truck	28.8	21.1
Combination Short-haul Truck	28.2	20.7
Combination Long-haul Truck	30.9	22.5

* Values rounded to the nearest tenth of a cent; All ICE vehicles (Diesel, Gasoline and CNG) had the same cost per mile for each source type. There are no MY 2027 FCEV.

Table 3-60 Maintenance and Repair Per Mile for Model Year 2027 Vehicles from Calendar Year 2027 to 2055 for each MOVES Source Type and Regulatory Class by Fuel Type for the Final Standards* (cents/mile in 2022 dollars, 3% discounting)

MOVES Source Type	**ICE**	**BEV**
Other Buses	30.7	22.3
Transit Bus	30.1	21.9
School Bus	30.7	22.3
Refuse Truck	29.1	21.2
Single Unit Short-haul Truck	26.9	19.8
Single Unit Long-haul Truck	26.1	19.2
Combination Short-haul Truck	25.7	19.0
Combination Long-haul Truck	27.7	20.3

* Values rounded to the nearest tenth of a cent; All ICE vehicles (Diesel, Gasoline and CNG) had the same cost per mile for each source type. There are no MY 2027 FCEV.

[1338] There are no changes to vehicle populations for MY 2027 between the final standards and reference cases for the MOVES source type of Combination Long-haul Truck, which is why the maintenance and repair cost per mile shows no change between the final standards and reference case in Table 3-68, Table 3-69, and Table 3-70.

Table 3-61 Maintenance and Repair Per Mile for Model Year 2027 Vehicles from Calendar Year 2027 to 2055 for each MOVES Source Type and Regulatory Class by Fuel Type for the Final Standards* (cents/mile in 2022 dollars, 7% discounting)

MOVES Source Type	ICE	BEV
Other Buses	19.0	13.9
Transit Bus	18.9	13.9
School Bus	19.0	13.9
Refuse Truck	19.1	14.0
Single Unit Short-haul Truck	18.7	13.9
Single Unit Long-haul Truck	18.5	13.8
Combination Short-haul Truck	18.5	13.8
Combination Long-haul Truck	18.8	13.9

* Values rounded to the nearest tenth of a cent; All ICE vehicles (Diesel, Gasoline and CNG) had the same cost per mile for each source type. There are no MY 2027 FCEV.

Table 3-62 Maintenance and Repair Per Mile for Model Year 2030 Vehicles from Calendar Year 2030 to 2055 for each MOVES Source Type and Regulatory Class by Fuel Type for the Final Standards* (cents/mile in 2022 dollars, 2% discounting)

MOVES Source Type	ICE	BEV	FCEV
Other Buses	32.4	23.1	25.0
Transit Bus	31.7	22.6	-
School Bus	32.4	23.1	-
Refuse Truck	30.6	21.8	-
Single Unit Short-haul Truck	28.0	20.0	-
Single Unit Long-haul Truck	26.8	19.2	-
Combination Short-haul Truck	26.4	18.9	20.8
Combination Long-haul Truck	28.9	20.6	22.5

* Values rounded to the nearest tenth of a cent; All ICE vehicles (Diesel, Gasoline and CNG) had the same cost per mile for each source type.

Table 3-63 Maintenance and Repair Per Mile for Model Year 2030 Vehicles from Calendar Year 2030 to 2055 for each MOVES Source Type and Regulatory Class by Fuel Type for the Final Standards* (cents/mile in 2022 dollars, 3% discounting)

MOVES Source Type	ICE	BEV	FCEV
Other Buses	27.7	19.7	21.4
Transit Bus	27.2	19.4	-
School Bus	27.7	19.7	-
Refuse Truck	26.5	18.9	-
Single Unit Short-haul Truck	24.6	17.5	-
Single Unit Long-haul Truck	23.7	17.0	-
Combination Short-haul Truck	23.5	16.8	18.6
Combination Long-haul Truck	25.2	18.0	19.7

* Values rounded to the nearest tenth of a cent; All ICE vehicles (Diesel, Gasoline and CNG) had the same cost per mile for each source type.

Table 3-64 Maintenance and Repair Per Mile for Model Year 2030 Vehicles from Calendar Year 2030 to 2055 for each MOVES Source Type and Regulatory Class by Fuel Type for the Final Standards* (cents/mile in 2022 dollars, 7% discounting)

MOVES Source Type	ICE	BEV	FCEV
Other Buses	15.6	11.2	12.2
Transit Bus	15.6	11.1	-
School Bus	15.6	11.2	-
Refuse Truck	15.6	11.2	-
Single Unit Short-haul Truck	15.3	11.0	-
Single Unit Long-haul Truck	15.2	10.9	-
Combination Short-haul Truck	15.2	10.9	12.1
Combination Long-haul Truck	15.4	11.0	12.2

* Values rounded to the nearest tenth of a cent; All ICE vehicles (Diesel, Gasoline and CNG) had the same cost per mile for each source type.

Table 3-65 Maintenance and Repair Per Mile for Model Year 2032 Vehicles from Calendar Year 2032 to 2055 for each MOVES Source Type and Regulatory Class by Fuel Type for the Final Standards* (cents/mile in 2022 dollars, 2% discounting)

MOVES Source Type	ICE	BEV	FCEV
Other Buses	30.5	21.6	23.1
Transit Bus	29.9	21.2	-
School Bus	30.5	21.7	-
Refuse Truck	29.0	20.6	-
Single Unit Short-haul Truck	26.6	18.9	-
Single Unit Long-haul Truck	25.5	18.1	-
Combination Short-haul Truck	25.2	17.9	19.3
Combination Long-haul Truck	27.5	19.5	20.9

* Values rounded to the nearest tenth of a cent; All ICE vehicles (Diesel, Gasoline and CNG) had the same cost per mile for each source type.

Table 3-66 Maintenance and Repair Per Mile for Model Year 2032 Vehicles from Calendar Year 2032 to 2055 for Each MOVES Source Type, ICE compared to BEV Costs for the Final Standards Case* (cents/mile in 2022 dollars, 3% discounting)

MOVES Source Type	ICE	BEV	FCEV
Other Buses	25.7	18.3	19.5
Transit Bus	25.3	18.0	-
School Bus	25.7	18.3	-
Refuse Truck	24.7	17.5	-
Single Unit Short-haul Truck	23.0	16.3	-
Single Unit Long-haul Truck	22.2	15.8	-
Combination Short-haul Truck	22.0	15.6	16.8
Combination Long-haul Truck	23.6	16.8	18.0

* Values rounded to the nearest tenth of a cent.

Table 3-67 Maintenance and Repair Per Mile for Model Year 2032 Vehicles Calendar Year 2032 to 2055 for Each MOVES Source Type, ICE to BEV for the Final Standards Case* (cents/mile in 2021 dollars, 7% discounting)

MOVES Source Type	ICE	BEV	FCEV
Other Buses	13.7	9.7	10.4
Transit Bus	13.6	9.7	-
School Bus	13.7	9.7	-
Refuse Truck	13.7	9.7	-
Single Unit Short-haul Truck	13.4	9.5	-
Single Unit Long-haul Truck	13.2	9.4	-
Combination Short-haul Truck	13.2	9.4	10.2
Combination Long-haul Truck	13.5	9.6	10.3

* Values rounded to the nearest tenth of a cent.

Table 3-68 Maintenance and Repair Per Mile for Model Year 2027 Vehicles from Calendar Year 2027 to 2055 for each MOVES Source Type and Regulatory Class Across All Fuel Types* (cents/mile in 2022 dollars, 2% discounting)

MOVES Source Type	Regulatory Class	Cost in Reference	Cost in Final Standards	Cost in Alternative	Final Standards Change from Reference	Alternative Change from Reference
Other Buses	LHD45	33.9	33.2	33.5	-0.6	-0.3
	MHD67	34.5	33.8	34.1	-0.7	-0.3
	HHD8	34.6	34.6	34.6	0.0	0.0
Transit Bus	LHD45	33.1	32.5	32.8	-0.6	-0.3
	MHD67	33.7	33.5	33.7	-0.3	0.0
	Urban Bus	33.8	33.8	33.8	0.0	0.0
School Bus	LHD45	34.0	33.2	33.6	-0.8	-0.5
	MHD67	34.5	33.2	33.7	-1.3	-0.8
	HHD8	34.6	34.6	34.6	0.0	0.0
Refuse Truck	MHD67	32.1	30.9	31.4	-1.1	-0.7
	HHD8	32.4	32.4	32.4	0.0	0.0
Single Unit Short-haul Truck	LHD45	29.0	28.2	28.5	-0.8	-0.6
	MHD67	29.3	28.8	29.1	-0.4	-0.2
	HHD8	29.5	29.5	29.5	0.0	0.0
Single Unit Long-haul Truck	LHD45	28.0	28.0	28.0	0.0	0.0
	MHD67	28.2	27.7	28.0	-0.5	-0.3
	HHD8	28.4	28.4	28.4	0.0	0.0
Combination Short-haul Truck	MHD67	27.8	27.6	27.8	-0.1	0.0
	HHD8	27.8	27.8	27.8	0.0	0.0
Combination Long-haul Truck	MHD67	30.8	30.8	30.8	0.0	0.0
	HHD8	30.8	30.8	30.8	0.0	0.0

* Values rounded to the nearest tenth of a cent; negative values denote lower costs, i.e., savings in expenditures.

Table 3-69 Maintenance and Repair Per Mile for Model Year 2027 Vehicles from Calendar Year 2027 to 2055 for each MOVES Source Type and Regulatory Class Across All Fuel Types* (cents/mile in 2022 dollars, 3% discounting)

MOVES Source Type	Regulatory Class	Cost in Reference	Cost in Final Standards	Cost in Alternative	Final Standards Change from Reference	Alternative Change from Reference
Other Buses	LHD45	29.6	29.0	29.3	-0.6	-0.3
	MHD67	30.1	29.5	29.8	-0.6	-0.3
	HHD8	30.2	30.2	30.2	0.0	0.0
Transit Bus	LHD45	29.0	28.5	28.8	-0.5	-0.3
	MHD67	29.6	29.3	29.5	-0.2	0.0
	Urban Bus	29.6	29.6	29.6	0.0	0.0
School Bus	LHD45	29.7	29.0	29.3	-0.7	-0.4
	MHD67	30.2	29.0	29.4	-1.1	-0.7
	HHD8	30.2	30.2	30.2	0.0	0.0
Refuse Truck	MHD67	28.5	27.5	27.9	-1.0	-0.6
	HHD8	28.8	28.8	28.8	0.0	0.0
Single Unit Short-haul Truck	LHD45	26.2	25.5	25.7	-0.7	-0.5
	MHD67	26.4	26.0	26.2	-0.4	-0.2
	HHD8	26.6	26.6	26.6	0.0	0.0
Single Unit Long-haul Truck	LHD45	25.4	25.4	25.4	0.0	0.0
	MHD67	25.6	25.1	25.4	-0.5	-0.2
	HHD8	25.8	25.8	25.8	0.0	0.0
Combination Short-haul Truck	MHD67	25.4	25.2	25.4	-0.1	0.0
	HHD8	25.4	25.4	25.4	0.0	0.0
Combination Long-haul Truck	MHD67	27.7	27.7	27.7	0.0	0.0
	HHD8	27.7	27.7	27.7	0.0	0.0

* Values rounded to the nearest tenth of a cent; negative values denote lower costs, i.e., savings in expenditures.

Table 3-70 Maintenance and Repair Per Mile for Model Year 2027 Vehicles from Calendar Year 2027 to 2055 for each MOVES Source Type and Regulatory Class Across All Fuel Types* (cents/mile in 2022 dollars, 7% discounting)

MOVES Source Type	Regulatory Class	Cost in Reference	Cost in Final Standards	Cost in Alternative	Final Standards Change from Reference	Alternative Change from Reference
Other Buses	LHD45	18.3	18.0	18.1	-0.3	-0.2
	MHD67	18.6	18.3	18.4	-0.3	-0.2
	HHD8	18.7	18.7	18.7	0.0	0.0
Transit Bus	LHD45	18.2	17.9	18.1	-0.3	-0.2
	MHD67	18.6	18.4	18.5	-0.1	0.0
	Urban Bus	18.6	18.6	18.6	0.0	0.0
School Bus	LHD45	18.4	18.0	18.1	-0.4	-0.3
	MHD67	18.6	18.0	18.2	-0.7	-0.4
	HHD8	18.7	18.7	18.7	0.0	0.0
Refuse Truck	MHD67	18.7	18.0	18.3	-0.6	-0.4
	HHD8	18.9	18.9	18.9	0.0	0.0
Single Unit Short-haul Truck	LHD45	18.2	17.7	17.9	-0.5	-0.3
	MHD67	18.4	18.1	18.2	-0.3	-0.1
	HHD8	18.5	18.5	18.5	0.0	0.0
Single Unit Long-haul Truck	LHD45	18.0	18.0	18.0	0.0	0.0
	MHD67	18.2	17.8	18.0	-0.3	-0.2
	HHD8	18.3	18.3	18.3	0.0	0.0
Combination Short-haul Truck	MHD67	18.3	18.2	18.3	-0.1	0.0
	HHD8	18.3	18.3	18.3	0.0	0.0
Combination Long-haul Truck	MHD67	18.8	18.8	18.8	0.0	0.0
	HHD8	18.8	18.8	18.8	0.0	0.0

* Values rounded to the nearest tenth of a cent; negative values denote lower costs, i.e., savings in expenditures.

Table 3-71 Maintenance and Repair Per Mile for Model Year 2030 Vehicles from Calendar Year 2030 to 2055 for each MOVES Source Type and Regulatory Class Across All Fuel Types* (cents/mile in 2022 dollars, 2% discounting)

MOVES Source Type	Regulatory Class	Cost in Reference	Cost in Final Standards	Cost in Alternative	Final Standards Change from Reference	Alternative Change from Reference
Other Buses	LHD45	29.3	29.1	29.3	-0.2	0.0
	MHD67	30.8	30.8	30.8	0.0	0.0
	HHD8	31.0	31.0	31.0	0.0	0.0
Transit Bus	LHD45	28.7	28.5	28.7	-0.2	0.0
	MHD67	30.1	30.1	30.1	0.0	0.0
	Urban Bus	30.4	29.9	30.3	-0.5	-0.1
School Bus	LHD45	29.7	29.1	29.4	-0.6	-0.3
	MHD67	30.9	29.0	29.5	-1.9	-1.4
	HHD8	31.1	30.3	30.8	-0.8	-0.4
Refuse Truck	MHD67	29.0	28.2	28.6	-0.7	-0.4
	HHD8	29.8	28.8	29.2	-1.0	-0.6
Single Unit Short-haul Truck	LHD45	26.0	25.1	25.4	-0.9	-0.6
	MHD67	26.6	26.4	26.6	-0.2	0.0
	HHD8	27.1	26.9	27.1	-0.3	-0.1
Single Unit Long-haul Truck	LHD45	25.0	25.0	25.0	0.0	0.0
	MHD67	25.5	25.1	25.4	-0.4	-0.1
	HHD8	26.0	25.8	26.0	-0.2	0.0
Combination Short-haul Truck	MHD67	25.8	25.5	25.6	-0.3	-0.1
	HHD8	25.8	25.1	25.3	-0.7	-0.5
Combination Long-haul Truck	MHD67	28.7	28.4	28.5	-0.3	-0.2
	HHD8	28.7	28.4	28.5	-0.3	-0.2

* Values rounded to the nearest tenth of a cent; negative values denote lower costs, i.e., savings in expenditures.

Table 3-72 Maintenance and Repair Per Mile for Model Year 2030 Vehicles from Calendar Year 2030 to 2055 for each MOVES Source Type and Regulatory Class Across All Fuel Types* (cents/mile in 2022 dollars, 3% discounting)

MOVES Source Type	Regulatory Class	Cost in Reference	Cost in Final Standards	Cost in Alternative	Final Standards Change from Reference	Alternative Change from Reference
Other Buses	LHD45	25.0	24.9	25.0	-0.2	0.0
	MHD67	26.3	26.3	26.3	0.0	0.0
	HHD8	26.5	26.5	26.5	0.0	0.0
Transit Bus	LHD45	24.6	24.4	24.6	-0.2	0.0
	MHD67	25.9	25.9	25.9	0.0	0.0
	Urban Bus	26.0	25.6	26.0	-0.4	-0.1
School Bus	LHD45	25.4	24.9	25.1	-0.5	-0.3
	MHD67	26.4	24.8	25.2	-1.6	-1.2
	HHD8	26.6	25.9	26.3	-0.7	-0.3
Refuse Truck	MHD67	25.1	24.5	24.8	-0.6	-0.3
	HHD8	25.8	24.9	25.2	-0.9	-0.6
Single Unit Short-haul Truck	LHD45	22.9	22.1	22.3	-0.8	-0.6
	MHD67	23.4	23.2	23.4	-0.2	0.0
	HHD8	23.9	23.6	23.8	-0.2	0.0
Single Unit Long-haul Truck	LHD45	22.1	22.1	22.1	0.0	0.0
	MHD67	22.6	22.2	22.4	-0.3	-0.1
	HHD8	23.0	22.8	23.0	-0.2	0.0
Combination Short-haul Truck	MHD67	22.9	22.6	22.8	-0.3	-0.1
	HHD8	22.9	22.3	22.5	-0.6	-0.4
Combination Long-haul Truck	MHD67	25.1	24.8	24.9	-0.3	-0.2
	HHD8	25.1	24.8	24.9	-0.3	-0.2

* Values rounded to the nearest tenth of a cent; negative values denote lower costs, i.e., savings in expenditures.

Table 3-73 Maintenance and Repair Per Mile for Model Year 2030 Vehicles from Calendar Year 2030 to 2055 for each MOVES Source Type and Regulatory Class Across All Fuel Types* (cents/mile in 2022 dollars, 7% discounting)

MOVES Source Type	**Regulatory Class**	**Cost in Reference**	**Cost in Final Standards**	**Cost in Alternative**	**Final Standards Change from Reference**	**Alternative Change from Reference**
Other Buses	LHD45	14.1	14.0	14.1	-0.1	0.0
	MHD67	14.8	14.8	14.8	0.0	0.0
	HHD8	15.0	15.0	15.0	0.0	0.0
Transit Bus	LHD45	14.1	14.0	14.1	-0.1	0.0
	MHD67	14.8	14.8	14.8	0.0	0.0
	Urban Bus	14.9	14.7	14.8	-0.2	0.0
School Bus	LHD45	14.3	14.0	14.2	-0.3	-0.1
	MHD67	14.9	14.0	14.2	-0.9	-0.7
	HHD8	15.0	14.6	14.8	-0.4	-0.2
Refuse Truck	MHD67	14.8	14.4	14.6	-0.4	-0.2
	HHD8	15.2	14.7	14.9	-0.5	-0.3
Single Unit Short-haul Truck	LHD45	14.2	13.8	13.9	-0.5	-0.3
	MHD67	14.6	14.4	14.6	-0.1	0.0
	HHD8	14.9	14.7	14.8	-0.2	0.0
Single Unit Long-haul Truck	LHD45	14.1	14.1	14.1	0.0	0.0
	MHD67	14.4	14.2	14.3	-0.2	-0.1
	HHD8	14.7	14.6	14.7	-0.1	0.0
Combination Short-haul Truck	MHD67	14.8	14.6	14.7	-0.2	-0.1
	HHD8	14.8	14.4	14.5	-0.4	-0.3
Combination Long-haul Truck	MHD67	15.3	15.2	15.2	-0.2	-0.1
	HHD8	15.3	15.2	15.2	-0.2	-0.1

* Values rounded to the nearest tenth of a cent; negative values denote lower costs, i.e., savings in expenditures.

Table 3-74 Maintenance and Repair Per Mile for Model Year 2032 Vehicles from Calendar Year 2032 to 2055 for each MOVES Source Type and Regulatory Class Across All Fuel Types* (cents/mile in 2022 dollars, 2% discounting)

MOVES Source Type	Regulatory Class	Cost in Reference	Cost in Final Standards	Cost in Alternative	Final Standards Change from Reference	Alternative Change from Reference
Other Buses	LHD45	27.0	24.6	26.7	-2.4	-0.2
	MHD67	28.6	28.6	28.6	0.0	0.0
	HHD8	29.0	29.0	29.0	0.0	0.0
Transit Bus	LHD45	26.4	24.1	26.2	-2.3	-0.2
	MHD67	28.1	28.0	28.1	-0.1	0.0
	Urban Bus	28.3	26.5	28.0	-1.8	-0.4
School Bus	LHD45	27.5	24.6	26.8	-2.8	-0.7
	MHD67	28.8	24.3	26.7	-4.5	-2.1
	HHD8	29.1	27.1	28.6	-2.0	-0.5
Refuse Truck	MHD67	27.1	25.7	26.9	-1.4	-0.2
	HHD8	28.1	25.7	27.1	-2.4	-1.0
Single Unit Short-haul Truck	LHD45	24.4	21.5	23.3	-2.9	-1.0
	MHD67	25.0	24.0	25.0	-1.1	-0.1
	HHD8	25.7	24.5	25.4	-1.2	-0.3
Single Unit Long-haul Truck	LHD45	23.4	22.6	23.4	-0.8	0.0
	MHD67	24.0	22.6	23.7	-1.4	-0.3
	HHD8	24.6	22.6	23.9	-2.0	-0.7
Combination Short-haul Truck	MHD67	24.4	23.2	24.2	-1.2	-0.2
	HHD8	24.5	21.9	23.5	-2.6	-1.0
Combination Long-haul Truck	MHD67	27.1	25.6	26.4	-1.5	-0.7
	HHD8	27.1	25.6	26.4	-1.5	-0.8

* Values rounded to the nearest tenth of a cent; negative values denote lower costs, i.e., savings in expenditures.

Table 3-75 Maintenance and Repair Per Mile for Model Year 2032 Vehicles from Calendar Year 2032 to 2055 for each MOVES Source Type and Regulatory Class Across All Fuel Types* (cents/mile in 2022 dollars, 3% discounting)

MOVES Source Type	Regulatory Class	Cost in Reference	Cost in Final Standards	Cost in Alternative	Final Standards Change from Reference	Alternative Change from Reference
Other Buses	LHD45	22.7	20.7	22.5	-2.0	-0.2
	MHD67	24.1	24.1	24.1	0.0	0.0
	HHD8	24.4	24.4	24.4	0.0	0.0
Transit Bus	LHD45	22.4	20.4	22.2	-2.0	-0.2
	MHD67	23.8	23.6	23.8	-0.1	0.0
	Urban Bus	24.0	22.4	23.7	-1.6	-0.3
School Bus	LHD45	23.1	20.8	22.6	-2.4	-0.6
	MHD67	24.3	20.5	22.5	-3.8	-1.8
	HHD8	24.5	22.8	24.1	-1.7	-0.4
Refuse Truck	MHD67	23.1	21.9	23.0	-1.2	-0.2
	HHD8	24.0	21.9	23.1	-2.0	-0.8
Single Unit Short-haul Truck	LHD45	21.0	18.6	20.2	-2.5	-0.9
	MHD67	21.6	20.7	21.6	-0.9	-0.1
	HHD8	22.2	21.1	22.0	-1.0	-0.2
Single Unit Long-haul Truck	LHD45	20.3	19.6	20.3	-0.7	0.0
	MHD67	20.9	19.7	20.6	-1.2	-0.2
	HHD8	21.4	19.7	20.8	-1.7	-0.6
Combination Short-haul Truck	MHD67	21.3	20.3	21.1	-1.1	-0.2
	HHD8	21.4	19.1	20.5	-2.2	-0.8
Combination Long-haul Truck	MHD67	23.3	22.0	22.7	-1.3	-0.6
	HHD8	23.3	22.0	22.7	-1.3	-0.7

* Values rounded to the nearest tenth of a cent; negative values denote lower costs, i.e., savings in expenditures.

Table 3-76 Maintenance and Repair Per Mile for Model Year 2032 Vehicles from Calendar Year 2032 to 2055 for each MOVES Source Type and Regulatory Class Across All Fuel Types* (cents/mile in 2022 dollars, 7% discounting)

MOVES Source Type	Regulatory Class	Cost in Reference	Cost in Final Standards	Cost in Alternative	Final Standards Change from Reference	Alternative Change from Reference
Other Buses	LHD45	12.1	11.1	12.0	-1.1	-0.1
	MHD67	12.9	12.9	12.9	0.0	0.0
	HHD8	13.0	13.0	13.0	0.0	0.0
Transit Bus	LHD45	12.1	11.0	11.9	-1.1	-0.1
	MHD67	12.8	12.8	12.8	-0.1	0.0
	Urban Bus	12.9	12.1	12.8	-0.8	-0.2
School Bus	LHD45	12.3	11.1	12.0	-1.3	-0.3
	MHD67	12.9	10.9	12.0	-2.0	-1.0
	HHD8	13.1	12.2	12.8	-0.9	-0.2
Refuse Truck	MHD67	12.8	12.1	12.7	-0.7	-0.1
	HHD8	13.2	12.1	12.8	-1.1	-0.5
Single Unit Short-haul Truck	LHD45	12.2	10.8	11.7	-1.4	-0.5
	MHD67	12.6	12.0	12.6	-0.6	0.0
	HHD8	12.9	12.3	12.8	-0.6	-0.1
Single Unit Long-haul Truck	LHD45	12.1	11.7	12.1	-0.4	0.0
	MHD67	12.5	11.8	12.3	-0.7	-0.1
	HHD8	12.8	11.8	12.4	-1.0	-0.4
Combination Short-haul Truck	MHD67	12.8	12.2	12.7	-0.6	-0.1
	HHD8	12.9	11.5	12.4	-1.3	-0.5
Combination Long-haul Truck	MHD67	13.3	12.6	12.9	-0.7	-0.4
	HHD8	13.3	12.6	12.9	-0.7	-0.4

* Values rounded to the nearest tenth of a cent; negative values denote lower costs, i.e., savings in expenditures.

Table 3-77 and Table 3-78 present the projected total maintenance and repair costs associated with the final standards and alternative, respectively. The total maintenance and repair costs are attributable to changes in new vehicle sales and vehicle populations. The maintenance and repair costs on a per vehicle basis are the same in the final standards and alternative, but as more HD ZEVs enter the HD fleet, the total maintenance and repair costs for the fleet of those vehicles correspondingly increases. The opposite is true for diesel, gasoline, and CNG vehicles as they phase out of the fleet such that the total maintenance and repair costs for the fleet of those vehicles decreases as more HD ZEVs enter the HD fleet.

Table 3-77 Annual Undiscounted Total Maintenance & Repair Costs for the Final Standards Relative to the Reference Case, Millions of 2022 dollars *

Calendar Year	Diesel Vehicles	Gasoline Vehicles	CNG Vehicles	BEVs	FCEVs	Total
2027	-$49	-$23	$0	$63	$0	-$9
2028	-$130	-$51	$0	$160	$0	-$28
2029	-$250	-$84	-$1	$280	$0	-$64
2030	-$480	-$120	-$2	$450	$24	-$130
2031	-$950	-$190	-$4	$790	$76	-$280
2032	-$1,800	-$310	-$7	$1,400	$190	-$580
2033	-$2,800	-$440	-$11	$2,100	$310	-$900
2034	-$4,000	-$570	-$15	$2,900	$450	-$1,300
2035	-$5,300	-$710	-$21	$3,800	$580	-$1,700
2036	-$6,700	-$850	-$26	$4,700	$750	-$2,200
2037	-$8,100	-$990	-$32	$5,600	$940	-$2,600
2038	-$9,500	-$1,100	-$39	$6,500	$1,100	-$3,000
2039	-$11,000	-$1,300	-$46	$7,400	$1,300	-$3,400
2040	-$12,000	-$1,400	-$53	$8,200	$1,500	-$3,900
2041	-$13,000	-$1,500	-$60	$9,100	$1,700	-$4,300
2042	-$15,000	-$1,600	-$67	$9,800	$1,800	-$4,600
2043	-$16,000	-$1,700	-$75	$11,000	$2,000	-$5,000
2044	-$17,000	-$1,800	-$82	$11,000	$2,200	-$5,300
2045	-$17,000	-$1,800	-$90	$12,000	$2,300	-$5,500
2046	-$18,000	-$1,900	-$97	$12,000	$2,400	-$5,700
2047	-$19,000	-$2,000	-$100	$12,000	$2,500	-$5,900
2048	-$19,000	-$2,000	-$110	$13,000	$2,600	-$6,100
2049	-$20,000	-$2,000	-$120	$13,000	$2,700	-$6,200
2050	-$20,000	-$2,100	-$130	$13,000	$2,800	-$6,400
2051	-$21,000	-$2,100	-$140	$14,000	$2,900	-$6,500
2052	-$21,000	-$2,200	-$150	$14,000	$2,900	-$6,600
2053	-$21,000	-$2,200	-$150	$14,000	$3,000	-$6,700
2054	-$22,000	-$2,200	-$160	$14,000	$3,100	-$6,800
2055	-$22,000	-$2,200	-$170	$14,000	$3,100	-$6,900

* Values rounded to two significant digits; negative values denote lower costs, i.e., savings in expenditures.

Table 3-78 Annual Undiscounted Total Maintenance & Repair Costs for the Alternative Relative to the Reference Case, Millions of 2022 dollars *

Calendar Year	Diesel Vehicles	Gasoline Vehicles	CNG Vehicles	BEVs	FCEVs	Total
2027	-$27	-$14	$0	$36	$0	-$5
2028	-$65	-$32	$0	$83	$0	-$15
2029	-$130	-$53	$0	$150	$0	-$35
2030	-$270	-$77	-$1	$260	$16	-$74
2031	-$510	-$110	-$1	$420	$49	-$150
2032	-$880	-$150	-$2	$650	$100	-$280
2033	-$1,300	-$190	-$4	$930	$160	-$410
2034	-$1,800	-$230	-$5	$1,200	$220	-$550
2035	-$2,300	-$260	-$7	$1,500	$290	-$720
2036	-$2,800	-$280	-$9	$1,800	$370	-$870
2037	-$3,300	-$300	-$11	$2,100	$450	-$1,000
2038	-$3,800	-$320	-$12	$2,400	$530	-$1,200
2039	-$4,200	-$330	-$14	$2,700	$620	-$1,300
2040	-$4,700	-$330	-$16	$2,900	$700	-$1,400
2041	-$5,100	-$330	-$18	$3,100	$780	-$1,500
2042	-$5,500	-$320	-$20	$3,300	$850	-$1,600
2043	-$5,800	-$300	-$22	$3,500	$920	-$1,700
2044	-$6,000	-$290	-$24	$3,600	$980	-$1,800
2045	-$6,200	-$270	-$26	$3,700	$1,000	-$1,800
2046	-$6,400	-$250	-$28	$3,700	$1,100	-$1,900
2047	-$6,500	-$230	-$29	$3,800	$1,100	-$1,900
2048	-$6,600	-$220	-$31	$3,800	$1,100	-$1,900
2049	-$6,700	-$200	-$33	$3,800	$1,200	-$2,000
2050	-$6,800	-$190	-$35	$3,900	$1,200	-$2,000
2051	-$6,900	-$180	-$37	$3,900	$1,300	-$2,000
2052	-$7,000	-$160	-$39	$3,900	$1,300	-$2,000
2053	-$7,000	-$150	-$41	$3,900	$1,300	-$2,000
2054	-$7,100	-$140	-$43	$3,900	$1,300	-$2,000
2055	-$7,100	-$130	-$45	$3,900	$1,300	-$2,000

* Values rounded to two significant digits; negative values denote lower costs, i.e., savings in expenditures.

3.4.7.4 Costs Associated with Insurance

As discussed in Preamble II.E.5, we did not take into account the cost of insurance on the user in the NPRM. A few commenters suggested we should consider the addition of insurance cost because the incremental cost of insurance for the ZEVs will be higher than ICE vehicles. We agree that insurance costs may differ between ICE vehicles and ZEVs and this is a cost that will be seen by the operator. Therefore, for the final rule analysis, we included the incremental insurance costs of a ZEV relative to a comparable ICE vehicle under the potential compliance pathway by incorporating an annual insurance cost equal to 3 percent of initial upfront vehicle technology RPE cost, as described in Section II.E.5 of the preamble. This annual cost was applied for each operating year of the vehicle.

To calculate the year over year insurance costs, EPA multiplied 3 percent of the initial vehicle technology package RPE by estimated sales for the final standards and reference cases, and continued the cost for each year that a vehicle operates. The difference between the final standards case and reference case as well as the alternative and reference case for insurance costs are shown on an annual basis for the entire fleet in Table 3-79.

Table 3-79 Annual Insurance Costs for the Final Standards and Alternative Relative to the Reference Case, Millions of 2022 Dollars*

Calendar Year	Final Standards Relative to Reference Case	Alternative Relative to Reference Case
2027	-$1.1	-$1.1
2028	-$5.4	-$4.0
2029	-$14	-$9.4
2030	-$18	-$12
2031	-$23	-$11
2032	-$20	-$7.1
2033	-$11	$0.44
2034	-$3.3	$8.5
2035	$1.8	$17
2036	$2.7	$25
2037	$3.4	$32
2038	-$1.4	$38
2039	-$7.7	$44
2040	-$15	$50
2041	-$26	$55
2042	-$38	$59
2043	-$49	$64
2044	-$63	$67
2045	-$78	$70
2046	-$93	$73
2047	-$110	$74
2048	-$130	$76
2049	-$140	$77
2050	-$160	$79
2051	-$180	$81
2052	-$190	$80
2053	-$210	$79
2054	-$230	$79
2055	-$250	$78
PV, 2%	-$1,300	$830
PV, 3%	-$1,000	$680
PV, 7%	-$460	$310
AV, 2%	-$60	$38
AV, 3%	-$55	$35
AV, 7%	-$38	$25

* Values show 2 significant digits; negative values denote lower costs, i.e., savings in expenditures.

3.4.7.5 Costs Associated with State Registration Fees on ZEVs

As discussed in Preamble II.E.5, we did not take into account the cost of state registration fees on ZEVs in the NPRM. Commenters suggested we should consider the addition of state registration fees on ZEVs because some states have adopted state ZEV registration fees in some cases to replace gasoline and diesel road tax revenue. Currently, many states do not have any additional registration fee for EVs. For the states that do, the registration fees are generally between $50 and $225 per year. While EPA cannot predict whether and to what extent other states will enact EV registration fees, we have nonetheless conservatively added an annual additional registration fee to all ZEV vehicles of $100 in our cost analysis. This annual cost was applied for each operating year of the vehicle. Table 3-80 shows the annual estimated state registration fees on BEVs on annual basis for both the final standards and alternative relative to the reference case.

Table 3-80 Annual State Registration Fees on ZEVs for the Final Standards and Alternative Relative to the Reference Case, Millions of 2022 Dollars*

Calendar Year	Final Standards Relative to Reference Case	Alternative Relative to Reference Case
2027	$2.6	$1.6
2028	$5.6	$3.3
2029	$8.9	$5.3
2030	$13	$7.8
2031	$22	$11
2032	$36	$16
2033	$49	$20
2034	$62	$24
2035	$74	$27
2036	$85	$29
2037	$97	$32
2038	$110	$34
2039	$120	$36
2040	$130	$37
2041	$140	$38
2042	$150	$40
2043	$160	$41
2044	$160	$42
2045	$170	$43
2046	$180	$44
2047	$190	$44
2048	$190	$45
2049	$200	$45
2050	$210	$46
2051	$210	$46
2052	$220	$46
2053	$220	$46
2054	$220	$46
2055	$230	$46
PV, 2%	$2,500	$660
PV, 3%	$2,100	$560
PV, 7%	$1,000	$300
AV, 2%	$110	$30
AV, 3%	$110	$29
AV, 7%	$85	$25

* Values show 2 significant digits.

3.4.7.6 Costs Associated with Battery Replacement and ICE Engine Rebuilding

As discussed in Preamble II.E.6, we did not take into account the cost of battery replacement and engine rebuild on the user in the NPRM. In the final rule, after consideration of comment, we added battery replacement and engine rebuild costs. Battery replacement and engine rebuild frequency and costs depend on MOVES vehicle source type and regulatory class. The BEV battery replacement and ICE engine rebuild cost and frequency of rebuild and replacement estimates on per vehicle basis are shown in Table 3-81.[1339]

To calculate the year over year battery replacement and ICE engine rebuild costs, EPA multiplied replacement RPE at the frequency shown for each MOVES source type and regulatory class in the lifetime year of replacement from Table 3-81 for each vehicle of the fleet that was still operating in their replacement year. Table 3-82 shows the annual estimated battery replacement and ICE engine rebuild costs on annual basis for both the final standards and alternative relative to the reference case.

[1339] Sanchez, James. Memorandum to docket EPA-HQ-OAR-2022-0985. "Estimating Battery Replacement and Engine Rebuild Costs". February 23, 2023.

Table 3-81 Battery Replacement and ICE Engine Rebuild Costs Frequency and Costs in 2022 Dollars

MOVES Source Type	MOVES Regulatory Class	Vehicle Type	Lifetime Year of Replacement	Replacement RPE
Other Buses	LHD45	BEV	15	$9,223
	MHD67		15	$14,576
Transit Bus	LHD45		15	$9,778
	MHD67		15	$17,389
	Urban Bus		15	$28,116
Refuse Truck	MHD67		15	$12,448
Combination Short-haul Truck	MHD67		15	$4,430
	HHD8		15	$3,725
Combination Long-haul Truck	HHD8		15	$22,126
Other Buses	LHD45	ICE Diesel	11	$7,175
	MHD67		14	$6,203
Transit Bus	LHD45		11	$7,175
	MHD67		14	$6,203
	Urban Bus		12	$6,953
Refuse Truck	MHD67		14	$6,203
Combination Short-haul Truck	MHD67		14	$6,203
	HHD8		12	$11,773
Combination Long-haul Truck	HHD8		12	$11,773
Other Buses	LHD45	ICE Gasoline	11	$7,175
	MHD67		11	$6,203
Transit Bus	LHD45		11	$7,175
	MHD67		11	$6,203
	Urban Bus		11	$6,953
Refuse Truck	MHD67		11	$6,203
Combination Short-haul Truck	MHD67		11	$6,953
	HHD8		11	$6,953
Combination Long-haul Truck	HHD8		11	$6,953
Other Buses	LHD45	ICE CNG	11	$7,175
	MHD67		14	$6,203
Transit Bus	LHD45		11	$7,175
	MHD67		14	$6,203
	Urban Bus		12	$6,953
Refuse Truck	MHD67		14	$6,203
Combination Short-haul Truck	MHD67		14	$6,203
	HHD8		12	$11,773
Combination Long-haul Truck	HHD8		12	$11,773

Table 3-82 Annual Battery Replacement and ICE Engine Rebuild Insurance Costs for the Final Standards and Alternative Relative to the Reference Case, Millions of 2022 Dollars*

Calendar Year	Final Standards Relative to Reference Case	Alternative Relative to Reference Case
2027	$0	$0
2028	$0	$0
2029	$0	$0
2030	$0	$0
2031	$0	$0
2032	$0	$0
2033	$0	$0
2034	$0	$0
2035	$0	$0
2036	$0	$0
2037	-$3.7	-$1.9
2038	-$2.9	-$1.0
2039	-$22	-$4.8
2040	-$47	-$27
2041	-$98	-$62
2042	-$210	-$110
2043	-$370	-$150
2044	-$340	-$120
2045	-$270	-$91
2046	-$150	-$51
2047	-$150	-$52
2048	-$150	-$52
2049	-$150	-$51
2050	-$150	-$50
2051	-$150	-$50
2052	-$150	-$50
2053	-$150	-$48
2054	-$150	-$46
2055	-$140	-$44
PV, 2%	-$1,900	-$710
PV, 3%	-$1,500	-$590
PV, 7%	-$720	-$280
AV, 2%	-$86	-$33
AV, 3%	-$80	-$31
AV, 7%	-$58	-$23

* Values show 2 significant digits; negative values denote lower costs, i.e., savings in expenditures.

3.4.7.7 Costs Associated with EVSE Replacement

As discussed in Preamble II.E.6, we did not take into account the cost of EVSE replacement on the user in the NPRM. In the final rule, after consideration of comment, we added EVSE replacement. There is limited data on the expected lifespan of charging infrastructure. We make the simplifying assumption that all depot EVSE ports have a 15-year equipment lifetime.[1340] After that, we assume they must be replaced at full cost. This assumption likely overestimates costs as some EVSE providers may opt to upgrade existing equipment rather than incur the cost of a full replacement. Some installation costs such as trenching or electrical upgrades may also not be needed for the replacement. Table 3-83 shows the annual estimated EVSE replacement costs on annual basis for both the final standards and alternative relative to the reference case.

Table 3-83 Annual EVSE Replacement Costs for the Final Standards and Alternative Relative to the Reference Case, Millions of 2022 Dollars*

Calendar Year	Final Standards Relative to Reference Case	Alternative Relative to Reference Case
2027	$0	$0
2028	$0	$0
2029	$0	$0
2030	$0	$0
2031	$0	$0
2032	$0	$0
2033	$0	$0
2034	$0	$0
2035	$0	$0
2036	$0	$0
2037	$0	$0
2038	$0	$0
2039	$0	$0
2040	$0	$0
2041	$370	$210
2042	$520	$240
2043	$610	$340
2044	$530	$300
2045	$1,100	$410
2046	$1,700	$520
2047	$1,600	$420
2048	$1,500	$320
2049	$1,300	$230
2050	$1,300	$210
2051	$1,300	$200
2052	$1,300	$180
2053	$1,300	$160
2054	$1,300	$140
2055	$1,300	$130
PV, 2%	$11,000	$2,700
PV, 3%	$8,700	$2,200
PV, 7%	$3,700	$1,000
AV, 2%	$500	$120
AV, 3%	$450	$110
AV, 7%	$300	$81

[1340] Borlaug, B., Salisbury, S., Gerdes, M., and Muratori, M. "Levelized Cost of Charging Electric Vehicles in the United States," 2020. Available online: *https://www.sciencedirect.com/science/article/pii/S2542435120302312?via%3Dihub*.

3.4.8 Analysis of Payback Periods

A payback period is the point in time at which savings from reduced operating expenses surpass increased upfront costs, typically estimated in years. The payback period for a new vehicle purchase is an important metric for many HD vehicle purchasers. In general, there is greater willingness to pay for new technology if that new technology "pays back" within an acceptable period of time. EPA calculated a payback period for each of the 101 example vehicles in HD TRUCS. These results are shown in RIA Chapter 2.9.2. We further calculated the average payback periods for the average of each regulatory group. These results are shown in RIA Chapter 2.10.6. Briefly, the incremental upfront costs for ZEVs are estimated in contrast to comparable ICE vehicles under the potential compliance pathway's technology packages. In these incremental upfront costs for ZEVs, EPA factors in the IRA battery and vehicle tax credits as discussed in RIA Chapter 3.3.2 and 3.4.2. Then EPA computed the expected operating costs differences between ZEV and ICE vehicles. When the operating cost savings offset the incremental upfront differences between ZEV and ICE vehicles, a breakeven point is met. The amount of time from purchase to the breakeven point is defined as the payback period.

3.5 Social Costs

To compute the social costs of the final standards, alternative and reference scenarios, we added the estimated total vehicle technology package RPE from Chapter 3.2.3, operating costs from Chapter 3.4.7, and total EVSE RPE from Chapter 3.4.3. All of the costs are computed for the MOVES final standards, alternative and reference cases and cost impacts are presented as the difference between the final standards and reference case or alternative and reference case. We note that the fuel costs in this subsection's social cost analysis are estimated pre-tax rather than what the purchaser will pay (i.e., the retail fuel price). In addition, the battery tax credit, vehicle tax credit, EVSE tax credit, excise tax, sales tax, and state registration fees on ZEVs, like fuel taxes, are treated as transfers and are not included in our social costs. We present transfers in Chapter 8.2 of this RIA.

3.5.1 Total Vehicle Technology Package RPE

Table 3-84 and Table 3-85 show the direct manufacturing costs, indirect costs, and total technology costs of the final standard and alternative options relative to the reference case. Values shown for a given calendar year are undiscounted values while discounted values are presented at 2-percent, 3-percent, and 7-percent discount rates. All values are shown in 2022 dollars.

Table 3-84 Total Package RPE Cost Impacts of the Final Standards Relative to the Reference Case, All Regulatory Classes and All Fuels, Millions of 2022 dollars*

Calendar Year	Direct Manufacturing Costs	Indirect Costs	Total Technology Package Costs
2027	$21	$9.0	$30
2028	-$9.7	-$4.1	-$14
2029	-$60	-$25	-$85
2030	$120	$49	$160
2031	$190	$79	$270
2032	$340	$140	$480
2033	$220	$91	$310
2034	$180	$76	$260
2035	$110	$47	$160
2036	$16	$6.80	$23
2037	-$18	-$7.50	-$25
2038	-$98	-$41	-$140
2039	-$160	-$69	-$230
2040	-$180	-$76	-$260
2041	-$230	-$98	-$330
2042	-$290	-$120	-$400
2043	-$280	-$120	-$390
2044	-$320	-$130	-$450
2045	-$360	-$150	-$510
2046	-$350	-$150	-$490
2047	-$370	-$160	-$530
2048	-$390	-$170	-$560
2049	-$420	-$180	-$590
2050	-$400	-$170	-$570
2051	-$420	-$180	-$590
2052	-$440	-$180	-$620
2053	-$450	-$190	-$640
2054	-$430	-$180	-$610
2055	-$420	-$170	-$590
PV, 2%	-$2,900	-$1,200	-$4,200
PV, 3%	-$2,300	-$950	-$3,200
PV, 7%	-$720	-$300	-$1,000
AV, 2%	-$130	-$56	-$190
AV, 3%	-$120	-$49	-$170
AV, 7%	-$59	-$25	-$83

* Values show 2 significant digits; negative values denote lower costs, i.e., savings in expenditures.

Table 3-85 Total Package RPE Cost Impacts of the Alternative Option Relative to the Reference Case, All Regulatory Classes and All Fuels, Millions of 2022 dollars*

Calendar Year	Direct Manufacturing Costs	Indirect Costs	Total Technology Package Costs
2027	$1.3	$0.53	$1.8
2028	-$23	-$9.5	-$32
2029	-$48	-$20	-$69
2030	$76	$32	$110
2031	$150	$62	$210
2032	$200	$83	$280
2033	$180	$74	$250
2034	$190	$79	$270
2035	$190	$82	$280
2036	$170	$71	$240
2037	$160	$69	$230
2038	$150	$61	$210
2039	$130	$57	$190
2040	$140	$57	$190
2041	$130	$55	$180
2042	$120	$49	$160
2043	$110	$47	$160
2044	$97	$41	$140
2045	$83	$35	$120
2046	$80	$34	$110
2047	$71	$30	$100
2048	$61	$26	$87
2049	$53	$22	$75
2050	$53	$22	$76
2051	$47	$20	$67
2052	$41	$17	$58
2053	$36	$15	$50
2054	$38	$16	$54
2055	$39	$16	$55
PV, 2%	$2,100	$880	$3,000
PV, 3%	$1,900	$780	$2,600
PV, 7%	$1,200	$490	$1,700
AV, 2%	$96	$40	$140
AV, 3%	$96	$40	$140
AV, 7%	$96	$40	$140

* Values show 2 significant digits; negative values denote lower costs, i.e., savings in expenditures.

3.5.2 Total EVSE RPE

Table 3-86 shows the EVSE cost in the reference, final standard and alternative cases, as well as the differences between the final standard and reference cases and the difference between the alternative and reference cases. Values shown for a given calendar year are undiscounted values while discounted values are presented at 2-percent, 3-percent, and 7-percent discount rates. All values are shown in 2022 dollars.

Table 3-86 Total EVSE Cost in the Reference, Final Standards, Alternative, Change between Final Standards and Reference Case, Change between Alternative and Reference Case; All Regulatory Classes and All Fuels, Millions of 2022 dollars*

Calendar Year	Cost in Reference	Cost in Final Standards	Cost in Alternative	Final Standards Change from Reference	Alternative Change from Reference
2027	$820	$1,300	$1,100	$440	$250
2028	$1,200	$1,800	$1,500	$610	$290
2029	$1,600	$2,300	$2,000	$730	$410
2030	$1,600	$2,300	$2,000	$630	$360
2031	$1,700	$3,000	$2,200	$1,300	$480
2032	$1,800	$3,800	$2,400	$2,000	$620
2033	$2,000	$3,900	$2,500	$1,900	$490
2034	$2,200	$3,900	$2,600	$1,700	$380
2035	$2,400	$4,000	$2,700	$1,600	$260
2036	$2,500	$4,100	$2,800	$1,600	$240
2037	$2,600	$4,100	$2,800	$1,500	$220
2038	$2,700	$4,200	$2,900	$1,500	$200
2039	$2,700	$4,300	$2,900	$1,500	$180
2040	$2,800	$4,300	$3,000	$1,500	$160
2041	$2,900	$4,400	$3,000	$1,500	$140
2042	$3,000	$4,400	$3,100	$1,400	$130
2043	$3,100	$4,500	$3,200	$1,400	$130
2044	$3,100	$4,500	$3,200	$1,400	$120
2045	$3,200	$4,500	$3,300	$1,400	$120
2046	$3,200	$4,600	$3,300	$1,300	$110
2047	$3,300	$4,600	$3,400	$1,300	$110
2048	$3,400	$4,600	$3,500	$1,300	$100
2049	$3,400	$4,700	$3,500	$1,300	$99
2050	$3,500	$4,800	$3,600	$1,200	$95
2051	$3,600	$4,800	$3,700	$1,200	$92
2052	$3,700	$4,900	$3,800	$1,200	$89
2053	$3,800	$5,000	$3,900	$1,200	$86
2054	$3,900	$5,000	$4,000	$1,200	$82
2055	$4,000	$5,100	$4,100	$1,100	$79
PV, 2%	$57,000	$86,000	$62,000	$28,000	$5,000
PV, 3%	$49,000	$74,000	$54,000	$25,000	$4,600
PV, 7%	$28,000	$44,000	$32,000	$15,000	$3,400
AV, 2%	$2,600	$3,900	$2,800	$1,300	$230
AV, 3%	$2,600	$3,800	$2,800	$1,300	$240
AV, 7%	$2,300	$3,600	$2,600	$1,300	$270

* Values show 2 significant digits; negative values denote lower costs, i.e., savings in expenditures.

3.5.3 Total Operating Cost

Table 3-87 and Table 3-88 show the total operating costs of the final standards case and alternative case relative to the reference case. Each table shows the operating costs for pre-tax fuel costs, DEF costs, maintenance and repair costs, insurance costs, battery replacement costs, EVSE replacement costs and the net operating cost. Values shown for a given calendar year are undiscounted values while discounted values are presented at 2-percent, 3-percent, and 7-percent discount rates. All values are shown in 2022 dollars.

Note that the fuel costs, DEF costs, and maintenance costs are shown as negative costs, or savings. This is expected as these costs are lower for BEVs and FCEVs and the final standards case (under the modeled potential compliance pathway) and alternative case include a greater number of BEVs and FCEVs than the reference case.

Table 3-87 Total Operating Cost Impacts of the Final Standards Relative to the Reference Case, All Regulatory Classes and All Fuels, Millions of 2022 dollars*

Calendar Year	Pre-Tax Fuel Costs	DEF Costs	Maintenance Costs	BEV Battery Replacement and ICE Engine Rebuild	Insurance	Total Operating Costs
2027	-$84	-$6.3	-$8.60	$0	-$1.1	-$100
2028	-$170	-$17	-$28	$0	-$5.4	-$220
2029	-$280	-$32	-$64	$0	-$14	-$390
2030	-$170	-$61	-$130	$0	-$18	-$380
2031	-$110	-$130	-$280	$0	-$23	-$540
2032	$37	-$250	-$580	$0	-$20	-$810
2033	$120	-$380	-$900	$0	-$11	-$1,200
2034	$170	-$500	-$1,300	$0	-$3.30	-$1,600
2035	$160	-$630	-$1,700	$0	$1.80	-$2,200
2036	$350	-$740	-$2,200	$0	$2.70	-$2,500
2037	$490	-$860	-$2,600	-$3.7	$3.40	-$3,000
2038	$640	-$960	-$3,000	-$2.9	-$1.40	-$3,300
2039	$810	-$1,100	-$3,400	-$22	-$7.70	-$3,700
2040	$980	-$1,200	-$3,900	-$47	-$15	-$4,100
2041	$990	-$1,200	-$4,300	-$98	-$26	-$4,300
2042	$1,100	-$1,300	-$4,600	-$210	-$38	-$4,600
2043	$1,100	-$1,400	-$5,000	-$370	-$49	-$5,100
2044	$1,200	-$1,400	-$5,300	-$340	-$63	-$5,400
2045	$1,200	-$1,500	-$5,500	-$270	-$78	-$5,100
2046	$880	-$1,500	-$5,700	-$150	-$93	-$4,900
2047	$800	-$1,600	-$5,900	-$150	-$110	-$5,400
2048	$670	-$1,600	-$6,100	-$150	-$130	-$5,800
2049	$540	-$1,600	-$6,200	-$150	-$140	-$6,300
2050	$430	-$1,700	-$6,400	-$150	-$160	-$6,600
2051	$420	-$1,700	-$6,500	-$150	-$180	-$6,800
2052	$410	-$1,700	-$6,600	-$150	-$190	-$7,000
2053	$390	-$1,800	-$6,700	-$150	-$210	-$7,100
2054	$370	-$1,800	-$6,800	-$150	-$230	-$7,300
2055	$350	-$1,800	-$6,900	-$140	-$250	-$7,400
PV, 2%	$9,500	-$21,000	-$73,000	-$1,900	-$1,300	-$76,000
PV, 3%	$7,900	-$17,000	-$60,000	-$1,500	-$1,000	-$63,000
PV, 7%	$3,900	-$8,700	-$30,000	-$720	-$460	-$32,000
AV, 2%	$430	-$950	-$3,300	-$86	-$60	-$3,500
AV, 3%	$410	-$900	-$3,100	-$80	-$55	-$3,300
AV, 7%	$310	-$710	-$2,400	-$58	-$38	-$2,600

* Values show 2 significant digits; negative values denote lower costs, i.e., savings in expenditures.

Table 3-88 Total Operating Cost Impacts of the Alternative Option Relative to the Reference Case, All Regulatory Classes and All Fuels, Millions of 2022 dollars*

Calendar Year	Pre-Tax Fuel Costs	DEF Costs	Maintenance Costs	BEV Battery Replacement and ICE Engine Rebuild	Insurance	Total Operating Costs
2027	-$50	-$3.2	-$5	$0	-$1.1	-$59
2028	-$97	-$7.3	-$15	$0	-$4	-$120
2029	-$160	-$15	-$35	$0	-$9.4	-$220
2030	-$94	-$35	-$74	$0	-$12	-$210
2031	-$13	-$68	-$150	$0	-$11	-$240
2032	$94	-$120	-$280	$0	-$7.1	-$310
2033	$190	-$170	-$410	$0	$0.44	-$380
2034	$280	-$210	-$550	$0	$8.5	-$470
2035	$350	-$260	-$720	$0	$17	-$600
2036	$510	-$300	-$870	$0	$25	-$630
2037	$650	-$340	-$1,000	-$1.9	$32	-$670
2038	$790	-$370	-$1,200	-$1.0	$38	-$710
2039	$930	-$410	-$1,300	-$4.8	$44	-$730
2040	$1,100	-$440	-$1,400	-$27	$50	-$760
2041	$1,100	-$460	-$1,500	-$62	$55	-$640
2042	$1,200	-$480	-$1,600	-$110	$59	-$670
2043	$1,300	-$500	-$1,700	-$150	$64	-$670
2044	$1,400	-$520	-$1,800	-$120	$67	-$670
2045	$1,400	-$530	-$1,800	-$91	$70	-$560
2046	$1,400	-$540	-$1,900	-$51	$73	-$520
2047	$1,400	-$550	-$1,900	-$52	$74	-$660
2048	$1,300	-$550	-$1,900	-$52	$76	-$800
2049	$1,300	-$560	-$2,000	-$51	$77	-$950
2050	$1,300	-$560	-$2,000	-$50	$79	-$1,000
2051	$1,300	-$570	-$2,000	-$50	$81	-$1,000
2052	$1,300	-$570	-$2,000	-$50	$80	-$1,100
2053	$1,300	-$570	-$2,000	-$48	$79	-$1,100
2054	$1,300	-$580	-$2,000	-$46	$79	-$1,100
2055	$1,300	-$580	-$2,000	-$44	$78	-$1,100
PV, 2%	$16,000	-$7,500	-$25,000	-$710	$830	-$13,000
PV, 3%	$13,000	-$6,200	-$21,000	-$590	$680	-$11,000
PV, 7%	$6,500	-$3,200	-$10,000	-$280	$310	-$6,100
AV, 2%	$750	-$340	-$1,100	-$33	$38	-$600
AV, 3%	$700	-$330	-$1,100	-$31	$35	-$580
AV, 7%	$530	-$260	-$850	-$23	$25	-$490

* Values show 2 significant digits; negative values denote lower costs, i.e., savings in expenditures.

3.5.4 Total Social Cost

Using the cost elements outlined in Chapters 3.2.3, 3.4.3, and 3.4.7, we have estimated the costs associated with the final rulemaking[1341]; costs associated with the final standards case and alternative case relative to the reference case are shown in Table 3-89 and Table 3-90, respectively. As noted earlier, costs are presented in 2022 dollars in undiscounted annual values

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[1341] More exactly, the estimated costs are for the potential compliance pathway we modeled to support the feasibility of the final standards.

along with net present values at 2-percent, 3-percent, and 7-percent discount rates with values discounted to the 2027 calendar year.

As shown in these tables, our analysis shows that the final standards scenario is estimated to have the lowest net costs, followed by the alternative and reference scenarios, respectively. The final standards case reflects the least costs because of the offsetting savings in fuel, repair and maintenance.

Table 3-89 Total Technology, Operating and EVSE Social Cost Impacts of the Final Standards Relative to the Reference Case, All Regulatory Classes and All Fuels, Millions of 2022 dollars*

Calendar Year	Total Technology Package Costs	Total Operating Costs	Total EVSE Costs	Sum
2027	$30	-$100	$440	$370
2028	-$14	-$220	$610	$380
2029	-$85	-$390	$730	$260
2030	$160	-$380	$630	$410
2031	$270	-$540	$1,300	$1,100
2032	$480	-$810	$2,000	$1,700
2033	$310	-$1,200	$1,900	$1,000
2034	$260	-$1,600	$1,700	$360
2035	$160	-$2,200	$1,600	-$450
2036	$23	-$2,500	$1,600	-$950
2037	-$25	-$3,000	$1,500	-$1,400
2038	-$140	-$3,300	$1,500	-$2,000
2039	-$230	-$3,700	$1,500	-$2,400
2040	-$260	-$4,100	$1,500	-$2,900
2041	-$330	-$4,300	$1,500	-$3,100
2042	-$400	-$4,600	$1,400	-$3,500
2043	-$390	-$5,100	$1,400	-$4,000
2044	-$450	-$5,400	$1,400	-$4,400
2045	-$510	-$5,100	$1,400	-$4,200
2046	-$490	-$4,900	$1,300	-$4,100
2047	-$530	-$5,400	$1,300	-$4,600
2048	-$560	-$5,800	$1,300	-$5,100
2049	-$590	-$6,300	$1,300	-$5,600
2050	-$570	-$6,600	$1,200	-$5,900
2051	-$590	-$6,800	$1,200	-$6,100
2052	-$620	-$7,000	$1,200	-$6,400
2053	-$640	-$7,100	$1,200	-$6,600
2054	-$610	-$7,300	$1,200	-$6,700
2055	-$590	-$7,400	$1,100	-$6,900
PV, 2%	-$4,200	-$76,000	$28,000	-$52,000
PV, 3%	-$3,200	-$63,000	$25,000	-$42,000
PV, 7%	-$1,000	-$32,000	$15,000	-$18,000
AV, 2%	-$190	-$3,500	$1,300	-$2,400
AV, 3%	-$170	-$3,300	$1,300	-$2,200
AV, 7%	-$83	-$2,600	$1,300	-$1,400

* Values show 2 significant digits; negative values denote lower costs, i.e., savings in expenditures.

Table 3-90 Total Technology, Operating and EVSE Social Cost Impacts of the Alternative Option Relative to the Reference Case, All Regulatory Classes and All Fuels, Millions of 2022 dollars*

Calendar Year	Total Technology Package Costs	Total Operating Costs	Total EVSE Costs	Sum
2027	$1.8	-$59	$250	$200
2028	-$32	-$120	$290	$130
2029	-$69	-$220	$410	$120
2030	$110	-$210	$360	$250
2031	$210	-$240	$480	$450
2032	$280	-$310	$620	$590
2033	$250	-$380	$490	$360
2034	$270	-$470	$380	$170
2035	$280	-$600	$260	-$66
2036	$240	-$630	$240	-$140
2037	$230	-$670	$220	-$220
2038	$210	-$710	$200	-$290
2039	$190	-$730	$180	-$350
2040	$190	-$760	$160	-$410
2041	$180	-$640	$140	-$310
2042	$160	-$670	$130	-$380
2043	$160	-$670	$130	-$380
2044	$140	-$670	$120	-$410
2045	$120	-$560	$120	-$320
2046	$110	-$520	$110	-$290
2047	$100	-$660	$110	-$460
2048	$87	-$800	$100	-$610
2049	$75	-$950	$99	-$780
2050	$76	-$1,000	$95	-$840
2051	$67	-$1,000	$92	-$880
2052	$58	-$1,100	$89	-$920
2053	$50	-$1,100	$86	-$960
2054	$54	-$1,100	$82	-$980
2055	$55	-$1,100	$79	-$1,000
PV, 2%	$3,000	-$13,000	$5,000	-$5,100
PV, 3%	$2,600	-$11,000	$4,600	-$3,800
PV, 7%	$1,700	-$6,100	$3,400	-$1,000
AV, 2%	$140	-$600	$230	-$230
AV, 3%	$140	-$580	$240	-$200
AV, 7%	$140	-$490	$270	-$83

* Values show 2 significant digits; negative values denote lower costs, i.e., savings in expenditures.

Chapter 4 Emission Inventories

4.1 Introduction

This chapter presents our analysis of the national emissions impacts of the final standards and the alternative (collectively referred to as control cases) relative to a baseline scenario that represents the U.S. without the final rule (referred to as the reference case). We estimated emission impacts for all calendar years from 2027 through 2055 from both downstream and some upstream sources. Downstream emissions are those emitted directly by a vehicle, including tailpipe and crankcase exhaust (from running, starts, or extended idle), evaporative emissions, refueling emissions, and particulate emissions from brake wear and tire wear. Upstream emissions are not emitted by the vehicle itself but can still be attributed to its operation. Examples include emissions from electricity generation for charging battery electric vehicles (BEVs), the creation of hydrogen fuel for fuel cell electric vehicles (FCEVs), the extracting and refining of crude, and the transporting of crude or refined fuels for internal combustion engine vehicles.

Our approach to modeling the emissions impacts of the final standards mirrors that of our proposal with some methodological updates. First, we estimated onroad downstream national inventories using an updated version of EPA's Motor Vehicle Emission Simulator (MOVES) model. The version of MOVES used for the emissions inventory modeling, MOVES4.R3,[1342] includes several updates from the latest widely available public version, MOVES4.0.0,[1343] which are discussed in Chapter 4.2. Second, we developed an updated reference case as described in Chapter 4.2.2. Third, we performed new power sector modeling runs to evaluate power sector emission impacts as described in 4.2.4. Fourth, we updated our refinery emission impacts methodology to better account for U.S. exports of gasoline and diesel, as described in 4.2.5.

In response to the proposal, several commenters noted that our reference case should quantitatively reflect not only the anticipated ZEV sales from the ACT rule in California and other states which have adopted it, but also ZEV adoption resulting from numerous other factors. The commenters specifically suggested to include: 1) state policies such as California's Advanced Clean Fleets[1344,1345] and Innovative Clean Transit[1346] rules and the NESCAUM MHD ZEV MOU[1347]; 2) manufacturer, fleet, and government commitments for producing and procuring ZEVs; 3) adoption for vehicles that reach cost parity with conventional vehicles; and

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[1342] Murray, Evan. Memorandum to Docket EPA-HQ-OAR-2022-0985. "MOVES4.R3". February 2024.

[1343] U.S. EPA. (2023). Motor Vehicle Emission Simulator: MOVES4. Office of Transportation and Air Quality. Available online: https://github.com/USEPA/EPA_MOVES_Model/releases/tag/MOVES4.0.0

[1344] California Air Resources Board. "Advanced Clean Fleets". Available online: https://ww2.arb.ca.gov/our-work/programs/advanced-clean-fleets

[1345] EPA received a waiver request under CAA section 209(b) and 209(e) from California for the ACF rule on November 15, 2023 (see *https://www.epa.gov/state-and-local-transportation/vehicle-emissions-california-waivers-and-authorizations#current*). EPA is currently reviewing the waiver request for the CA ACF rule. Because EPA action on California's waiver request is pending, we did not include the full effects of ACF in the reference case.

[1346] California Air Resources Board. "Innovative Clean Transit". Available online: https://ww2.arb.ca.gov/our-work/programs/innovative-clean-transit

[1347] NESCAUM MOU. "Multi-State Medium- and Heavy-Duty Zero Emission Vehicle Memorandum of Understanding." March 29, 2022. Available online: https://www.nescaum.org/documents/mhdv-zev-mou-20220329.pdf

4) the billions of dollars of programs to support HD ZEV deployment in the BIL and the IRA. We revised the reference case for this final rulemaking to include greater HD ZEV adoption than in the NPRM reference case, as described and explained in Chapter 4.2.2.

We also received comment questioning how many ZEVs will be sold nationwide as a result of ACT. Given the comments on variability in HD ZEV adoption projections absent the final standards, and the corresponding potential uncertainty in the reference case this variability implies, we also performed a sensitivity analysis using a reference case that has reduced HD ZEV adoption. We present this sensitivity analysis in Chapter 4.10.

In the NPRM analysis, we used identical rates of brake and tire wear (non-exhaust) particulate emissions for HD diesels and HD ZEVs. Some commenters requested that EPA model increased non-exhaust for HD ZEVs, relative to comparable ICE vehicles, and argued specifically that HD ZEVs should have increased tirewear emissions and therefore we should model higher non-exhaust for HD ZEVs versus comparable ICE vehicles.

Based on engineering principles, it would be reasonable to expect HD ZEVs to have offsetting trends in brakewear and tirewear emissions. On the one hand, ZEVs tend to be heavier than comparable ICE vehicles and have greater torque at low speeds, both of which are expected to increase tirewear emissions. On the other hand, ZEVs are often equipped with regenerative braking systems. When a vehicle is using regenerative brakes, some of the kinetic energy from slowing the vehicle is directed to the motor. In a friction braking system, this kinetic energy is normally converted to heat, so there is less material wear and emissions from brakes.

However, both of these expectations are based on engineering principles and are highly uncertain for several reasons. First, there is no data and little literature on the brakewear and tirewear emission rates of HD ZEVs specifically. Studies on non-exhaust emissions, including all of those cited by the commenters, focus on light-duty BEVs because those vehicles are greater in number and adoption. Second, the relationship between vehicle weight, torque, and braking systems on non-exhaust emission depends greatly on the vehicles engineering, especially on vehicle components such as the electric motor, axle configurations, tires, and brake systems. This important fact is recognized by all the literature sources cited by the commenters.

Given the uncertainty in projecting non-exhaust emissions from HD ZEVs, and the fact that it’s reasonable to project offsetting trends for brakewear and tirewear, we did not update our modeling of HD ZEV brakewear and tirewear emissions for the final rule. We discuss this in more detail in the Chapter 13 of the Response to Comments document. However, in response to these comments, we present downstream $PM_{2.5}$ emissions that include brakewear and tirewear more explicitly throughout this chapter of the RIA.

We model emissions from electricity generation units (EGUs) that result from increased energy demand from heavy-duty electric vehicles using the 2022 post-IRA version of the Integrated Planning Model (IPM), which is a linear programming model that forecasts EGU operation and emissions by calculating the most cost-effective way for the electricity generation and transmission system to meet its total demand. IPM accounts for many variables that impact the operation and emissions of EGUs, including total energy demand (including reserve requirements and peak load demand), planned EGU retirements, finalized rules that impact EGU operation, fuel prices, infrastructure buildout costs, and congressional action like the Inflation

Reduction Act.[1348] More details on IPM and the specific version used in this analysis can be found online[1349] and in the docket.[1350]

We received several comments on our EGU emissions modeling using IPM, specifically as it relates to modeling upstream emissions of FCEVs. In the NPRM, we assumed all hydrogen used for FCEVs would be produced via electrolysis of water using electricity from the grid and could therefore be entirely represented as additional demand to EGUs and modeled using IPM. We received several comments on our EGU emissions modeling using IPM, specifically as it relates to modeling upstream emissions of FCEVs. Many commenters noted that hydrogen in the U.S. today is primarily produced via steam methane reforming (SMR), for which there are associated pollutant emissions, and asserted that an analysis of upstream FCEV emissions which does not consider this fact would be incomplete. We maintain our approach from the NPRM for the final rulemaking analysis, as is discussed in Chapter 4.2.4.2.

In the final rule analysis, to address these comments we performed a comparative analysis that looks at the relative difference in emissions from various hydrogen fuel production pathways, including SMR. We compare emissions from these additional hydrogen production pathways to electrolysis to provide relative context for how emissions would differ under different scenarios in addition to the potential compliance pathway modeled for the final standards. This comparative analysis is discussed in detail in Chapter 4.8.

We modeled emissions from refineries by adjusting an existing refinery inventory to account for reduced domestic fuel demand driven by HD ZEV adoption under the potential compliance pathway in response to the final standards. The refinery inventory adjustments were developed using MOVES projections of liquid fuel demand for both the reference case and control cases.

In the NPRM analysis we assumed that 93 percent of the drop in domestic demand would be reflected in reduced refinery activity. We received several comments noting that, in response to lower domestic demand, U.S. refineries would increase exports and continue refining similar volumes of liquid fuels. After consideration of these comments, for the final rule, we projected that 50 percent of the drop in domestic demand would be reflected in reduced refinery activity. This is described in more detail in Chapter 4.2.5.

We received several comments on the scope of upstream emissions to be considered and estimated by EPA. We updated the modeling for the final rule to include the three most significant sectors in terms of understanding the impact of the standards on overall emissions (downstream, EGUs and refineries) in more detail than the proposal. We did not estimate impacts on emissions from other sectors with comparatively smaller potential impacts, like those

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[1348] The IRA contains a number of tax credit provisions that affect power sector operations. The 2022 post-IRA version of IPM models the following IRA provisions: the Clean Electricity Investment and Production Tax Credits (sections 13702 and 13701), the credit for Carbon Capture and Sequestration (section 13104), the Zero-Emission Nuclear Power Production Credit (section 13105), the Credit for the Production of Clean Hydrogen (section 13204), and the Advanced Manufacturing Production Tax Credit (section 13502). Thus, these IRA provisions are quantitatively reflected in our upstream modeling.

[1349] U.S. EPA. “Post-IRA 2022 Reference Case”. Power Sector Modeling. April 5, 2023. Available online: https://www.epa.gov/power-sector-modeling/post-ira-2022-reference-case

[1350] U.S. EPA. “Documentation for EPA’s Power Sector Modeling Platform v6 Using the Integrated Planning Model Post-IRA 2022 Reference Case”. March 2023. Available online: https://www.epa.gov/system/files/documents/2023-03/EPA%20Platform%20v6%20Post-IRA%202022%20Reference%20Case.pdf related to the extraction or transportation of fuels for either EGUs or refineries or the emissions from infrastructure buildout that may be necessary to support the level of HD ZEV adoption we model in the potential compliance pathway for the final standards. Detailed discussion of the comments we received on upstream modeling and our responses can be found in Chapter 13 of the RTC.

The downstream emission inventories were developed using a single national modeling domain (which includes the 50 U.S. states and the District of Columbia, but not any U.S. territories), referred to as national or default scale in MOVES. Our upstream emissions modeling also uses a single national modeling domain, so our estimated emissions impacts cover the full national inventory. Emissions impacts in other domains, such as particular regions or localities in the United States, are likely to differ from the impacts presented in this chapter. These impacts are discussed for the final standards in Chapters 4.3 (downstream emissions), 4.4 (upstream emissions), 4.5 (net emissions impacts), and 4.6 (cumulative GHG emissions impacts). Chapter 4.7 compares emission inventory impacts of the final standards and the alternative.

This chapter includes several sensitivity analyses and appendices. Chapter 4.8 presents our analysis of the upstream emissions impact of different hydrogen production pathways and Chapter 4.9 presents our analysis of refinery emissions impacts should refineries change exports in different ways than our main case analysis. To better understand and explain the differences in emission impact estimates between the NPRM and FRM, Chapter 4.10 presents a sensitivity analysis for a reference case which resembles the one we used in the NPRM and Chapter 4.11 directly compares the proposed and final standards based on our updated FRM modeling tools and methodologies.

Finally, Appendix B to this RIA contains detailed discussion of HD ZEV adoption rates and tables showing the ZEV adoption rates we model in MOVES for the reference and control cases.

4.2 Model Data and Methodologies

To quantify the emissions impacts of the final standards and the alternative, EPA developed an updated version of MOVES, called MOVES4.R3. Detailed descriptions of the underlying data and algorithms in MOVES are documented in technical reports that can be found online[1351] and in the docket.[1352] MOVES4.R3 and its supporting databases can also be found in the docket.[1342] Specific updates made to MOVES4.R3, relative to MOVES4.0.0, can be found in Chapter 4.2.1.

We used MOVES4.R3 to estimate the downstream emission impacts of the final standards and the alternative. First, we estimated emissions for the reference scenario that represents the U.S. without the final rule. Then we estimated emissions for the final standards (using the potential compliance pathway we modeled to support the feasibility of those standards) and separately estimated emissions for the alternative (collectively referred to as control cases). We calculated the emission reductions of both GHGs and non-GHGs for the control cases as the emission inventory difference between those cases and the reference case. All model inputs,

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[1351] U.S. EPA. “MOVES Onroad Technical Reports: MOVES4”. MOVES Onroad Technical Reports. August 2023.

[1352] Murray, Evan. Memorandum to Docket EPA-HQ-OAR-2022-0985. “MOVES4.0.0 Technical Reports”. February 2024.

MOVES run specification (runspec) files, scripts used for the analysis, and the version of MOVES used to generate the emissions inventories, are found in the docket.[1353]

The reference and control cases were run entirely using MOVES4.R3 default data except for HD ZEV populations. The reference case was run using the HD ZEV populations described in Chapter 4.2.2 and the control cases were run using the HD ZEV populations described in Chapter 4.2.3. Each heavy-duty ZEV sale added in both the reference and control cases beyond what is in the MOVES4.R3 default data is assumed to displace the sale of a comparable ICE vehicle, and we assume that no ICE fuel type (gasoline, diesel, or CNG) is more likely to be displaced than any other. All other activity inputs, including total VMT by source type, age distributions, road type distributions, vehicle speeds, off-network idling, hotelling, and starts were kept the same between the reference and the control cases. Emission rates and adjustments were kept the same as well, including energy consumption rates for all vehicle types. Finally, geographic fuels inputs were kept the same for the reference and control cases.

We used IPM to estimate the EGU emission impacts of the control cases. In the final rule analysis, we improved the estimates of EGU emissions by accounting for the IRA. It is worth noting that the ZEV adoption rates in the IPM runs are not identical to the ZEV adoption rates and energy demand for the reference and control cases described in Chapters 4.2.2 and 4.2.3. Chapter 4.2.4 contains detailed discussion of how we generated IPM inputs from MOVES and how we accounted for differences between IPM scenarios we modeled and the final control cases for this rulemaking.

Refineries are another upstream emissions source that we expect will be impacted by increased adoption of HD ZEVs. We developed a methodology to estimate the impact the final standards will have on emissions from refineries based on an existing refinery inventory from the emissions modeling platform,[1354,1355] projections of refining activity from the Energy Information Administration's (EIA) Annual Energy Outlook 2023 (AEO2023),[1356] and the fuel consumption output from the MOVES runs for each scenario. Chapter 4.2.5 contains a detailed discussion of the methodology we used to estimate the change in refinery emissions, including discussion of scenarios we explored regarding how U.S. refineries may change their exports in response to lower domestic demand.

4.2.1 Updates to MOVES4.R3

MOVES defines vehicles using a combination of source type and regulatory class, where source type roughly defines a vehicle's vocation or usage pattern, and regulatory class defines a vehicle's gross vehicle weight rating (GVWR) or weight class. Table 4-1 defines MOVES source types and Table 4-2 defines MOVES regulatory classes. In relation to the final standards, we

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[1353] Murray, Evan. Memorandum to Docket EPA-HQ-OAR-2022-0985. "MOVES Inputs and Post-Processing Materials: HD GHG Phase 3 FRM Modeling". March 2024.

[1354] The emissions modeling platform is a product of the National Emissions Inventory Collaborative consistent of more than 245 employees of state and regional air agencies, EPA, and Federal Land Management agencies. It includes a full suite of base year (2016) and projection year (2023 and 2028) emission inventories modeled using EPA's full suite of emissions modeling tools, including MOVES, SMOKE, and CMAQ.

[1355] U.S. EPA. "2016v3 Platform". September 22, 2023. Available online: https://www.epa.gov/air-emissions-modeling/2016v3-platform.

[1356] U.S. Energy Information Administration (EIA). "Annual Energy Outlook 2023". U.S. Department of Energy. March 16, 2023. Available online: https://www.eia.gov/outlooks/aeo/

synonymize combination short-haul tractors (MOVES source type 61) with day cabs and combination long-haul tractors (MOVES source type 62) with sleeper cabs.

Table 4-1 MOVES source type definitions

sourceTypeID	Source Type Description
11	Motorcycle
21	Passenger Car
31	Passenger Truck
32	Light Commercial Truck
41	Other Bus
42	Transit Bus
43	School Bus
51	Refuse Truck
52	Single Unit Short-haul Truck
53	Single Unit Long-haul Truck
54	Motor Home
61	Combination Short-haul Truck
62	Combination Long-haul Truck

Table 4-2 MOVES regulatory class definitions

regClassID	Regulatory Class Name	Regulatory Class Description and GVWR Range
10	MC	Motorcycle
20	LDV	Light Duty Vehicles
30	LDT	Light Duty Trucks
41	LHD2B3	Chassis-certified Class 2b and 3 Trucks 8,500 lbs < GVWR ≤ 14,000 lbs
42	LHD45	Class 4 and 5 Trucks and engine-certified Class 3 Trucks 14,000 lbs < GVWR ≤ 19,500 lbs
46	MHD67	Class 6 and 7 Trucks 19,500 lbs < GVWR ≤ 33,000 lbs
47	HHD8	Class 8a and 8b Trucks GVWR > 33,000 lbs
48	Urban Bus	Urban Bus (see 40 CFR 86.091-2)[1357]
49	Gliders	Glider Vehicles (see EPA-420-F-15-904)[1358]

MOVES4.R3 does not contain any major algorithmic changes or updates compared to MOVES4.0.0, making the models similar in terms of modeling capabilities and outputs. However, MOVES4.R3 includes a few data updates to better model the reference and control cases for this rulemaking.

MOVES4.R3 contains updated energy consumption rates for HD BEVs. MOVES calculates HD BEV energy consumption using the Energy Efficiency Ratio (EER) of a BEV to a diesel vehicle so that the energy consumption of a HD BEV can be calculated using diesel energy

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[1357] CFR part 86.091-2. Available online: https://www.govinfo.gov/content/pkg/CFR-1998-title40-vol12/pdf/CFR-1998-title40-vol12-sec86-091-2.pdf

[1358] U.S. EPA. “Frequently Asked Questions about Heavy-Duty ‘Glider Vehicles’ and ‘Glider Kits’. July 2015. Available online: https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100MUVI.PDF consumption rates, as shown in Equation 4-1. The EER for a BEV is generally greater than 1, indicating that BEVs are more energy efficient than their diesel counterparts.

Equation 4-1 Calculation of HD BEV energy consumption rates using Energy Efficiency Ratio (EER)

$$\text{Energy}_{\text{BEV}} = \frac{\text{Energy}_{\text{diesel}}}{\text{EER}}$$

MOVES4.R3 contains updated EERs based on our technology assessment in HD TRUCS[1359] that was discussed in Chapter 2. MOVES4.R3's updated EERs are specified by source type and regulatory class (Table 4-3), as opposed to being specific only by source type in the NPRM. EERs are only included for valid source type and regulatory class combinations in MOVES.

Table 4-3 MOVES4.R3 Energy Efficiency Ratios for HD BEVs

Source Type	LHD45 regClassID 42	MHD67 regClassID 46	HHD8 regClassID 47	Urban Bus regClassID 48
Other Buses sourceTypeID 41	4.24	3.85	2.71	
Transit Buses sourceTypeID 42	3.60	3.64	3.67	3.67
School Buses sourceTypeID 43	3.91	4.06	3.16	
Refuse Trucks sourceTypeID 51	3.85	3.85	3.71	
Single Unit Short-Haul Trucks sourceTypeID 52	3.80	3.46	3.03	
Single Unit Long-Haul Trucks sourceTypeID 53	3.49	2.93	2.40	
Motor Homes sourceTypeID 54	3.35	3.09	3.06	
Combination Short-Haul Trucks sourceTypeID 61		2.26	2.18	
Combination Long-Haul Trucks sourceTypeID 62		2.02	2.02	

Under this approach, even though the EERs stay constant for all model years, HD BEVs will see a similar level of increase in efficiency as their diesel counterparts from EPA's HD GHG Phase 2 rule, as well as associated aerodynamic improvements that we believe will apply to all engine technologies.

In addition, MOVES4.R3 contains an updated scaling factor used to calculate FCEV energy consumption from BEV energy consumption. This scaling factor incorporates all operational differences between the two vehicle types, including differences in energy conversion efficiency and other MOVES effects such as temperature and charging efficiency adjustments for BEVs. The FCEV:BEV scaling factor in MOVES4.R3 was updated to be 1.21 based on our technology assessment in HD TRUCS.

[1359] Heavy-Duty Technology Resource Use Case Scenario (HD TRUCS) is EPA's technology assessment tool for developing technology packages for the final standards. See RIA Chapter 2.

Overall, both the HD BEV EER update and the FCEV:BEV scaling factor update increase the overall energy efficiency of HD ZEVs of most vehicle types in MOVES4.R3 when compared to the proposal and MOVES4.0.0.

Lastly, MOVES4.R3 contains an update to energy consumption and CO_2 emission rates for light- and medium-duty ICE vehicles (regulatory classes 20, 30, and 41) to make it consistent with EPA's Optimization Model for reducing Emissions of Greenhouse Gases from Automobiles (OMEGA)[1360] modeling of previously finalized light-duty GHG rules.[1361] Overall, this decreases light- and medium-duty ICE energy demand and GHG emissions in both reference and control scenarios compared to MOVES4.0.0.

4.2.2 MOVES Inputs for the Reference Case

In modeling heavy-duty ZEV populations in the reference case, a scenario that represents the United States without the final standards, we considered several different factors related to purchaser acceptance of new technologies as discussed in RIA Chapter 2, along with three factors described below and in RIA Chapter 1. We also considered comments received from a variety of stakeholders.

First, the market has evolved such that early HD ZEV models are in use today for some applications and HD ZEVs are expected to expand to many more applications, as discussed in RIA Chapters 1.1, 1.5, and 1.7. Additionally, manufacturers have announced plans to rapidly increase their investments in ZEV technologies over the next decade. Second, the IRA and the BIL provide many monetary incentives for the production and purchase of ZEVs in the heavy-duty market, as well as incentives for electric vehicle charging infrastructure. Third, there have been actions by states to accelerate the adoption of heavy-duty ZEVs.

Absent the final standards, the State of California's Advanced Clean Trucks (ACT) program imposes minimum ZEV sales requirements beginning in model year 2024 in California and states that have adopted the program under CAA section 177. EPA granted the waiver of preemption for California's ACT rule waiver under CAA section 209(b) on March 30, 2023.[1362] As of the time of our inventory analysis, ACT had been adopted by seven other states under CAA section 177.[1363] Because ACT is an existing final rule that is enforceable in several states, it is one of our primary sources for determining the reference case ZEV adoption rates.

To calculate national ZEV adoption in the reference case, we developed HD ZEV adoption rates at the state level by splitting states into two groups. California and the seven states that have finalized adoption of ACT as of the time of our inventory analysis are referred to as ACT states,

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[1360] U.S. EPA. "Optimization Model for reducing Emissions of Greenhouse Gases from Automobiles (OMEGA)." Office of Transportation and Air Quality. Available online: https://www.epa.gov/regulations-emissions-vehicles-and-engines/optimization-model-reducing-emissions-greenhouse-gases#omega-2.1.0

[1361] 79 FR 23414 and 86 FR 74434.

[1362] 88 FR 20688. April 6, 2023. Available online: https://www.govinfo.gov/content/pkg/FR-2023-04-06/pdf/2023-07184.pdf

[1363] At the time we performed the inventory modeling analysis, seven states had adopted ACT in addition to California. Oregon, Washington, New York, New Jersey, and Massachusetts adopted ACT beginning in MY 2025 while Vermont adopted ACT beginning in MY 2026 and Colorado in MY 2027. Three other states, New Mexico, Maryland, and Rhode Island adopted ACT (beginning in MY 2027) in November and December of 2023, but there was not sufficient time for us to incorporate them as ACT states in our modeling.

and the remaining 42 states are referred to as non-ACT states.[1364] We created separate reference case scenarios for ACT and non-ACT states, and the resulting national adoption rates are the average of the two weighted by the portion of the heavy-duty vehicle sales[1365] they represent.

The adoption rates for ACT states are based on the ZEV adoption volumes required by the ACT rule, which are presented in Table 4-4.

Table 4-4 HD ZEV adoption rates in California's ACT rule

Model Year	Class 4-8 Vocational Vehicle Group[a] Source Types 41-54	Class 7-8 Tractors Group Source Types 61, 62
2024	9%	5%
2025	11%	7%
2026	13%	10%
2027	20%	15%
2028	30%	20%
2029	40%	25%
2030	50%	30%
2031	55%	35%
2032	60%	40%
2033	65%	40%
2034	70%	40%
2035 and beyond	75%	40%

[a] The ACT program includes ZEV adoption rates for a Class 2b-3 Vocational Vehicle Group, which we also included in our reference case modeling. However, we did not model the final standards as increasing ZEV adoption in this vehicle group, so they are not presented here. Class 2b-3 Vocational Vehicle Group ZEV adoption rates can be found in Appendix B to this RIA.

The adoption rates presented in Table 4-4 refer only to ACT's vehicle groupings which are less detailed than both MOVES vehicle types and the EPA regulatory categories and subcategories for HD vehicles. The ACT rule groups all Class 4–8 vocational vehicles together and all tractors together. Manufacturers must comply with the rule by ensuring that all deficits generated within the groups are offset by credits. For example, a manufacturer's fleet of Class 4–8 vocational vehicles could comply either by meeting the ZEV sales percentage requirement for the model year for all vehicle types within that group, or by generating credits from selling more ZEVs than required for some vehicles (e.g., Class 4 step vans) and using those credits to sell fewer ZEVs than required for others (e.g., Class 8 box trucks). In order to reflect this flexibility and some of the nuances of ZEV suitability for different vehicle types, we apportioned HD ZEV adoption by vehicle type in both ACT and non-ACT states in consideration of our technology assessment described in preamble Section II and RIA Chapter 2.

[1364] In this analysis, the states that adopted ACT via CAA section 177 are treated as non-ACT states until the model year in which ACT becomes effective. For example, Colorado is considered a non-ACT state for MYs prior to 2027, but an ACT state thereafter. New Mexico, Maryland, and Rhode Island are never treated as ACT states because they adopted ACT after most of our modeling was already complete.

[1365] We based the proportion of national HD by state on vehicle registration data in IHS2020, a source of vehicle registration data by county from IHS Markit. We used MY 2020 registrations because it was the most recent MY data available. However, the MY 2020 data set encompassed a partial year of registrations, so we also included MY 2019 registrations which cover the full year.

Our technology assessment shows that ZEV adoption is more likely for lighter vocational vehicles than for heavier ones. This consideration was factored into the ACT rule using weight class modifiers, which specify that Class 6–7 (MHD) vocational vehicles earn 1.5 times as many credits and deficits as Class 4–5 (LHD) vocational vehicles, and Class 8 (HHD) vocational vehicles earn two times as many credits and deficits as Class 4–5 (LHD) vocational vehicles.[1366] These ratios of 2 Class 4–5 to 1.5 Class 6–7 to 1 Class 8 are similar to our projected adoption rates of LHD, MHD, and HHD vocational ZEVs demonstrated in HD TRUCS for MYs 2027 and 2032 in the technology packages developed as a potential compliance pathway for the final rule, as discussed in preamble Section II and RIA Chapter 2. To apportion ZEV adoption for vocational vehicles by weight class, we assumed that the ZEV adoption rate for LHD vocational vehicles is double the adoption rate for HHD vocational vehicles and the adoption rate for MHD vocational vehicles is 1.5 times the adoption rate of HHD vocational vehicles. We used this assumption to calculate adoption rates of an ACT-compliant fleet of vocational vehicles in ACT states in every MY.

Similarly, our technology assessment suggests that ZEV adoption is more likely for day cab tractors than for sleeper cab tractors. We calculated an ACT-compliant fleet of tractors in ACT states by assuming that sleeper cab tractors achieve the ZEV adoption rates shown in our NPRM technology package, including a phase-in of 2 percent, 4 percent, and 7 percent ZEV adoption in MYs 2027, 2028, and 2029, respectively. We then calculated how many day cab tractor ZEVs would be needed for the tractors to comply as a group.

MOVES requires ZEV adoption rates to be specified by source type and regulatory class. For the purposes of incorporating our projected ACT-compliant adoption rates into MOVES, we calculated vocational vehicle adoption rates by regulatory class and applied the same adoption rate for all source types. We calculated tractor adoption rates by source type and applied the same adoption rate for all regulatory classes.

The ZEV adoption rates for ACT states are shown in Table 4-5. In general, we modeled all ZEV adoption as BEVs except for some HHD vocational vehicles, short-haul tractors, and long-haul tractors, which we modeled as FCEVs because they travel long distances and/or have heavy loads as discussed in RIA Chapter 2. As discussed in RIA Chapter 1.8, we considered FCEVs only in the MY 2030 and later timeframe to better ensure that we have provided adequate time for early-market hydrogen-infrastructure development. More details on the specific adoption rates used for constructing the reference case, by technology, regulatory class, and source type, can be found in Appendix B to this RIA.

[1366] All Class 4–8 vocational vehicles are grouped together to determine compliance with the ACT rule, so the result of the credits is that four sales of LHD vocational ZEVs or three sales of MHD vocational ZEVs could offset the sale two HHD vocational ZEVs.

Table 4-5 Reference case ZEV adoption rate for ACT states

Model Year	LHD Vocational	MHD Vocational	HHD Vocational	Short-Haul Tractors	Long-Haul Tractors
2024	11.6%	8.7%	5.8%	7.5%	0.0%
2025	14.1%	10.6%	7.1%	10.5%	0.0%
2026	16.7%	12.5%	8.3%	14.9%	0.0%
2027	25.6%	19.2%	12.8%	21.4%	2.0%
2028	38.5%	28.9%	19.2%	27.9%	4.0%
2029	51.2%	38.4%	25.6%	33.9%	7.0%
2030	63.7%	47.8%	31.8%	39.8%	10.0%
2031	69.8%	52.4%	34.9%	42.4%	20.0%
2032	76.1%	57.1%	38.0%	47.4%	25.0%
2033	82.4%	61.8%	41.2%	47.4%	25.0%
2034	88.6%	66.5%	44.3%	47.4%	25.0%
2035 and beyond[A]	94.8%	71.1%	47.4%	47.4%	25.0%

[A] Adoption rates in the vehicle categories shown can vary from model year to model year despite the overall level of ZEV adoption driven by emission standards remaining unchanged. This is because MOVES projects variations in vehicle sales by source type and regulatory class across model years. This can lead to small variations in adoption rates, within a few percent, over time as sales of some vehicle types increase and others decrease.

In developing the ZEV adoption rates for non-ACT states in the reference case, we used CALSTART's “Zeroing In On Zero-Emission Trucks, May 2023 Market Update” report that summarizes historical ZEV deployment for medium- and heavy-duty vehicles[1367] in all 50 states. It is the only data source we found that provides a quantitative, state-by-state assessment of HD ZEV adoption and therefore is the best source we can use to estimate future HD ZEV adoption at the state level.[1368] This allows us to compare ZEV adoption in non-ACT states relative to ACT states to calculate a sales ratio, which we then use to project ZEV adoption rates absent the final standards. Specifically, we calculate that for model years 2017–2022, non-ACT states have adopted 39.4 percent of medium- and heavy-duty ZEVs and ACT states have adopted 60.6 percent of medium- and heavy-duty ZEVs.[1369] Furthermore, 22.8 percent of medium- and heavy-duty vehicles were registered in ACT states in 2022 and 77.2 percent were registered in non-ACT states.[1370] Combining these, we calculate a sales ratio of 0.192, which we multiply by the ACT ZEV adoption rate in the near term to project non-ACT ZEV adoption rates.

The geographic discrepancy in ZEV deployment and truck registrations likely stems from ZEV-supportive policies in ACT states (even prior to implementation of ACT in MY 2024), such as California’s Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project (HVIP),[1371] which help to facilitate early deployments of ZEV technologies. Thus, we expect the ZEV sales

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[1367] CALSTART’s report provides data on Class 2b–8 vehicles. The data from this report used to develop ZEV adoption rates for non-ACT states includes all Class 2b–8 vehicles in aggregate. While this rulemaking covers Class 4–8 vehicles and incomplete Class 2b–3 vehicles, which comprise a small share of all Class 2b–3 vehicles, the report’s data was the most comprehensive data we could find to project ZEV adoption rates occurring independently of the final rule.

[1368] CALSTART. “Zeroing In On: ZETs May 2023 Market Update”. May 2023. Available online: https://calstart.org/zio-zets-may-2023-market-update/

[1369] Based on Figure 1 of CALSTART’s report.

[1370] Based on Figure 4 of CALSTART’s report.

[1371] California Air Resources Board. Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project (HVIP). Available online: https://californiahvip.org/

ratio between ACT and non-ACT states to stay constant through the 2020s and into the 2030s. As described in RIA Chapter 1 and 2, in recent years, at the federal level, the IRA and the BIL have been providing many incentives for deploying medium- and heavy-duty ZEVs and supporting infrastructure, and these incentives generally end by 2032. Beyond then, we expect that the IRA and the BIL will have helped to spur nationwide deployment of ZEVs and supporting infrastructure such that the ZEV adoption rate in non-ACT states trends towards parity with the ZEV adoption rate in ACT states. Additionally, CALSTART's May 2023 Market Update report notes that 44 percent of medium- and heavy-duty ZEV deployments in 2022 were in ACT states and 56 percent were in non-ACT states.[1372] In comparison with the cumulative 2017–2022 deployment proportions, noted above as 60.6 percent in ACT states and 39.4 percent in non-ACT states, this suggests the proportion of ZEVs sold in non-ACT states, relative to ACT states, may increase over time. This further supports the notion that the ZEV adoption rate in non-ACT states will trend towards parity with ACT states, which would eventually result in a sales ratio of 1.0.

We model the sales ratio in non-ACT states as a constant value of 0.192 through MY 2032, then linearly increase it from 0.2 to 0.42 from MY 2033 until MY 2055. Through stakeholder outreach with the trucking community—including manufacturers, dealers, and fleets—and through our own analyses, we understand tractors and heavy heavy-duty vocational vehicles to be more challenging applications for ZEV technology than other vocational vehicles, so we model the sales ratio for those segments as half of the rest of the market. Thus, the sales ratio for tractors and Class 8 vocational vehicles is 0.096 through MY 2032 and reaches 0.21 in MY 2055. The sales ratios are summarized in Table 4-6 below.

Table 4-6 Sales ratios for projecting reference case ZEV adoption in non-ACT States

Model Year[A]	**LHD, MHD Vocational Vehicles**	**HHD Vocational, Short-Haul Tractors, Long-Haul Tractors**
2027–2032	0.192	0.096
2033	0.200	0.100
2034	0.210	0.105
2035	0.220	0.110
…	…	…
2055	0.420	0.210

[A] The sales ratios for model years 2036 through 2054 increase linearly between the ratios in model years 2035 and 2055.

Table 4-7 shows the reference case ZEV adoption rate for non-ACT states for model years 2024 through 2035. These adoption rates are calculated by multiplying the adoption rates in Table 4-5 by the sales ratios in Table 4-6. Adoption rates increase linearly from MY 2035

[1372] As explained in the report, Colorado was not included as an ACT state in the report because it describes the market through 2022 and Colorado adopted the ACT rule in April 2023. We do include Colorado as an ACT state. The report does not provide sufficient data to re-calculate 2022 ZEV deployments in ACT states to include Colorado. However, given that Colorado accounts for 1.7 percent of cumulative 2017–2022 ZEV deployments across the U.S., the 2022 ratio of 44 percent ZEV deployments in ACT states and 56 percent in non-ACT states is not likely to be significantly different when including Colorado as an ACT state. New Mexico, Maryland, and Rhode Island are not included as ACT states in the report or our modeling because they adopted ACT after most of our modeling was complete.

through MY 2055. Appendix B to this RIA contains the breakdown of non-ACT ZEV adoption rates in the reference case by model year, source type, regulatory class, and ZEV technology.

Table 4-7 Reference case ZEV adoption rate for non-ACT states

Model Year[A]	LHD Vocational	MHD Vocational	HHD Vocational	Short-Haul Tractors	Long-Haul Tractors
2024	2.2%	1.7%	0.6%	0.7%	0.0%
2025	2.7%	2.0%	0.7%	1.0%	0.0%
2026	3.2%	2.4%	0.8%	1.4%	0.0%
2027	4.9%	3.7%	1.2%	2.1%	0.2%
2028	7.4%	5.5%	1.8%	2.7%	0.4%
2029	9.8%	7.4%	2.5%	3.3%	0.7%
2030	12.2%	9.2%	3.1%	3.8%	1.0%
2031	13.4%	10.1%	3.4%	4.1%	1.9%
2032	14.6%	11.0%	3.7%	4.6%	2.4%
2033	16.5%	12.4%	4.1%	4.7%	2.5%
2034	18.6%	14.0%	4.7%	5.0%	2.6%
2035	20.9%	15.6%	5.2%	5.2%	2.7%
…	…	…	…	…	…
2055	38.6%	29.0%	9.7%	9.9%	5.3%

[A] The ZEV adoption rates for model years 2036 through 2054 increase linearly between the adoption rates in model years 2035 and 2055. Appendix B to this RIA presents the adoption rates for each model year from 2024 through 2055.

Finally, the national reference case HD ZEV adoption rates, based on a sales-weighting of state-specific adoption rates, are presented in Table 4-8. Appendix B to this RIA contains a breakdown of the national ZEV adoption rates in the reference case by model year, source type, regulatory class, and ZEV technology.

Table 4-8 National heavy-duty ZEV adoption in the reference case

Model Year[A]	LHD Vocational	MHD Vocational	HHD Vocational	Short-Haul Tractors	Long-Haul Tractors
2024	3.2%	2.2%	1.1%	1.0%	0.0%
2025	5.4%	3.7%	2.4%	2.2%	0.0%
2026	6.4%	4.4%	2.8%	3.2%	0.0%
2027	10.1%	6.9%	4.6%	4.7%	0.4%
2028	15.2%	10.4%	6.9%	6.1%	0.7%
2029	20.2%	13.8%	9.2%	7.4%	1.3%
2030	25.2%	17.2%	11.4%	8.7%	1.9%
2031	27.6%	18.9%	12.5%	9.3%	3.7%
2032	30.1%	20.5%	13.6%	10.4%	4.7%
2033	33.1%	22.6%	14.9%	10.5%	4.8%
2034	36.2%	24.9%	16.2%	10.8%	4.9%
2035	39.5%	27.2%	17.5%	11.0%	5.0%
…	…	…	…	…	…
2055	52.0%	37.3%	20.3%	15.1%	7.2%

[A] The ZEV adoption rates for model years 2036 through 2054 increase linearly between the adoption rates in model years 2035 and 2055. Appendix B to this RIA presents the adoption rates for each model year from 2024 through 2055.

Our reference case methodology has sources of uncertainty. While our methodology is based on the best HD ZEV deployment data we can find, there is still little data on current HD ZEV deployment, which makes projecting to 2032 and beyond challenging. For example, the CALSTART report notes several thousand ZEVs whose deployment they could not locate between ACT or non-ACT states, which introduces uncertainty into the calculated sales ratio for non-ACT states. In light of this uncertainty, we performed a sensitivity analysis in which we analyzed the final standards against a different reference case in Chapter 4.10.

4.2.3 MOVES Inputs for the Final Standards and the Alternative

In modeling the control cases for the final standards and the alternative, we analyze the impact of the final CO_2 emission standards on a heavy-duty fleet that is projected in our potential compliance pathway to include both ICE vehicles and an increase in ZEV adoption. In our modeling, we project that the final emission standards are achieved through increased adoption of HD vehicle and engine technologies to reduce GHG emissions. Examples of these GHG-reducing technologies that manufacturers may choose to adopt include ICE vehicle technologies, heavy-duty battery electric vehicle (BEV) technologies and fuel cell vehicle (FCEV) technologies. We projected the emission reductions from the modeled potential compliance pathway's technology packages described in preamble section II and RIA Chapter 2.10. As we note there, manufacturers may elect to comply using a different combination of HD vehicle and engine technologies than we modeled. In fact, we developed additional example potential compliance pathways that meet the final Phase 3 MY 2027 through MY 2032 and later CO_2 emission standards (see Chapter 2.11). These pathways would achieve the same level of vehicle CO_2 emission reductions and downstream CO_2 emission reductions discussed later in this RIA chapter.

Our modeling of the ICE vehicle portions of the technology packages reflect CO_2 emission improvements projected in previously promulgated standards, notably HD GHG Phase 2; thus, we do not model an increase in ICE vehicle efficiency resulting from the final standards. Future HD ZEV populations in MOVES at the national level for the final standards and alternative were informed by HD TRUCS based on the technology assessment for BEVs and FCEVs discussed in preamble Sections II and IX and RIA Chapter 2. We aggregated HD TRUCS' 101-Vehicle-ID level national ZEV adoption rates by MOVES source type and regulatory class combination with a sales-weighted average of Vehicle IDs in each combination for MYs 2027 and 2032, with ZEV adoption rates for MYs 2028–2031 phased-in similarly to the final and alternative standards. For model years after 2032, ZEV adoption for each source type and regulatory class combination was held constant at the MY 2032 level.

We then added two constraints to ZEV adoption: a) in no combination of MY, source type, regulatory class, and location (i.e., ACT state or non-ACT state) would ZEV adoption in either control case (i.e., final standards or the alternative) be lower than in the reference case, and b) HD ZEV sales would first meet the requirements of the ACT rule in California and the states which have adopted the ACT rule under CAA section 177, and then sales would increase further in all other states in order to meet our projections of national ZEV adoption reflected in our modeled potential compliance pathway (described in preamble Section II and RIA Chapter 2).

Table 4-9 and Table 4-10 show the ZEV adoption rates used in modeling the final and alternative standards, respectively, in MOVES from 2027 through 2032. Further discussion of the ZEV adoption rates by technology, model year, source type, regulatory class, and location can be found in Appendix B to this RIA.

Table 4-9 National heavy-duty ZEV adoption in the control case for the final standards

Model Year	LHD Vocational	MHD Vocational	HHD Vocational[a]	Short-Haul Tractors	Long-Haul Tractors[b]
2027	18.4%	13.5%	4.6%	5.3%	0.4%
2028	23.6%	16.7%	9.4%	8.4%	0.7%
2029	28.8%	20.0%	11.9%	11.9%	1.3%
2030	34.0%	23.2%	14.5%	16.3%	6.2%
2031	47.5%	32.0%	20.1%	27.7%	12.5%
2032	61.2%	40.7%	25.7%	39.9%	25.0%

[a] For HHD vocational vehicles, we are not finalizing revisions to MY 2027 standards. ZEV adoption for these vehicles in this model year was set to be equal to the reference case.

[b] For sleeper cab tractors, which are represented by long-haul tractors (source type 62) in MOVES, we did not propose and are not finalizing revisions to MY 2027 standards or new standards for MYs 2028 or 2029. ZEV adoption for this source type in these model years was set to be equal to the reference case.

Table 4-10 National heavy-duty ZEV adoption in the control case for the alternative

Model Year	LHD Vocational	MHD Vocational	HHD Vocational[a]	Short-Haul Tractors	Long-Haul Tractors[b]
2027	15.7%	10.4%	4.6%	4.7%	0.4%
2028	20.9%	13.7%	7.3%	6.5%	0.7%
2029	26.1%	16.9%	9.8%	10.0%	1.3%
2030	31.3%	20.4%	12.3%	13.5%	5.0%
2031	36.0%	23.3%	14.5%	17.0%	10.0%
2032	40.7%	26.3%	16.6%	20.5%	15.0%

[a] For HHD vocational vehicles, we are not finalizing revisions to MY 2027 standards. ZEV adoption for these vehicles in this model year was set to be equal to the reference case.

[b] For sleeper cab tractors, which are represented by long-haul tractors (source type 62) in MOVES, we did not propose and are not finalizing revisions to MY 2027 standards or new standards for MYs 2028 or 2029. ZEV adoption for this source type in these model years was set to be equal to the reference case.

4.2.4 EGU Emissions Analysis Methodology

Because of the lead times necessary to complete our IPM modeling for the final rulemaking analysis, we had to develop IPM input scenarios before our analysis was complete for the final standards. Therefore, we developed reference and control scenarios which do not directly match the reference and control cases used in our final rulemaking analysis, but that we used on an interim basis. We ran these scenarios with the 2022 post-IRA version of IPM.

We fully document the differences between these interim scenarios and the final scenarios in a memo to the docket.[1373] Relative to the final reference case, the interim reference case has a higher level of HD ZEV adoption, specifically in non-ACT states. The interim control case is based on the proposed standards and has similar levels of ZEV adoption, with some updates to the split between BEV and FCEV adoption based on our technology assessment in HD TRUCS.

[1373] Murray, Evan. Memorandum to Docket EPA-HQ-OAR-2022-0985. “Modeling Inputs for IPM Modeling in the Final Rulemaking Inventory Analysis”. February 29, 2024.

Overall, both the interim reference and control cases represent greater electricity demand than their respective final rulemaking cases. In terms of understanding the impacts of the final standards on the U.S. electricity grid, we consider these interim scenarios to be conservative, especially in the near term. Nonetheless, the differences between the interim and final scenarios are small compared to the difference between IPM defaults and the final scenarios. Therefore, we use the IPM results to calculate adjusted inventories that provide a good approximation of the EGU emissions impact of the final standards and alternative.

Chapter 4.2.4.1 discusses how we developed IPM inputs for each scenario and Chapter 4.2.4.2 discusses the methodology we developed to estimate EGU emissions impacts for the control cases using IPM's outputs. We calculated refinery emissions by adjusting an existing refinery inventory. Chapter 4.2.5 discusses the methodology we used to estimate refinery emission impacts.

4.2.4.1 IPM Input Files

The only IPM input that we needed to update to model reference and control scenarios is the total electricity demand. IPM's default electricity demand is based on the Energy Information Administration (EIA) Annual Energy Outlook 2023 (AEO2023),[1356] which does not include the full forecasted ZEV adoption in the reference case. Relative to AEO2023, the interim reference case reflects increased HD ZEV adoption. Therefore, we developed IPM input files specific to the demand of electric vehicles not captured by IPM's defaults, which we call incremental heavy-duty demand input files.[1374,1375]

We developed a set of incremental heavy-duty demand input files for our interim reference case and another set for our interim control case. To calculate EV electricity demand for these scenarios, we performed state-by-state MOVES runs to account for state-specific HD ZEV adoption rates similar to those discussed in Chapter 4.2.2.

IPM requires grid demand to be specified by day type (i.e., for an average weekday and weekend day), hour of the day, and by each of IPM's geographic regions. We first calculated total energy demand for a typical weekend day and weekday for both BEVs and FCEVs using MOVES output. Because MOVES energy consumption output for BEVs represents the total grid demand related to the running and charging of the vehicles, we used MOVES output for BEVs with no further processing.

However, MOVES does not capture upstream emissions due to the production of hydrogen for FCEVs. Hydrogen in the U.S. today is primarily produced via steam methane reforming (SMR), largely as part of petroleum refining and ammonia production. Given the BIL and IRA provisions that meaningfully incentivize reducing the emissions and carbon intensity of hydrogen production, as well as new transportation and other demand drivers and potential future

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[1374] We also provided incremental light-duty demand input files to IPM based on the reference case for the proposed Multi-Pollutant Emissions Standards for Model Years 2027 and Later Light-Duty and Medium-Duty Vehicles rule (FR 88 29184). Incremental light-duty demand input files were generated using OMEGA. More details on light-duty BEV energy demand relative to the IPM default demand can be found in the draft Regulatory Impact Analysis, Chapter 5.

[1375] U.S. EPA. "Multi-Pollutant Emissions Standards for Model Years 2027 and Later Light-Duty and Medium-Duty Vehicles: Draft Regulatory Impact Analysis". April 2023. Available online: https://nepis.epa.gov/Exe/ZyPDF.cgi/P10175J2.PDF?Dockey=P10175J2.PDF regulation, we anticipate there will be a shift in how hydrogen is produced. Therefore, we made a simplifying assumption that the increased levels of hydrogen necessary to fuel FCEVs will be produced using grid electrolysis. Thus, all hydrogen production is represented as additional demand to EGUs and the emissions are modeled using IPM.

The relative emissions impact of hydrogen production via SMR versus grid electrolysis depends on how electricity is produced, which varies significantly by region across the country. Electrolysis powered by electricity from the grid on average in the U.S. may overestimate the upstream emissions impacts that are attributable to HD FCEVs in our analysis. New electrolysis project announcements predominantly pair electrolyzers wth zero-carbon energy sources.[1376] As the carbon intensity of the grid declines over time in response to the BIL and IRA and incentives, these impacts should be mitigated.[1377]

To better understand the possible emission impacts of the hydrogen production necessary to fuel HD FCEVs, we conducted a comparative analysis of multiple hydrogen production pathways including SMR and autothermal reforming (ATR) compared to grid-powered electrolysis. The methodology and results of this sensitivity analysis are discussed in RIA Chapter 4.8. While we present the emission impacts of the electrolysis scenario, the emission impacts of hydrogen production scenarios discussed in Chapter 4.8 offer a qualitative range for the upstream emissions that will result from the increased FCEV adoption projected in the modeled potential compliance pathway for the final standards.

For our inventory modeling, we developed yearly scalar multipliers to apply to MOVES FCEV energy consumption to model emissions for hydrogen production coming from electrolysis. The resulting energy demand represents the total grid demand from the hydrogen production necessary to support the levels of FCEVs projected in our principal compliance pathway. First, we assumed hydrogen is produced by a series of decentralized, grid-powered polymer electrolyte membrane (PEM) electrolyzer systems, each with a hydrogen production capacity around 1,500 kilograms per day.[1378,1379] Next, we assumed the gaseous hydrogen is compressed and pre-cooled for delivery to vehicles using grid-powered electrical equipment. Finally, we assumed a linear improvement between our estimated current and future efficiency for hydrogen production. The linear interpolation is between current values that start in 2025 and future values represented for 2055, assuming a period of diffusion for more efficient electrolysis technology improvements to spread. The final scaling factors range from 1.748 in 2025 to 1.616 in 2055.

We allocated total daily demand of FCEVs and BEVs by the hour of day separately. FCEV energy demand is allocated uniformly across all hours of the day because hydrogen fuel can be produced and compressed at any time of day.

[1376] For electrolyzers using renewable energy, a fraction of electricity consumed may come from the grid, which is more carbon intensive, to address intermittency of renewable energy.

[1377] U.S. Department of Energy. “Pathways to Commercial Liftoff: Clean Hydrogen”. March 2023. Available online: https://liftoff.energy.gov/wp-content/uploads/2023/03/20230320-Liftoff-Clean-H2-vPUB.pdf.

[1378] This is based on assumptions from the Hydrogen Analysis Production (H2A) Model from the National Renewable Energy Laboratory (NREL).

[1379] National Renewable Energy Laboratory (NREL). “H2A: Hydrogen Analysis Production Model: Version 3.2018”. Available online: https://www.nrel.gov/hydrogen/h2a-production-archive.html

We developed charging load profiles to reflect the share of total daily demand from BEV charging that we expect to occur each hour for both weekdays and weekends. Because vehicle use and charging patterns vary by application, we developed individual charging profiles for each of MOVES heavy-duty source types based on soak or hotelling data in MOVES.[1380]

Except for long-haul vehicle types, we used soak times of 12 or more hours[1381] as a proxy for when a vehicle may be parked at a depot, warehouse, or other off-shift location and can charge. We assume charging activity to be evenly distributed across the 12 hours of soak time before the vehicle starts. For long-haul vehicles, we instead calculate charging profiles using MOVES hotelling data in lieu of available soak data. Hotelling data accounts for the length of time that a vehicle is parked while en route and represents an opportunity for charging. Hotelling data is applied directly and does not assume the same 12-hour proxy as these vehicles may not regularly return to a depot for off-shift charging.

We expect that the charging beginning time and duration will vary due to different energy consumption, charging equipment, and the charging preferences of BEV owners or operators. Finally, charging profiles for each source type were weighted by their share of electricity demand to calculate overall HD BEV national charging profiles for weekdays and weekends. We calculated separate HD BEV charging profiles for each calendar year run in IPM and for both the interim reference and control cases.

The HD BEV charging profiles used for the interim reference case for the calendar years in which we ran IPM are shown in Figure 4-1 (weekdays) and Figure 4-2 (weekends). The small differences in the profiles for each year reflect the dependency that charging profiles have on the BEV fleet composition, as does the difference in the general profile shape between weekdays and weekends.

[1380] Soaking is the time between when a vehicle is powered off and when it starts again, so it indicates when vehicles are not driving and may have an opportunity to charge. Hotelling is the hours spent by drivers of long-haul trucks with their trucks parked during mandatory rest periods.

[1381] For our NPRM analysis we assumed all vehicles had 12 hours of dwell time to charge at depots. As discussed in Chapter 2.6.2.1.4, we have updated dwell times in our final rule analysis to values ranging from 7.4 to 14.5 hours depending on vehicle type. Due to the lead times necessary to complete our IPM modeling for the final rulemaking analysis, we used the NPRM assumption when developing load profiles for calculating IPM inputs for the interim scenarios.

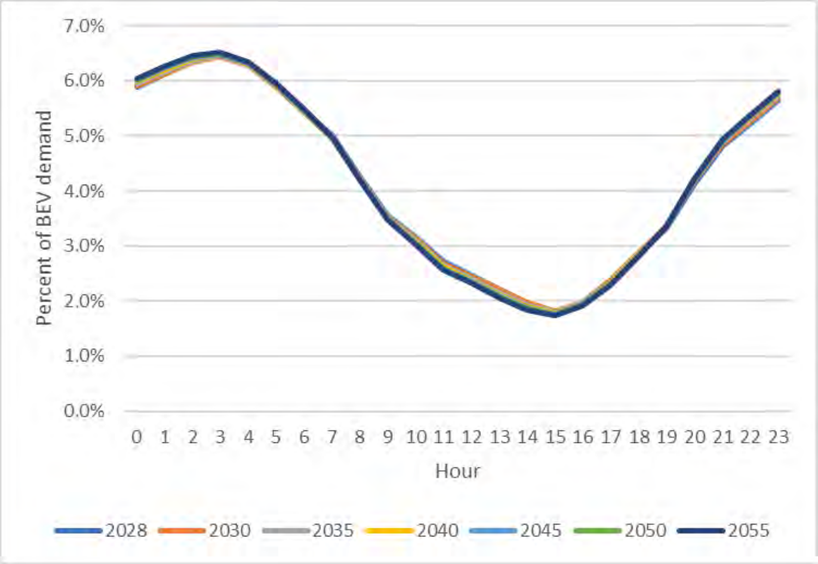

Figure 4-1 Heavy-duty BEV charging profiles for weekdays for the interim reference case

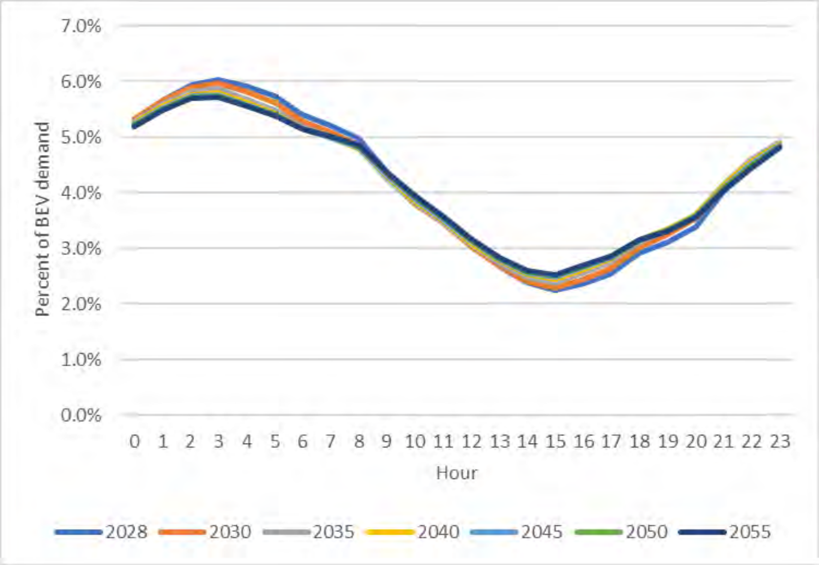

Figure 4-2 Heavy-duty BEV charging profiles for weekends for the interim reference case

Finally, IPM requires grid demand to be geographically allocated by IPM region. We developed regional allocation factors based on county-level CO_2 emissions in the 2016v2 emissions modeling platform.[1382] We used CO_2 emissions as our basis for regional allocation because CO_2 scales well with VMT while capturing differing fleet characteristics in different

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[1382] U.S. EPA. "2016v2 Platform". January 23, 2023. Available online: https://www.epa.gov/air-emissions-modeling/2016v2-platform counties. IPM includes a mapping of each county to an IPM region, which we used to aggregate county allocation factors by IPM region.

4.2.4.2 EGU Inventory Calculation Methodology

The IPM runs we performed to estimate EGU emissions were based on interim reference and control cases. Because they aren't identical to our final reference and control cases, we developed a methodology to estimate the increase in EGU emissions from the final standards and the alternative using emission factors calculated from the IPM output.

We calculated emission factors that relate an increase in EGU emissions to an increase in HD ZEV energy demand. This approach does not yield perfectly accurate emissions estimates because the power generation mix, and therefore EGU emissions, depend on the total energy demand. However, the changes in HD ZEV energy consumption between our interim and final scenarios is small enough that this approach provides a good approximation for calculating changes in EGU emission inventories.

We calculated emission factors in terms of the incremental change in emissions and energy consumption and therefore call them incremental EGU emission factors. They are calculated as the change in EGU emissions from a reference to a control case divided by the change in HD ZEV energy consumption from the same reference and control case, as expressed in Equation 4-2.

Equation 4-2 Calculation method of an incremental EGU emission factor from a reference and control cases

$$incremental\ EGU\ emission\ factor = \frac{Emissions_{control} - Emissions_{reference}}{EnergyDemand_{control} - EnergyDemand_{reference}}$$

Table 4-11 shows the incremental EGU emission factors we calculated for four calendar years and the GHGs and criteria pollutants we estimated using IPM. These factors represent the increase in EGU emissions, in U.S. tons, per terawatt-hour of increased grid demand from HD ZEVs. We calculated incremental EGU emissions factors for 2035, 2040, 2045, and 2050 because IPM runs only include a few calendar years.

Table 4-11 Incremental EGU emission factors used to estimate EGU emissions increases attributable to additional HD ZEV adoption in the final rulemaking

Pollutant	**Incremental EGU Emission Factor (U.S. Tons / Terawatt-Hour)**			
	2035	**2040**	**2045**	**2050**
Carbon Dioxide (CO_2)	443,304	78,249	98,012	81,195
Methane (CH_4)	28.2	6.5	2.3	1.6
Nitrous Oxide (N_2O)	3.9	0.9	0.3	0.2
Nitrogen Oxides (NO_X)	133.6	18.4	9.8	8.7
Particulate Matter ($PM_{2.5}$)	19.5	3.9	3.7	2.9
Sulfur Dioxide (SO_2)	161.2	13.5	4.0	0.4
Volatile Organic Compounds (VOC)	6.4	1.2	2.1	1.1

EGU emission factors decrease into the future, as higher-emitting power generation technologies like coal and natural gas combustion are phased out in favor of renewable sources. This is especially apparent in the emission factors of sulfur dioxide (SO_2), which decrease by more than 99% from 2035 to 2050 as coal is almost entirely phased out.

Because the EGU emission factors are calculated based on the increase in emissions attributable specifically to the increase in demand from HD ZEVs, they capture the effects that HD ZEVs have on EGU emissions. These effects include factors such as the geographic distribution of ZEVs, the types of roads they operate o the time of day they charge, and the electricity generation mix used to provide the electricity, among other factors.

To estimate the impact of the final standards and alternative on EGU emissions, we multiply the incremental EGU emission factors by the additional HD ZEV energy demand modeled for each scenario estimated in MOVES4.R3. For year-over-year inventories, we use the emission factor from the year closest to each calendar year, such that 2027 through 2037 use the rate from 2035, 2038 through 2042 use the rate from 2040, and so on. The rate from 2050 was used to estimate EGU emissions from 2051 through 2055.

This methodology represents a good approximation of how we expect EGU emissions to increase because of increased HD ZEV adoption with the final standards under the potential compliance pathway and the alternative. But the calculated emission inventory estimates are not likely to be identical to those that would result from running IPM for the final reference and control cases, as opposed to the interim scenarios. There are, therefore, several caveats and limitations in the interpretation of the results from this analysis.

First, as stated earlier in this section, we do not have IPM runs that directly correlate to the reference case used throughout this rulemaking. Because there is no total inventory calculated for the reference case, relative comparisons between the control cases and reference case (such as percent changes) are not possible. Second, by only considering the additional energy demand and energy consumption of HD ZEVs, we capture how characteristics specific to their operation affect EGU emissions. However, this method is not able to quantitatively isolate these effects, nor is it able to partition EGU emissions to HD ZEVs of specific vehicle types such as by source type, regulatory class, or model year.

4.2.5 Refinery Emissions Analysis Methodology

We developed the refinery emission inventory impact estimates using a similar approach to how we developed EGU emission inventory impact estimates. Specifically, we calculated emission factors which related a change in refinery emissions to a change in refinery activity. To estimate the refinery emission impact, we calculated the change in refinery activity using MOVES fuel consumption multiplied by the emission factors.

The starting point for estimating the refinery inventories was the 2016v3 emissions modeling platform, which includes projection years of 2023 and 2026.[1383] Starting from the 2026 refinery

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[1383] U.S. EPA. “2016v3 Platform”. September 22, 2023. Available online: https://www.epa.gov/air-emissions-modeling/2016v3-platform inventory, we calculated a refinery inventory for each calendar year in 5-year increments from 2030 to 2050 using growth factors calculated from the AEO2023.[1384]

Refineries in the United States refine more products than gasoline and diesel fuel, and some refineries do not refine any onroad fuels. We reviewed the facilities included in the 2016 refinery sector in the emissions modeling platform and omitted facilities that did not produce gasoline or diesel fuel. We then calculated scaling factors to apportion total emissions from refineries specifically to the refining of gasoline and diesel versus other refined fuels and refinery operations. The scaling factors are based on the relative energy demand of refining various fuels calculated by Wang et al. (2004).[1385] Wang et al. expressed the energy demand of refining fuels in terms of mass and included outputs that are not refinery products (i.e., fuel gas), so we removed non-refinery products and adjusted the energy demand factors to be based on volume instead of mass.

Relative emissions related to the refining of various products are determined primarily by the energy needed to refine those products, but also depend on pollutant-specific emissions specific to refining those products. For example, the refining of gasoline causes higher methane emissions than an equivalent volume of diesel. We developed pollutant-specific apportionment factors based on relative emissions of refining gasoline, diesel, and other products using emission factors from GREET 2021.[1386] We use the apportionment factors to calculate the portion of the refinery inventory attributable to the refining of each fuel type. Final apportionment factors for each pollutant we modeled in our refinery analysis appear in Table 4-12.

[1384] Specifically, within the emissions modeling platform, a projection packet was prepared for 2026 projected out to 2050 using AEO2023 for refineries. AEO categories were mapped to source classification codes (SCCs) and SCC+ North American Industry Classification System (NAICS) combinations (with SCC+NAICS taking precedence if a mapping exists for the refinery NAICS, which are 32411/324110) using the usual industrial source AEO-SCC and AEO-SCC-NAICS cross references “xrefs” from past platforms. Only refineries NAICS and SCCs which have refinery emissions were included when making the packet, so the 2026-2050 packet is not something that can be used to project the entire point source non- IPM “ptnonipm” sector. Each record in the packet references the refineries NAICS so that it can be applied to the entire ptnonipm sector without changing any non-refineries.

[1385] Wang, M., Lee, H. & Molburg, J. Allocation of energy use in petroleum refineries to petroleum products. Int J LCA 9, 34–44 (2004). https://doi.org/10.1007/BF02978534

[1386] Wang, Michael, Elgowainy, Amgad, Lee, Uisung, Bafana, Adarsh, Banerjee, Sudhanya, Benavides, Pahola T., Bobba, Pallavi, Burnham, Andrew, Cai, Hao, Gracida, Ulises, Hawkins, Troy R., Iyer, Rakesh K., Kelly, Jarod C., Kim, Taemin, Kingsbury, Kathryn, Kwon, Hoyoung, Li, Yuan, Liu, Xinyu, Lu, Zifeng, Ou, Longwen, Siddique, Nazib, Sun, Pingping, Vyawahare, Pradeep, Winjobi, Olumide, Wu, May, Xu, Hui, Yoo, Eunji, Zaimes, George G., and Zang, Guiyan. Greenhouse gases, Regulated Emissions, and Energy use in Technologies Model ® (2021 Excel). Computer Software. U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy (EERE). 11 Oct. 2021. Web. doi:10.11578/GREET-Excel-2021/dc.20210902.1.

Table 4-12 Refinery emission apportionment factors by fuel type

Pollutant	Refinery Emissions Apportionment Factor		
	Gasoline	Diesel	Other
Carbon Dioxide (CO_2)	0.591	0.061	0.348
Methane (CH_4)	0.640	0.053	0.307
Nitrous Oxide (N_2O)	0.583	0.063	0.354
Nitrogen Oxides (NO_X)	0.610	0.056	0.334
Particulate Matter ($PM_{2.5}$)	0.620	0.054	0.326
Sulfur Dioxide (SO_2)	0.596	0.058	0.346
Volatile Organic Compounds (VOC)	0.570	0.058	0.372

Table 4-13 shows how we estimated 2050 refinery emissions that are attributable to the refining of gasoline and diesel fuel. We begin with the total refinery inventory. Then, we apportion that to refineries that refine onroad fuels, and then we further apportion emissions to be specific to the refining of gasoline and the refining of diesel.

Table 4-13 Refinery emission inventory apportioned by refinery type and fuel type

Pollutant	Emission Inventory by Refinery Group (U.S. Tons)		Inventory Apportioned by Fuel Type (U.S. Tons)	
	All Refineries	Refineries that produce gasoline and diesel	Gasoline	Diesel
Carbon Dioxide (CO_2)	203,808,672	186,521,729	110,234,342	11,377,825
Methane (CH_4)	11,105	9,743	6,235	514
Nitrous Oxide (N_2O)	1,712	1,593	928	100
Nitrogen Oxides (NO_X)	81,607	77,830	47,437	4,335
Particulate Matter ($PM_{2.5}$)	19,243	18,253	11,324	976
Sulfur Dioxide (SO_2)	26,287	23,501	14,017	1,373
Volatile Organic Compounds (VOC)	64,091	57,829	32,972	3,374

To estimate refinery emission rates using the fuel-specific refinery inventories, we estimated total refinery activity in terms of gasoline and diesel produced. AEO2023 has projections for total onroad fuel demand of diesel and gasoline through 2050[1387] but the United States is a net exporter of gasoline and diesel. We therefore included exports of liquid fuels in our estimates of the total fuel refined by U.S. refineries.

AEO2023 does not include estimated exports of gasoline and diesel through 2050. Instead, it presents estimates of net exports of total refined liquid fuels.[1388] To estimate exports of gasoline and diesel, we scaled measured 2022 exports into the future using growth factors from AEO2023. Implicit in this approach is the assumption that the relative change in exports of those two fuels is highly correlated with exports of all refined liquid fuels.

We use combined net exports and domestic demand for gasoline and diesel fuel to estimate the total refinery activity in terms of gallons of fuel refined. Finally, we calculate refinery emission rates that relate a change in onroad fuel consumption to a change in refinery emissions.

[1387] AEO2023 Table 11, rows “Liquid Fuels: Liquid Fuels Use: by Fuel: Motor Gasoline: Reference case” and “Liquid Fuels: Liquid Fuels Use: by Fuel: Diesel: Reference case”

[1388] AEO2023 Table 11, “Liquid Fuels: Net Product Imports: Reference case”

Table 4-14 presents the refinery emission rates for gasoline and Table 4-15 presents the refinery emission rates for diesel.

Table 4-14 Refinery emission rates for the refining of gasoline

Pollutant	**Refinery Emission Rate (U.S. Tons / Billion Gallons of Gasoline)**				
	2030	**2035**	**2040**	**2045**	**2050**
Carbon Dioxide (CO_2)	731,207	765,753	794,514	811,236	814,381
Methane (CH_4)	42.5	44.3	45.8	46.2	46.1
Nitrous Oxide (N_2O)	6.2	6.4	6.7	6.8	6.9
Nitrogen Oxides (NO_X)	317.4	332.1	345	350.6	350.5
Particulate Matter ($PM_{2.5}$)	76.1	79.5	82.4	83.7	83.7
Sulfur Dioxide (SO_2)	94.6	99	102.5	104	103.6
Volatile Organic Compounds (VOC)	225.7	235.8	243.3	245.5	243.6

Table 4-15 Refinery emission rates for the refining of diesel

Pollutant	**Refinery Emission Rate (U.S. Tons / Billion Gallons of Diesel)**				
	2030	**2035**	**2040**	**2045**	**2050**
Carbon Dioxide (CO_2)	146,741	146,209	146,442	148,050	153,504
Methane (CH_4)	6.8	6.7	6.7	6.7	6.9
Nitrous Oxide (N_2O)	1.3	1.3	1.3	1.3	1.4
Nitrogen Oxides (NO_X)	56.4	56.1	56.3	56.7	58.5
Particulate Matter ($PM_{2.5}$)	12.7	12.7	12.7	12.8	13.2
Sulfur Dioxide (SO_2)	18	17.9	17.9	18	18.5
Volatile Organic Compounds (VOC)	44.9	44.6	44.4	44.4	45.5

The refinery emission rates can be paired with an estimate of reduced refinery activity to estimate the impact of the final standards. We estimate the change in refinery activity by assuming a reduction in onroad fuel demand will lead to a reduction in the total amount of fuel refined. However, U.S. refineries can theoretically respond to lower domestic demand by increasing volumes of exported liquid fuels, thus allowing them to refine at the same volume and leaving refinery emissions unchanged.

For projecting the emissions inventory impacts for the NPRM, we estimated that 7% of the reduced domestic demand for refined fuels would be made up by increased net exports[1389] based on a comparison of the reference case and low economic growth case in AEO2021.[1390] In other words, we projected that U.S. refineries would largely decrease their refined fuel production as U.S. refined product demand decreases. However, we also recognized the large uncertainty in this assumption. We received comments from several organizations that refineries would increase net exports more than we assumed and thus not reduce their production as much.

There are several reasons to expect refineries to increase net exports should domestic demand for refined fuels drop in the future. First, many refineries refine other products, such as

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[1389] An increase in net exports can be the result of increased exports, reduced imports, or both. For the FRM analysis, we do model a decrease in net imports, discussed in RIA Chapter 6.5 and RIA Chapter 7.3.

[1390] U.S. Energy Information Administration (EIA). “Annual Energy Outlook 2021”. U.S. Department of Energy. February 3, 2021. Available online: https://www.eia.gov/outlooks/archive/aeo21/

petrochemical feedstocks, in addition to onroad fuels. These petrochemical feedstocks have economic value of their own so refineries which may be earning lower margins for onroad fuels can earn a larger return from these other products. Thus, refineries coproducing petrochemicals are more likely to continue to produce onroad fuels despite decreasing demand for refined products.[1391] Second, U.S. refiners often find it economically advantageous to refine crude oil in the United States because feedstock prices (both natural gas and crude oil prices) tend to be lower, thus leading to higher profit margins.[1392]

The higher profit margins experienced by U.S. refineries (which start in 2005) would be expected to result in lower imports and higher exports, and this has indeed occurred. Figure 4-3 shows net U.S. import data from the U.S. from the U.S. Energy Information Administration for gasoline and diesel fuel,[1393] plotted with crude prices.[1394]

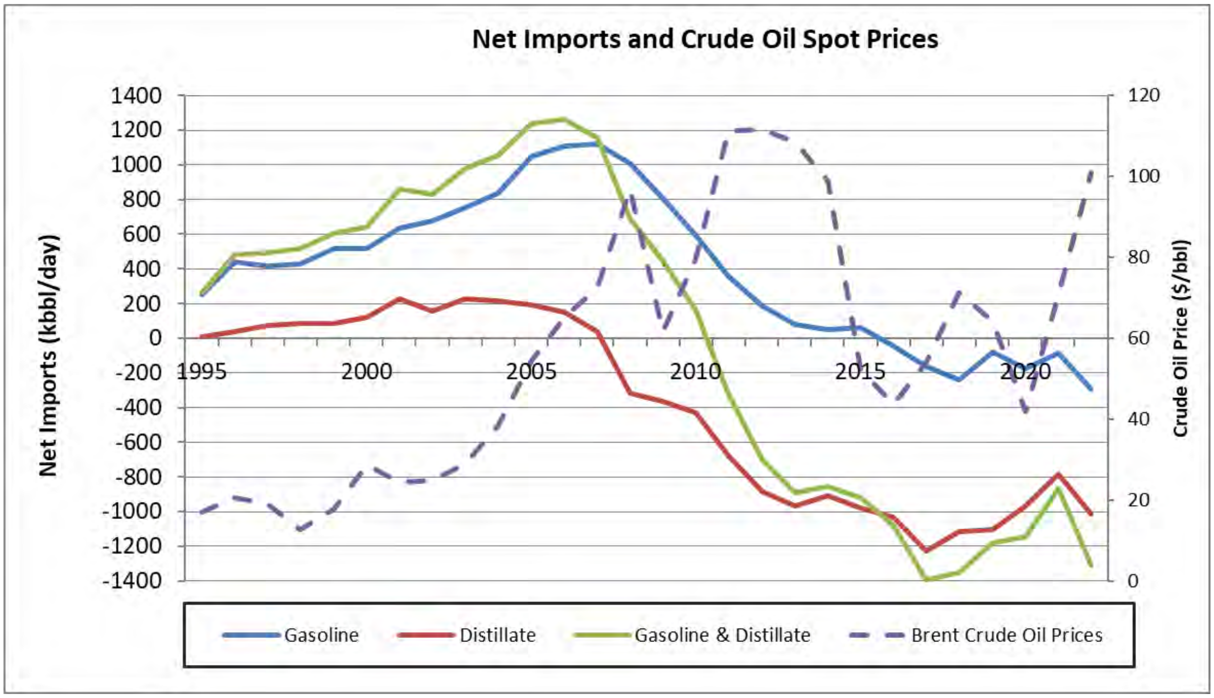

Figure 4-3 Net U.S. imports of refined liquid fuels and crude oil prices since 1995

We can see an increase in net exports (apparent in the plot as a decrease in net imports) starting in 2006 associated with improved U.S. refinery margins. The increase in net exports corresponds with an increase in crude oil prices.

[1391] Erwin Seba. “Shell weighs shut Louisiana refinery’s future as Baton Rouge firm promotes bid”. Reuters. May 24, 2021. Available online: https://www.reuters.com/business/finance/shell-weighs-shut-louisiana-refinerys-future-baton-rouge-firm-promotes-bid-2021-05-24/

[1392] U.S. Energy Information Administration. “Lower crude feedstock costs contribute to North American refinery profitability.” Today in Energy.June 5, 2014. Available online: https://www.eia.gov/todayinenergy/detail.php?id=16571

[1393] U.S. Energy Information Administration. “Imports by Area of Entry, Petroleum and Other Liquids”. January 31, 2024. Available online: https://www.eia.gov/dnav/pet/pet_move_imp_dc_NUS-Z00_mbblpd_a.htm

[1394] U.S. Energy Information Administration. “Spot Prices, Petroleum and Other Liquids”. February 14, 2024. Available online; https://www.eia.gov/dnav/pet/pet_pri_spt_s1_a.htm

Despite the favorable economic conditions for refiners in the United States, there have been some refinery closures and conversions in recent years, in some cases associated with the lower domestic fuel demand caused by the COVID-19 pandemic. Decisions by oil industry company boards of directors to begin pivoting away from producing fossil fuels is also beginning to figure into how they manage their company assets. For example, Shell cited a desire to pivot towards lower carbon fuel options, among other reasons, as a reason to close its Convent, Louisiana refinery at the end of 2020.[1395] Additionally, several refiners have recently opted to fully or partially convert their petroleum refineries to produce renewable diesel, including refineries in North Dakota,[1396] New Mexico,[1397] Wyoming,[1397] and Oklahoma.[1398]

The closure or conversion of some U.S. refineries in recent years despite better refinery profit margins suggests the closure or conversion of additional refineries, such as those that have lower margins or face other issues, is likely as domestic demand for gasoline and diesel fuel declines. The extent to which U.S. refineries keep operating, shut down, or are converted is difficult to project since it depends on the economics of individual refineries, the economic condition of the parent company, and the long-term strategy pursued by each company's board for providing a return to its shareholders.

After carefully considering stakeholder comments, the more desirable economic conditions for refiners in the U.S., and the closure and conversion of some U.S. refineries over the past several years, we updated our projection of how refineries will be impacted by this rulemaking. We project refinery emissions by assuming that U.S. refineries would increase net exports to offset half of the reduction in domestic demand for refined product. Thus, the total decrease in refinery activity, measured in gallons of gasoline and diesel refined, is half of the estimated drop in domestic fuel demand. This assumption is also supported by recent refining industry study that projected how increased transportation electrification would affect refinery production in different regions. The study evaluates three different electrification scenarios and, for each one, the authors estimate North American refinery volumes decreasing relative to most other global refining regions they modeled.[1399]

However, there remains significant uncertainty in how U.S. refineries will respond to lower demand for liquid onroad fuels. Therefore, we performed a sensitivity analysis, presented in

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[1395] Kristen Mosbrucker. "Without a buyer, Shell may convert shuttered Convent refinery into alternative fuels facility".; The Advocate. October 14, 2021. Available online: https://www.theadvocate.com/baton_rouge/news/business/without-a-buyer-shell-may-convert-shuttered-convent-refinery-into-alternative-fuel-facility/article_54ff85f2-2d18-11ec-af75-13fba5943b71.html

[1396] Bismarck State College. "Marathon converts Dickinson Refinery to renewable diesel plant; wind turbines to power site". May 26, 2021. Available online: https://bismarckstate.edu/news/dixrefinery/

[1397] HF Sinclair Corporation. "HollyFrontier Announces Expansion of Renewables Business". June 1, 2020. Available online: https://www.hollyfrontier.com/investor-relations/press-releases/Press-Release-Details/2020/HollyFrontier-Announces-Expansion-of-Renewables-Business

[1398] Biomass Magazine. "CVR To Move Forward With Wynnewood Conversion In Early 2022." November 2, 2021. Available online: https://biomassmagazine.com/articles/cvr-to-move-forward-with-wynnewood-conversion-in-early-2022-18449

[1399] Cherry Ding, Alexandre Ferro, Tim Fitzgibbon, and Piort Szabat. "Refining in the energy transition through 2040". Oil and Gas Practice, McKinsey & Company. November 3, 2022. Available online: https://www.mckinsey.com/industries/oil-and-gas/our-insights/refining-in-the-energy-transition-through-2040

Chapter 4.9, in which we assume that 80 percent of the drop in domestic fuel demand will be offset by an increase in net exports, instead of 50 percent.

Like our IPM modeling, the total refinery emission inventory used to calculate the emission rates does not directly correlate to our final reference case. The refinery inventories are based on AEO2023, which assumes much lower rates of vehicle electrification than in our reference case. As was the case for our EGU modeling, our methodology accounts for these differences in total fuel demand, but does not calculate an inventory that represents the final rule reference case. Therefore, calculating relative changes compared to a total reference case inventory, like percent change in emissions, is not possible. Because we calculate an emission inventory impact instead of an inventory itself, and because we assume a portion of the change in onroad fuel demand will be offset by increased net exports, it is also impossible to attribute emission inventory impacts to particular vehicle types such as by MOVES source type, regulatory class, or model year.

4.3 National Downstream Emission Inventory Impacts of the Final Standards

This section presents the impacts of the final standards on downstream emissions of GHGs and on several criteria pollutants and air toxics. All emission inventories were modeled using MOVES national domain, which includes the 50 states and the District of Columbia but not any U.S. commonwealths or territories.

Because we anticipate an increase in the adoption of HD ZEVs under the modeled potential compliance pathway for the final standards for MYs 2027 through 2032 and later, we expect downstream reductions of additional GHGs (methane and nitrous oxide) as well as reductions of criteria pollutants and air toxics. We modeled the final standards in MOVES4.R3 only by increasing the adoption of HD ZEVs (including both BEVs and FCEVs), which means the driving factor behind all estimated emission reductions in this analysis is the displacement of HD ICE vehicles with HD ZEVs.

The modeled downstream emission reductions are smaller than we presented in the NPRM. This is mostly because in the final rule analysis we assumed increased HD ZEV adoption levels in the reference case; it is not necessarily indicative that the final standards are meaningfully less stringent than the proposed standards.

Chapter 4.3.1 presents the inventory changes for three analysis years: 2035, 2045, and 2055. Chapter 4.3.2 presents year-over-year emission impacts from 2027 through 2055, including cumulative emission reductions. Chapter 4.3.3 discusses these impacts in more detail, including by vehicle type and fuel type, for calendar year 2055.

4.3.1 Analysis Year Impacts

Our estimates of the downstream emission reductions of GHGs that will result from the final standards relative to the reference case are presented in Table 4-16 for calendar years 2035, 2045, and 2055. Total GHG emissions, or CO_2 equivalent (CO_2e), are calculated by summing all GHG emissions multiplied by their 100-year Global Warming Potential (GWP). The GWP values used in Table 4-16 are consistent with the 2014 IPCC Fifth Assessment Report (AR5).[1400]

[1400] IPCC, 2014: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. Available online: https://www.ipcc.ch/site/assets/uploads/2018/02/SYR_AR5_FINAL_full.pdf

Table 4-16 Annual downstream heavy-duty GHG emission reductions from the final standards in calendar years (CYs) 2035, 2045, and 2055

Pollutant	**100-year GWP**	**CY 2035 Reductions**		**CY 2045 Reductions**		**CY 2055 Reductions**	
		Million Metric Tons	**Percent**	**Million Metric Tons**	**Percent**	**Million Metric Tons**	**Percent**
Carbon Dioxide (CO_2)	1	32.5	9%	66.3	19%	70.0	20%
Methane (CH_4)	28	0.002	3%	0.006	10%	0.009	12%
Nitrous Oxide (N_2O)	265	0.005	9%	0.01	19%	0.01	20%
CO_2 Equivalent (CO_2e)	---	*33.8*	*9%*	*69.1*	*19%*	*73.0*	*20%*

In 2055, we estimate that the final standards will reduce downstream emissions of CO_2 from heavy-duty vehicles by 20 percent, methane by 12 percent, and nitrous oxide by 20 percent, resulting in a reduction of 20 percent for total CO_2 equivalent emissions from heavy-duty vehicles. Table 4-16 also shows that most of the GHG emission reductions are from CO_2, which represents approximately 96 percent of all heavy-duty GHG emission reductions from the final standards.

Table 4-17 presents our estimates of the downstream emission reductions of criteria pollutants and air toxics from heavy-duty vehicles that will result from the final standards in calendar years 2035, 2045, and 2055 relative to the reference case.

Table 4-17 Annual downstream heavy-duty criteria pollutant and air toxic emission reductions from the final standards in calendar years (CYs) 2035, 2045, and 2055

Pollutant	**CY 2035 Reductions**		**CY 2045 Reductions**		**CY 2055 Reductions**	
	U.S. Tons	**Percent**	**U.S. Tons**	**Percent**	**U.S. Tons**	**Percent**
Nitrogen Oxides (NO_X)	10,801	3%	47,027	16%	54,268	20%
Particulate Matter ($PM_{2.5}$)[A]	126	2%	302	5%	331	5%
Volatile Organic Compounds (VOC)	3,014	6%	6,426	17%	7,242	20%
Sulfur Dioxide (SO_2)	126	9%	256	19%	270	20%
Carbon Monoxide (CO)	49,273	6%	117,155	17%	131,014	19%
1,3-Butadiene	7	11%	14	27%	14	27%
Acetaldehyde	62	6%	138	17%	160	17%
Benzene	38	8%	80	22%	82	25%
Formaldehyde	41	4%	100	14%	126	15%
Naphthalene[B]	3	5%	6	22%	6	23%

[A] $PM_{2.5}$ estimates include both exhaust and non-exhaust emissions, but all modeled reductions come from exhaust emissions. Relative exhaust $PM_{2.5}$ reductions are similar to other criteria pollutants with reductions of 3% in 2035, 18% in 2045, and 21% in 2055.

[B] Naphthalene includes both gas and particle phase emissions.

In 2055, we estimate the final standards will reduce heavy-duty vehicle emissions of NO_X by 20 percent, $PM_{2.5}$ by 5 percent, VOC by 20 percent, and SO_2 by 20 percent. Reductions in air toxics in 2055 range from 15 percent for formaldehyde to 27 percent for 1,3-butadiene.

4.3.2 Year-Over-Year Impacts

Table 4-18 shows the year-over-year reductions in methane and nitrous oxide emissions that we project will result from the final standards, in metric tons. Table 4-19 presents the year-over-year CO_2 emission reductions and total GHG emission reductions in terms of CO_2-equivalent mass. Table 4-20 presents the year-over-year reductions in criteria pollutant emissions.

Table 4-18 Year-over-year CH_4 and N_2O emission reductions from the final standards

Calendar Year	CH_4 Reductions		N_2O Reductions	
	Metric Tons	Percent	Metric Tons	Percent
2027	22	0.0%	57	0.1%
2028	85	0.1%	147	0.3%
2029	152	0.2%	269	0.5%
2030	238	0.4%	508	0.9%
2031	432	0.7%	1,038	1.9%
2032	763	1.3%	1,995	3.7%
2033	1,088	1.9%	2,938	5.5%
2034	1,451	2.5%	3,860	7.2%
2035	1,803	3.1%	4,741	8.9%
2036	2,156	3.8%	5,552	10.5%
2037	2,584	4.6%	6,299	11.9%
2038	3,094	5.6%	6,973	13.2%
2039	3,577	6.5%	7,578	14.5%
2040	4,033	7.3%	8,123	15.4%
2041	4,461	8.0%	8,610	16.4%
2042	4,873	8.7%	9,030	17.2%
2043	5,264	9.3%	9,375	17.9%
2044	5,637	9.8%	9,646	18.5%
2045	5,992	10.2%	9,849	19.0%
2046	6,345	10.6%	10,009	19.3%
2047	6,688	10.9%	10,118	19.5%
2048	7,024	11.1%	10,181	19.7%
2049	7,371	11.5%	10,229	19.8%
2050	7,735	11.7%	10,295	19.9%
2051	8,085	11.8%	10,345	20.0%
2052	8,432	11.9%	10,383	20.1%
2053	8,783	12.0%	10,409	20.1%
2054	9,139	12.1%	10,421	20.1%
2055	9,497	12.1%	10,422	20.0%

Table 4-19 Year-over-year CO_2 and CO_2e emission reductions from the final standards

Calendar Year	CO_2 Reductions		Total GHG (CO_2e) Reductions	
	MMT	Percent	MMT	Percent
2027	0.5	0.1%	0.5	0.1%
2028	1.2	0.3%	1.3	0.3%
2029	2.1	0.5%	2.2	0.5%
2030	3.8	0.9%	3.9	0.9%
2031	7.4	1.9%	7.7	1.9%
2032	14.0	3.6%	14.5	3.6%
2033	20.4	5.3%	21.2	5.3%
2034	26.6	7.0%	27.7	7.0%
2035	32.5	8.7%	33.8	8.6%
2036	37.9	10.2%	39.4	10.2%
2037	42.8	11.7%	44.6	11.7%
2038	47.3	13.0%	49.2	13.0%
2039	51.3	14.2%	53.4	14.2%
2040	54.9	15.3%	57.2	15.3%
2041	58.1	16.3%	60.5	16.3%
2042	60.9	17.2%	63.4	17.1%
2043	63.2	17.9%	65.8	17.8%
2044	64.9	18.5%	67.7	18.4%
2045	66.3	19.0%	69.0	18.9%
2046	67.3	19.3%	70.2	19.3%
2047	68.1	19.6%	70.9	19.5%
2048	68.5	19.8%	71.4	19.7%
2049	68.8	19.9%	71.7	19.9%
2050	69.2	20.0%	72.2	20.0%
2051	69.5	20.1%	72.5	20.1%
2052	69.8	20.1%	72.8	20.1%
2053	69.9	20.2%	72.9	20.1%
2054	70.0	20.1%	73.0	20.1%
2055	70.0	20.1%	73.0	20.0%

Table 4-20 Year-over-year emission inventory reductions for the final standards for select criteria pollutants

Calendar Year	NO_X Reductions		Total $PM_{2.5}$ Reductions		VOC Reductions	
	U.S. Tons	Percent	U.S. Tons	Percent	U.S. Tons	Percent
2027	146	0.0%	4	0.0%	87	0.1%
2028	361	0.0%	8	0.1%	189	0.3%
2029	632	0.1%	12	0.1%	302	0.5%
2030	1,096	0.2%	18	0.2%	452	0.7%
2031	2,151	0.4%	33	0.3%	798	1.4%
2032	4,060	0.8%	57	0.6%	1,380	2.5%
2033	5,984	1.3%	80	0.9%	1,956	3.7%
2034	8,156	1.9%	103	1.2%	2,502	5.0%
2035	10,801	2.6%	126	1.5%	3,014	6.3%
2036	14,190	3.6%	150	1.9%	3,497	7.5%
2037	18,253	5.0%	173	2.6%	3,975	9.1%
2038	23,298	6.6%	196	3.0%	4,444	10.5%
2039	27,990	8.2%	217	3.3%	4,858	11.7%
2040	32,356	9.9%	236	3.7%	5,222	12.8%
2041	36,284	11.5%	254	4.0%	5,543	13.7%
2042	39,794	12.9%	270	4.2%	5,830	14.6%
2043	42,704	14.2%	283	4.5%	6,069	15.4%
2044	45,101	15.3%	294	4.6%	6,268	16.2%
2045	47,027	16.2%	302	4.8%	6,426	16.8%
2046	48,634	17.0%	309	4.9%	6,562	17.2%
2047	49,890	17.6%	315	5.0%	6,689	17.6%
2048	50,809	18.1%	319	5.1%	6,782	18.1%
2049	51,597	18.6%	322	5.1%	6,861	18.4%
2050	52,379	19.0%	325	5.1%	6,935	18.7%
2051	53,003	19.3%	327	5.2%	7,016	19.0%
2052	53,490	19.6%	329	5.2%	7,101	19.3%
2053	53,857	19.8%	330	5.1%	7,166	19.5%
2054	54,120	19.9%	331	5.1%	7,213	19.7%
2055	54,268	20.0%	331	5.1%	7,242	19.8%

We expect emission reductions to be small in earlier years as the final standards phase in. As ZEVs represent an increasing proportion of the heavy-duty vehicle fleet, we expect emission reductions to grow into the future. Table 4-18, Table 4-19, and Table 4-20 show that emission reductions will increase over time, as more ICE vehicles are displaced by ZEVs.

Figure 4-4, Figure 4-5, and Figure 4-6 show yearly downstream GHG inventories for the reference case and the final standards. The emissions estimates for methane and nitrous oxide are presented in terms of their true mass and are not converted to CO_2 equivalent mass.

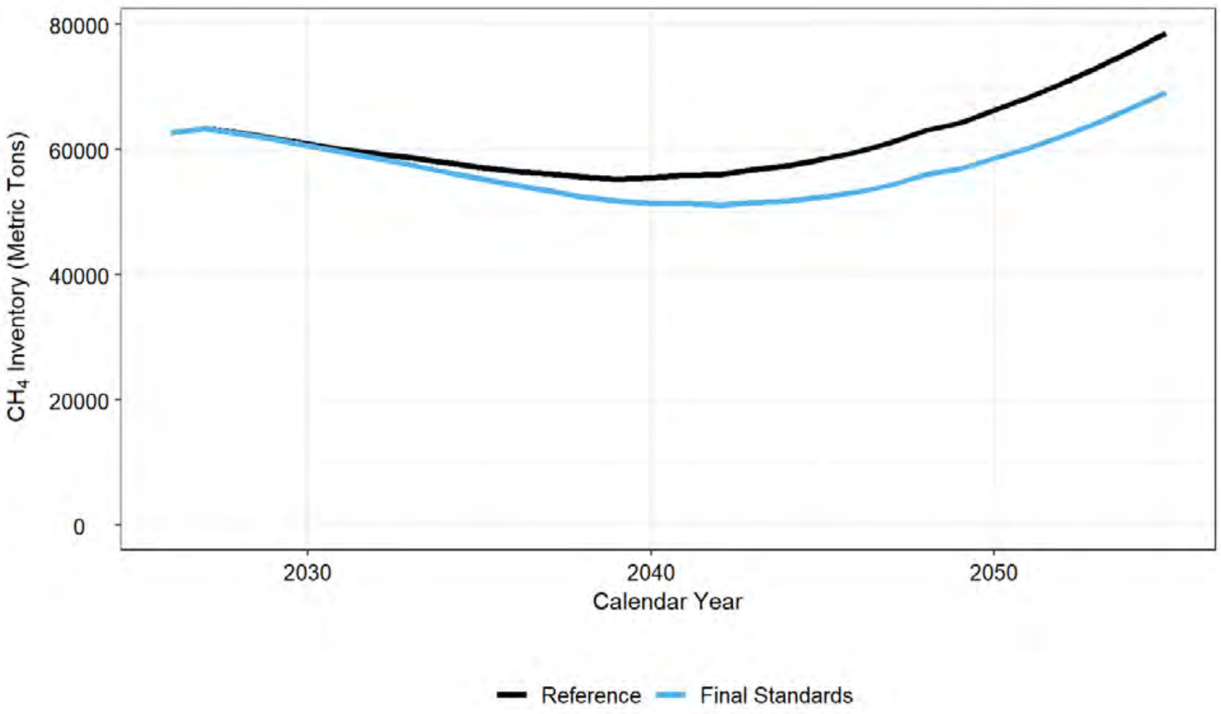

Figure 4-4 Yearly downstream CH_4 inventory for the reference case and final standards from 2027 through 2055

MOVES4.R3 models increasing methane emissions in the future based primarily on the increased adoption of heavy-duty vehicles fueled by compressed natural gas (CNG). We expect the final standards under the potential compliance pathway to increase demand for ZEVs in the 2030s and therefore reduce demand for CNG. While we project there is CNG growth in the future anyway, we project the moderating of this growth by ZEVs displacing CNG would result in significant reductions in methane emissions.

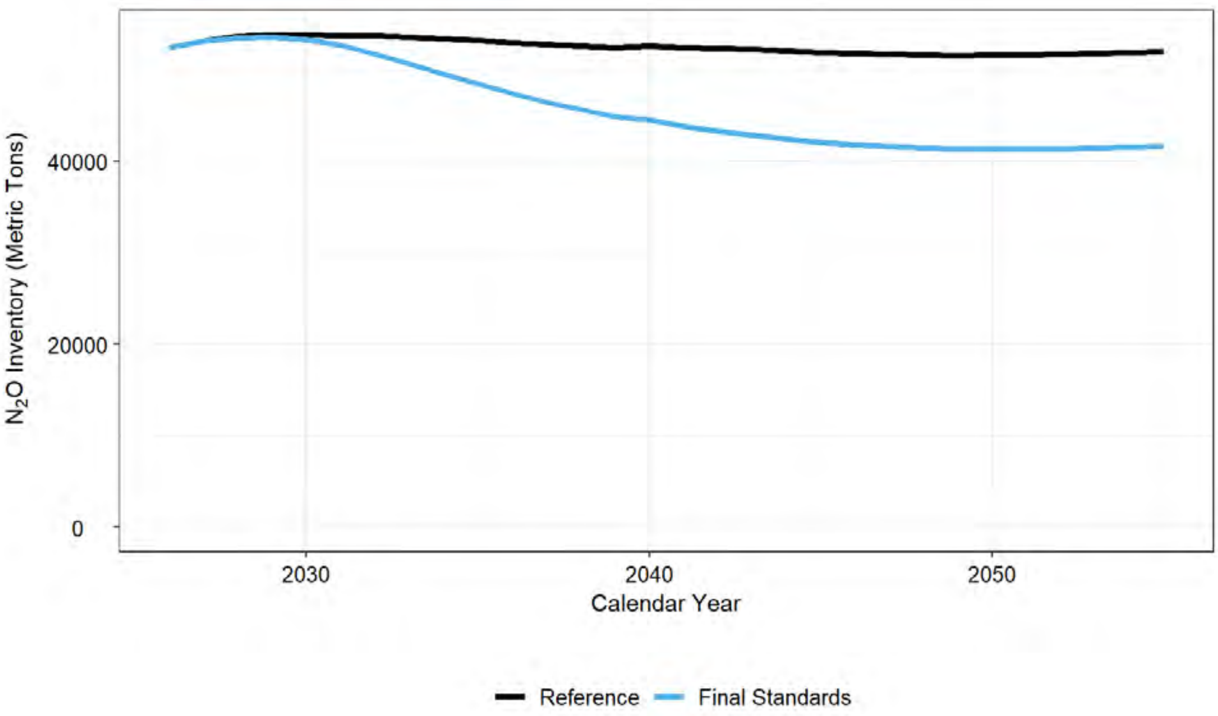

Figure 4-5 Yearly downstream N_2O inventory for the reference case and final standards from 2027 through 2055

In MOVES4.R3, the N_2O inventory is highly correlated with the VMT of HD ICE vehicles. While overall HD VMT grows in future years, the VMT of HD ICE vehicles doesn't change much because HD ZEV adoption increases, even in the reference case. In our modeled potential compliance pathway, we project the final standards would further reduce the number of HD ICE vehicles on the road as the fleet turns over to ZEVs, and therefore, N_2O emissions are reduced through the 2030s and 2040s for the final standards.

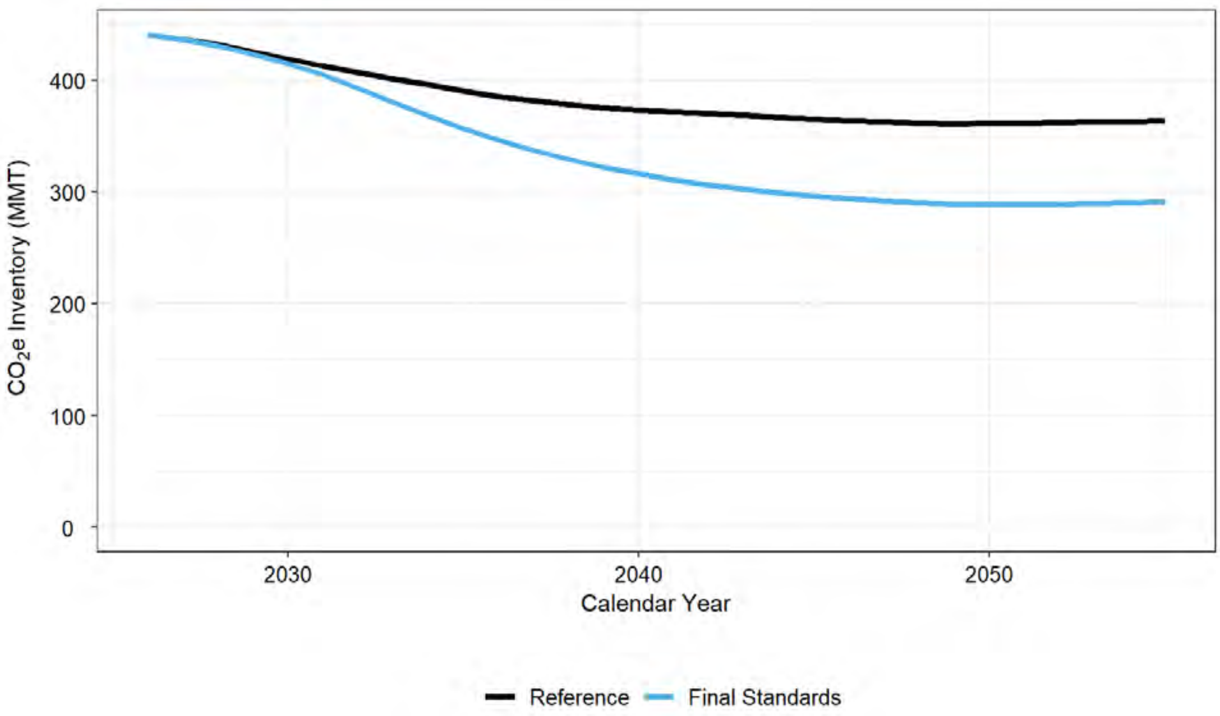

Figure 4-6 Yearly downstream CO_2e inventory for the reference case and final standards from 2027 through 2055

In the reference case, we project CO_2 and CO_2e emissions to decrease from 2027 through 2055 as HD ZEV adoption grows as described in Chapter 4.2.2 and older ICE vehicles (model years 2015 and earlier) age out of the fleet. As HD ZEV adoption levels off after California's ACT rule is fully phased in and HD VMT increases, the GHG inventory stops decreasing in the late 2040s. While this trend applies to the final standards scenario as well, we expect the greater adoption of HD ZEVs under the potential compliance pathway would result in much greater GHG emission reductions through the 2030s and 2040s.

Figure 4-7, Figure 4-8, and Figure 4-9 show the yearly inventories for NOX, $PM_{2.5}$, and VOC, respectively.

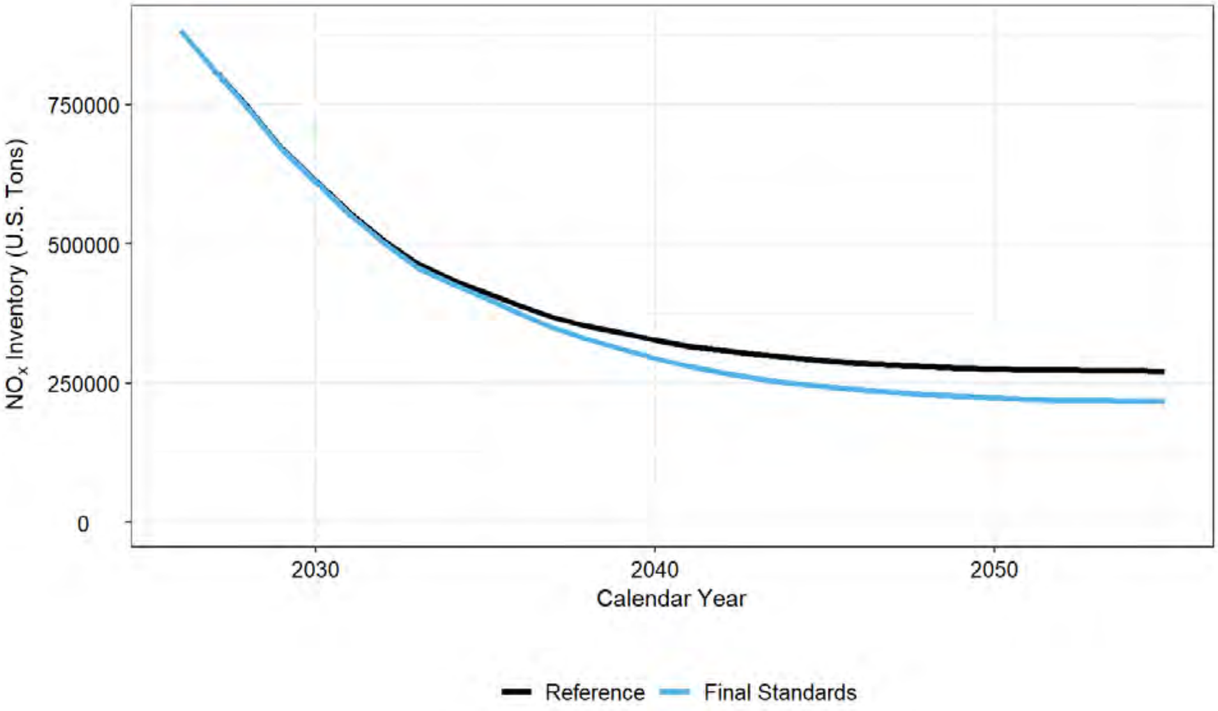

Figure 4-7 Yearly downstream NO_X inventory for the reference case and final standards from 2027 through 2055

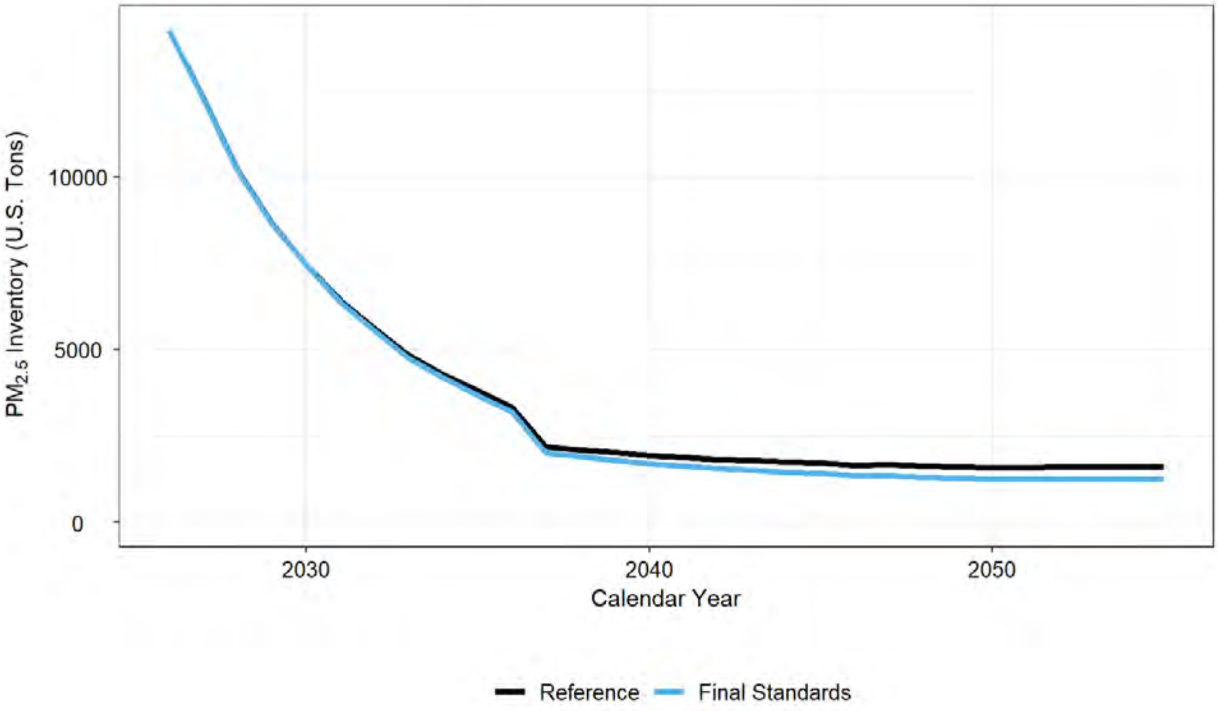

Figure 4-8 Yearly downstream $PM_{2.5}$ inventory for the reference case and final standards from 2027 through 2055

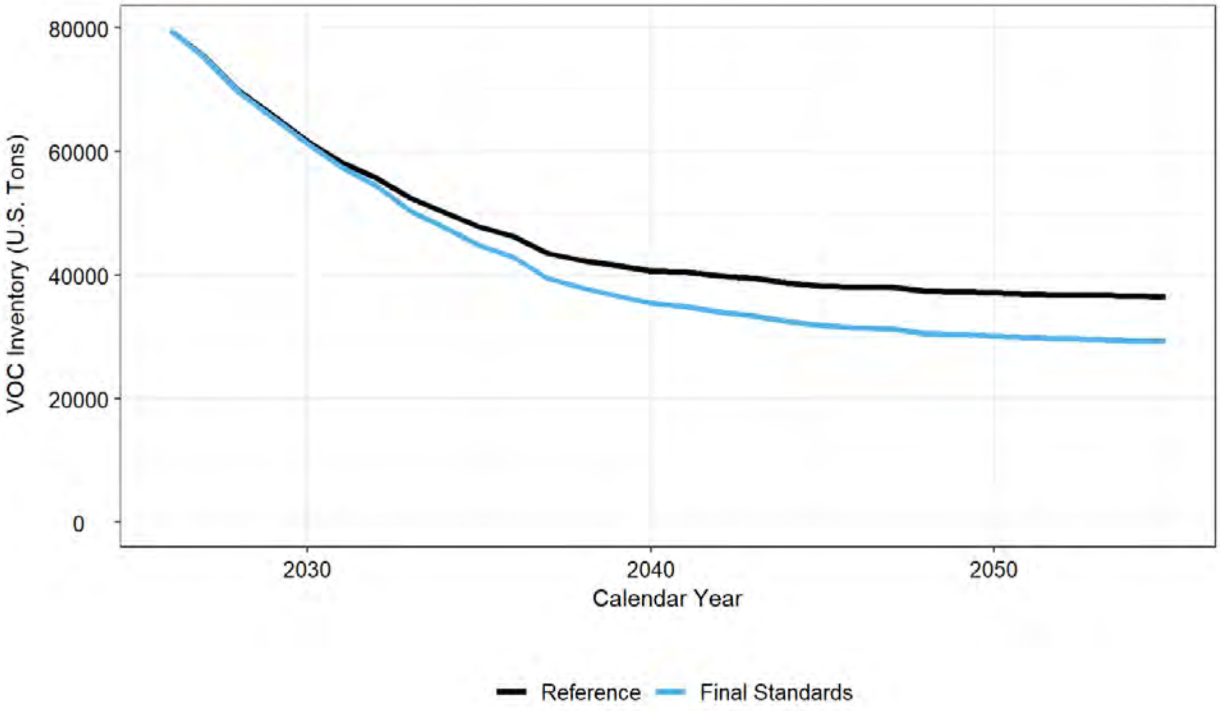

Figure 4-9 Yearly downstream VOC inventory for the reference case and final standards from 2027 through 2055

Due to the HD2027 Low NOx standards,1401 NOX emissions are projected to decrease significantly through 2055 in the reference case, but we project the adoption of ZEVs under the potential compliance pathway in the final standards case would lead to additional reductions. The projected $PM_{2.5}$ inventory shows a decline through the 2030s with a notable drop from calendar year 2036 to 2037, due to the complete fleet turnover of HD diesel vehicles without diesel particulate filters (DPFs) in MOVES. The HD $PM_{2.5}$ inventory shows little change afterward in the reference case largely because brake and tire wear represent a significant portion of the inventory, but we estimate the inventory with the final standards would continue to decrease modestly. Finally, the VOC emission inventory shows a similar trend as NOX, with emissions projected to decrease from 2027 through 2055. This is mostly because of HD ZEVs displacing LHD gasoline vehicles in the reference case. The projected increased ZEV adoption under the potential compliance pathway in the final standards case would lead to additional emission reductions.

4.3.3 Detailed Emission Impacts

This section presents detailed discussion of the downstream emission we project from the final standards, including emission reductions by regulatory class, source type, fuel type, and emission process. For the purposes of this section, we combine tailpipe and crankcase processes, such that the running process represents both running tailpipe and crankcase processes. This is also the case for starts and extended idle.

[1401] 88 FR 4296, March 27, 2023.

In our modeling of the reference case and control cases, we model a heavy-duty fleet that includes both ICE vehicles and ZEVs. As previously explained in this chapter, our modeling of ICE vehicles reflects CO_2 emission improvements driven by already existing regulations, such as HD GHG Phase 2, but we do not model an increase in ICE vehicle efficiency under the potential compliance pathway for the final standards. The emission reductions projected for the final standards represent the reduction of emissions due to a greater adoption of ZEVs phasing out ICE vehicles in the HD fleet under the potential compliance pathway.

In the following figures, we present a detailed breakdown of the emission reductions of various pollutants that we expect will result from the final standards (reflecting our modeled potential compliance pathway), with breakdowns by MOVES regulatory class, source type, fuel type, and emission process. Figure 4-10 contains breakdowns for carbon dioxide (CO_2), Figure 4-11 for methane (CH_4), Figure 4-12 for nitrogen oxides (NO_X), Figure 4-13 for $PM_{2.5}$, and finally Figure 4-14 for volatile organic compounds (VOC).

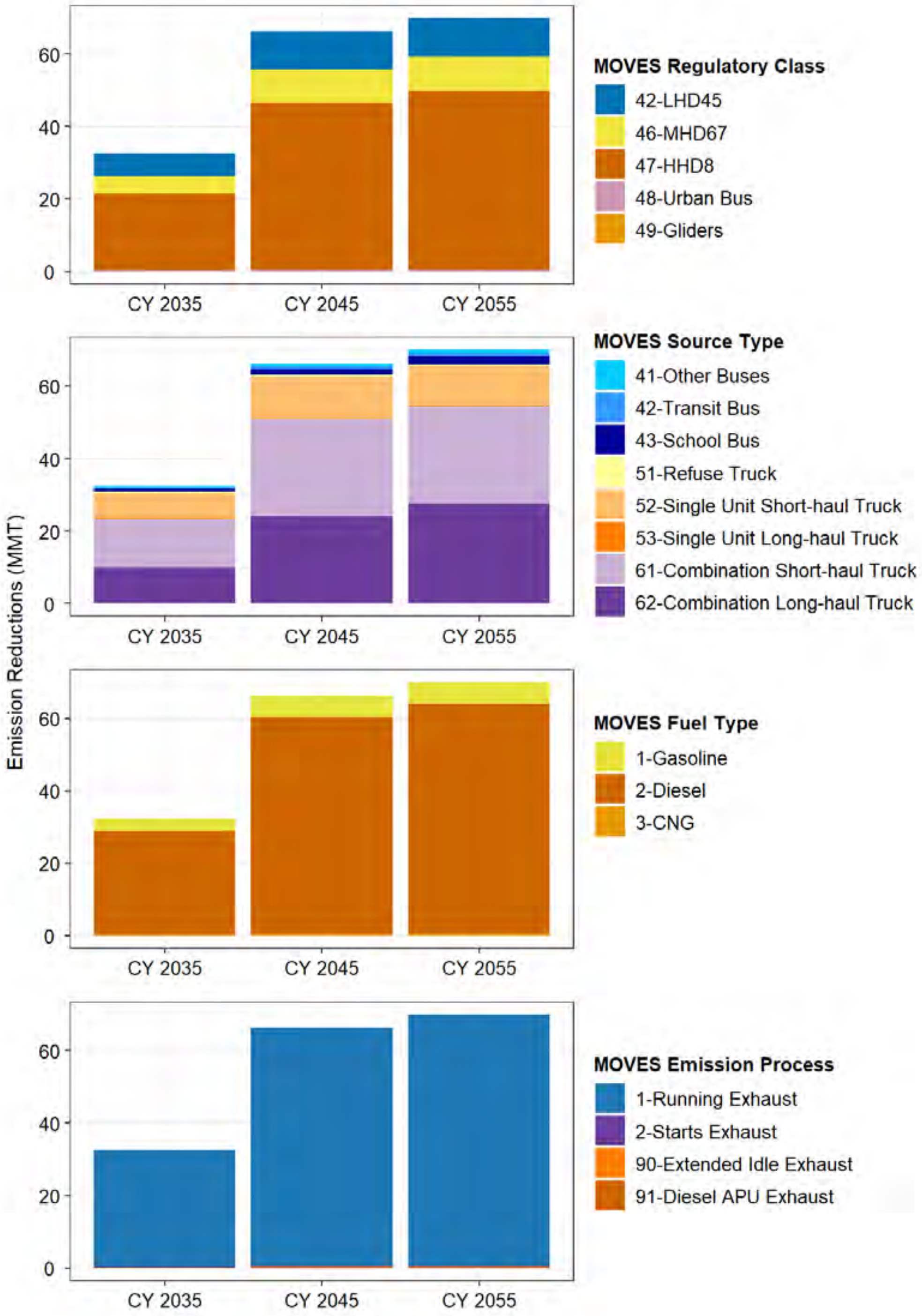

Figure 4-10 Downstream CO_2 reductions from the final standards by regulatory class, source type, fuel type, and emission process for calendar years (CY) 2035, 2045, and 2055

Because CO_2 is the primary combustion product for all ICE fuel types, CO_2 emission reductions can help visualize which ICE vehicle types are most displaced by ZEVs in our modeling of the compliance pathway we analyzed to develop the final standards. While HD

ZEVs displace vehicles of all fuel types and vehicle types, the largest increase in HD ZEV adoption relative to the reference case occurs for diesel tractors and heavy heavy-duty vehicles.

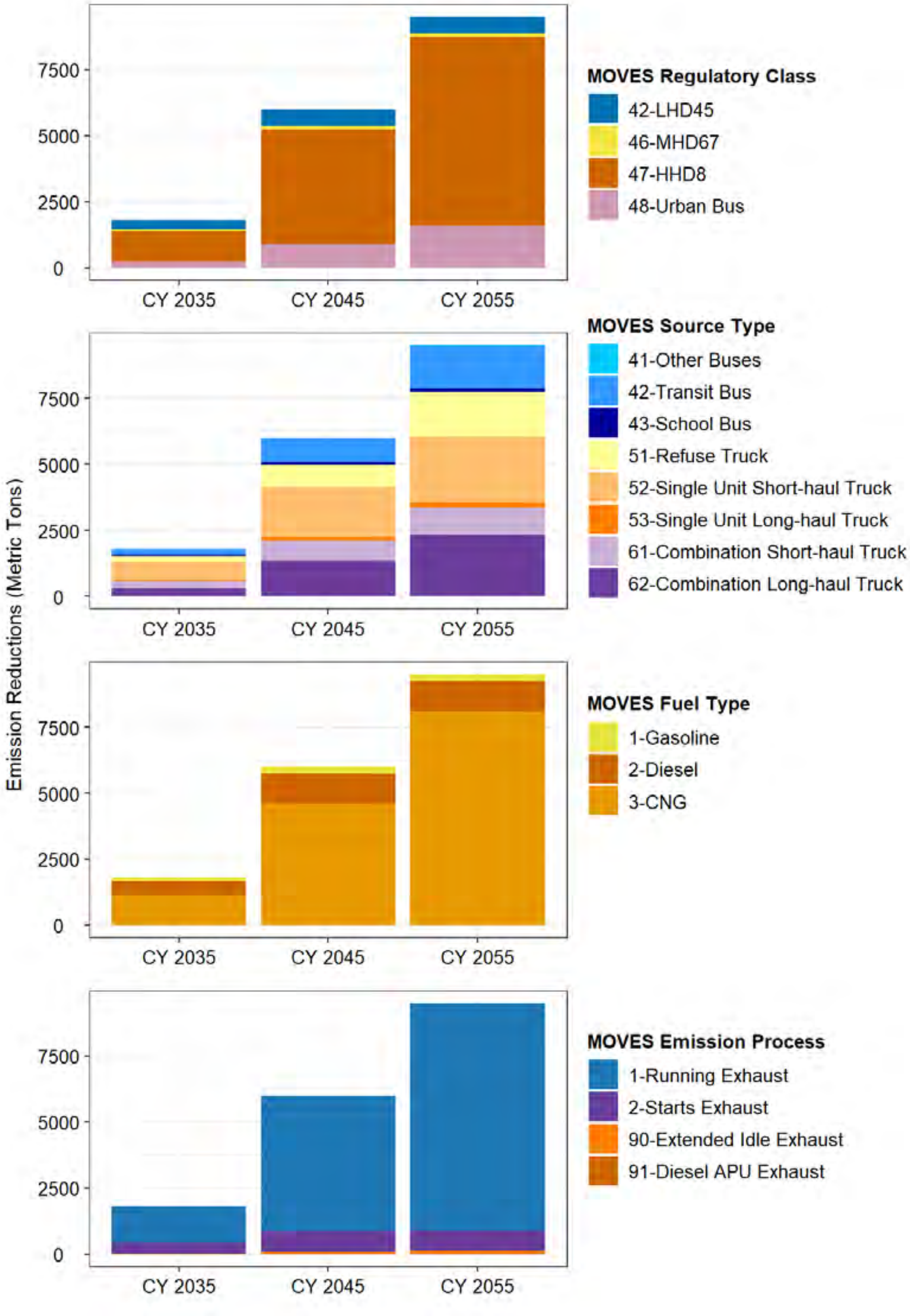

Figure 4-11 Downstream CH_4 reductions from the final standards by regulatory class, source type, fuel type, and emission process for calendar years (CY) 2035, 2045, and 2055

CNG vehicles represent the largest source of HD methane emissions in MOVES4.R3 despite their small population. This is because methane emission rates for CNG vehicles are at least 30 times greater than comparable gasoline and diesel vehicles. We project most methane reductions, therefore, will come from displacing CNG vehicles with ZEVs. MOVES4.R3 only models CNG for the Class 8 and urban bus regulatory classes (IDs 47 and 48), so all modeled methane emission reductions from CNG come from ZEV adoption for buses and heavy heavy-duty trucks. We project only modest methane emission reductions from displacement of gasoline and diesel vehicles with ZEVs.

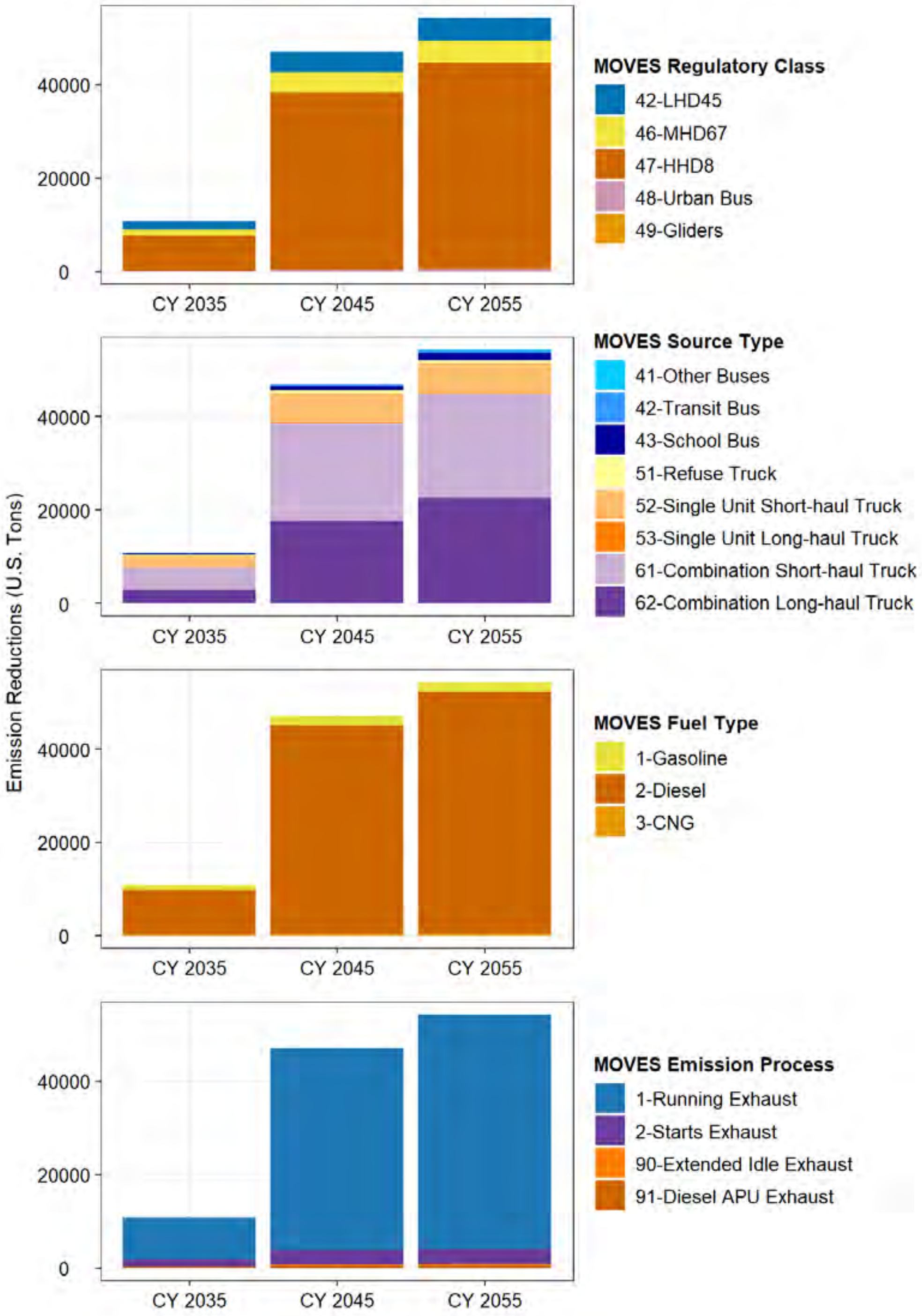

Figure 4-12 Downstream NO_X reductions from the final standards by regulatory class, source type, fuel type, and emission process for calendar years (CY) 2035, 2045, and 2055

Just as HD methane emissions are driven by CNG vehicles, HD NO_X emissions are driven by diesel vehicles. We expect that most NO_X reductions will come from ZEV adoption in combination trucks because they represent a large portion of diesel vehicles now and in the future.

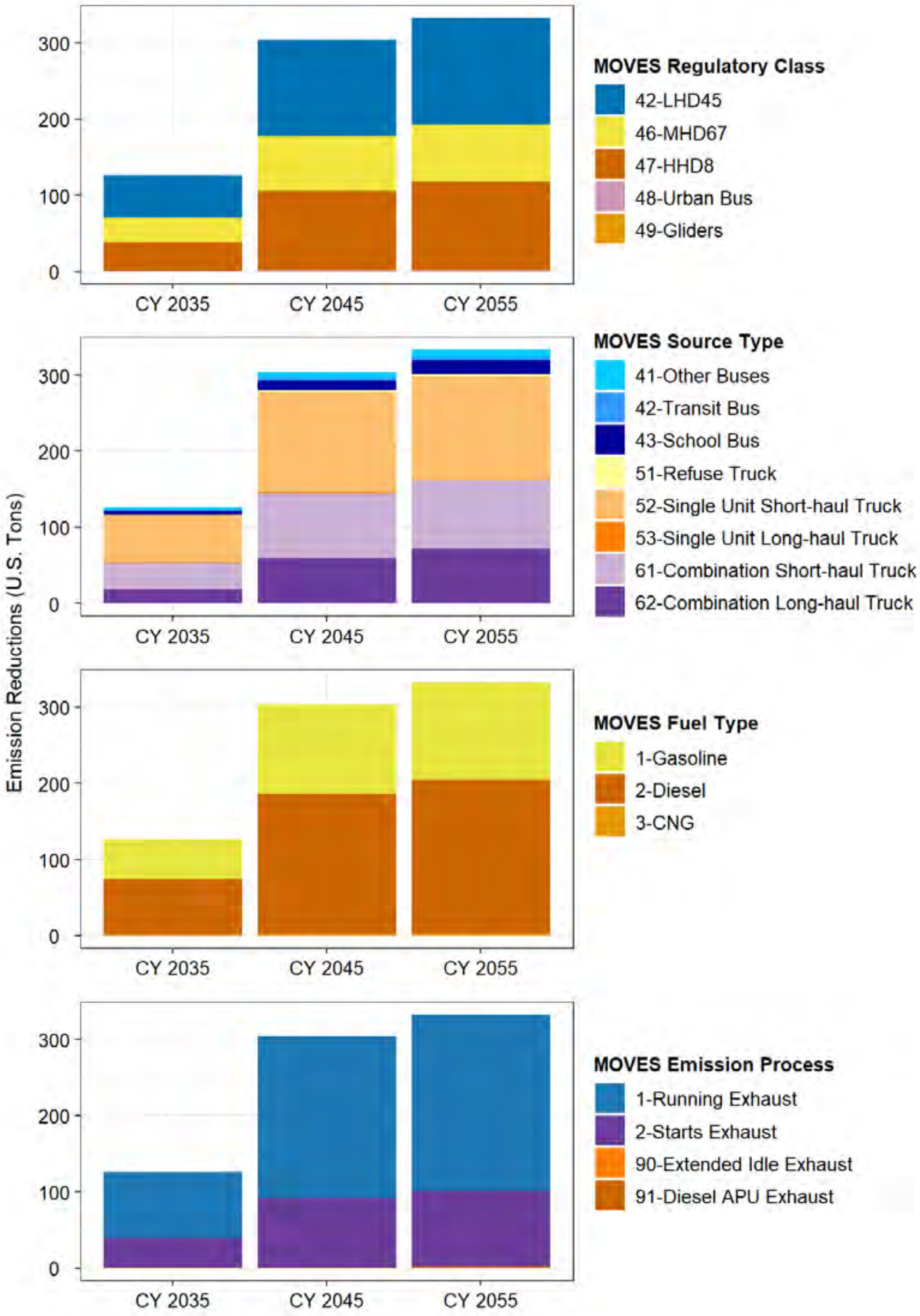

Figure 4-13 Downstream $PM_{2.5}$ reductions from the final standards by regulatory class, source type, fuel type, and emission process for calendar years (CY) 2035, 2045, and 2055

Brake and tire wear are important sources of heavy-duty $PM_{2.5}$ emissions. However, MOVES4.R3 models identical brakewear and tirewear emission rates between HD ICE and HD ZEV vehicles, as discussed in Chapter 4.1. Therefore, all modeled $PM_{2.5}$ emission reductions are driven by tailpipe emission reductions as HD ZEVs displace HD ICE vehicles.

Many heavy-duty gasoline vehicles have higher $PM_{2.5}$ emission rates than heavy-duty diesel vehicles because manufacturers install particulate filters in diesel engines to meet the PM standards, while gasoline engines can meet the same PM standards without particulate filters.[1402] Therefore, the projected total $PM_{2.5}$ emissions impact of the standards is sensitive to the number of HD gasoline vehicles displaced by ZEVs. We consequently estimate that the final standards will result in greater $PM_{2.5}$ emission reductions from light and medium HD vehicles than heavy HD vehicles, due to the number of HD gasoline vehicles in each of those groups. The most significant source of reductions is expected to be from single-unit short-haul trucks that are Class 5 and below.

[1402] The use of particulate filters typically results in PM emissions nearly an order of magnitude below the standard, where the engine-based controls in gasoline engines result in a smaller margin to the standards.

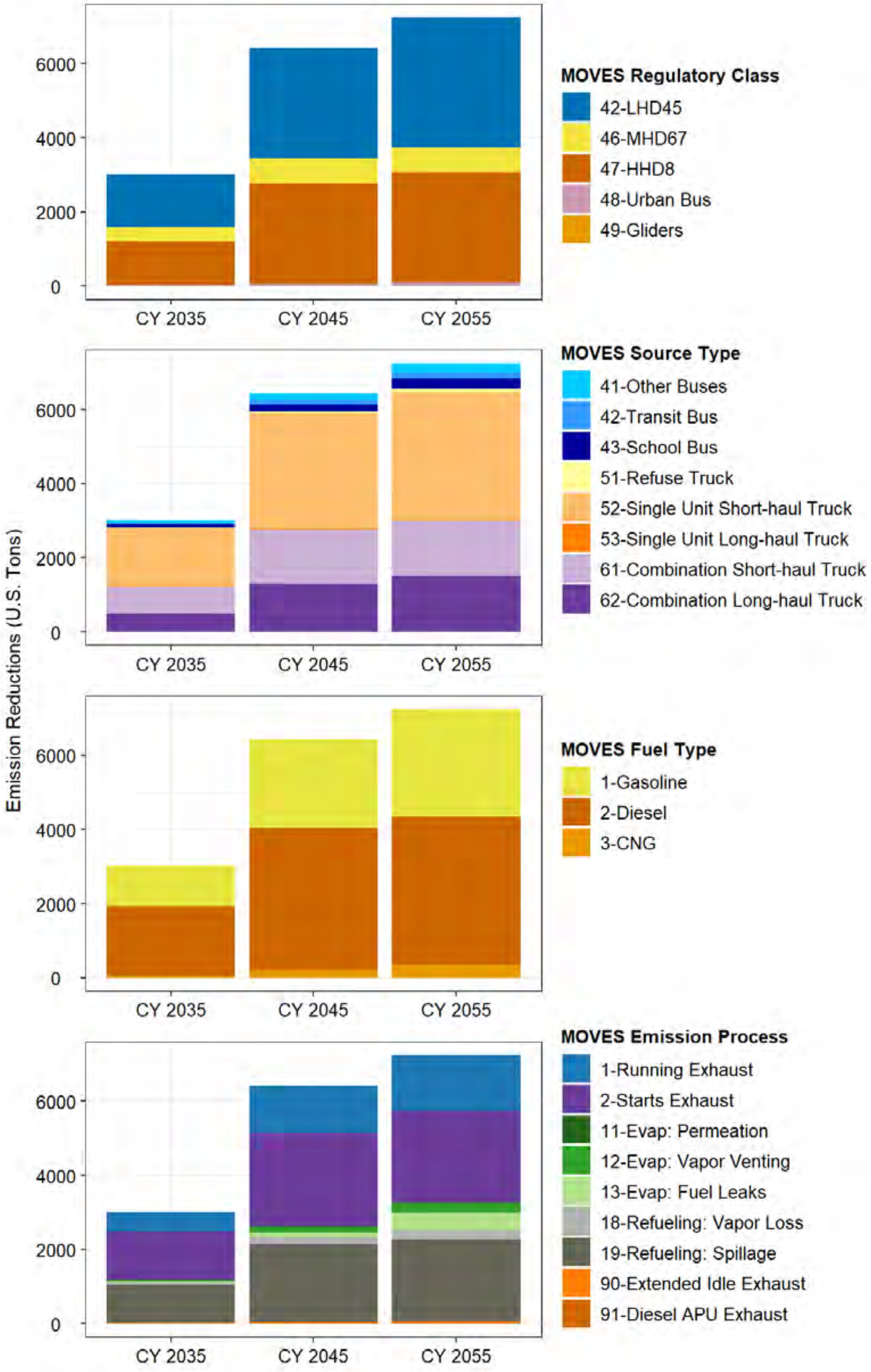

Figure 4-14 Downstream VOC reductions from the final standards by regulatory class, source type, fuel type, and emission process for calendar years (CY) 2035, 2045, and 2055

The detailed emission reductions of VOC are representative of reductions for air toxics, such as benzene, formaldehyde, and 1,3-butadiene. Most heavy-duty VOC emissions come from gasoline vehicles. VOC emissions occur during gasoline combustion while a vehicle is running or starting (especially during starts before emission controls are fully effective), evaporation while a vehicle is parked, or evaporation while a vehicle is refueling. As a result, we project a significant portion of VOC emissions reductions will result from ZEVs displacing HD gasoline vehicles, which are mostly light HD vehicles such as delivery trucks or gasoline buses. VOCs can also be emitted from diesel or CNG combustion and refueling (especially when fuel is spilled), so we project some VOC reductions can also be attributed to ZEVs displacing HD diesel vehicles.

In summary, we model that the displacement of HD ICE vehicles of all fuel types with HD ZEVs under the potential compliance pathway will drive broad emission reductions—we expect the displacement of diesel HD vehicles will be the primary source of NO_X reductions; we project the displacement of gasoline light HD trucks will be the primary source of $PM_{2.5}$ and VOC reductions; and we anticipate the displacement of HD CNG vehicles will be the primary source of methane reductions.

We project smaller emission reductions in this final rule analysis than we projected in the NPRM because of the increased ZEV adoption in the reference case. Our increased reference case ZEV adoption is greatest for light heavy-duty vehicles, which means LHD gasoline vehicles make up a much smaller portion of the HD fleet in the final reference case than in our NPRM reference case. Therefore, emissions reductions for pollutants which are driven by emissions from gasoline vehicles, most notably $PM_{2.5}$ and VOCs, are much smaller in our final rule analysis than our NPRM analysis.

4.4 National Upstream Emission Inventory Impacts of the Final Standards

While we expect that downstream emissions reductions will result from increased adoption of HD ZEVs in the final standards, we expect the final standards will increase emissions from electricity generation units (EGUs) under our potential compliance pathway because the energy to operate ZEVs comes from electricity. We also estimate that the final emission standards will reduce demand for liquid fuel and reduce emissions from refineries.

EGU emissions estimates are based on IPM output as described in Chapter 4.2.4. IPM produces emissions estimates for a more limited set of pollutants than MOVES. We have IPM estimates for NO_X, $PM_{2.5}$, VOC, and SO_2 emissions only, so we do not present the larger set of criteria and air toxic pollutants in this analysis like we did for downstream emissions. MOVES and IPM estimate emissions for an identical set of GHGs, including carbon dioxide, methane, and nitrous oxide. Our estimates of refinery emissions include the same set of criteria pollutants and GHGs as our EGU estimates.

As discussed in Chapter 4.2.4, the methodology used to estimate EGU and refinery emissions cannot estimate a total EGU emissions inventory for the reference scenario. Therefore, relative comparisons between the reference and the control scenarios (e.g., percent changes) are not possible and only the emissions impacts in absolute tons from the final standards are presented.

4.4.1 Analysis Year Impacts

Our estimates of the changes in GHG emissions from EGUs due to the final standards, relative to the reference case, are presented below in Table 4-21 for calendar years 2035, 2045, and 2055, in million metric tons (MMT). Our estimates for additional criteria pollutant emissions are presented in Table 4-22.

Table 4-21 Annual GHG emission increases from EGUs from the final standards in calendar years (CYs) 2035, 2045, and 2055

Pollutant	**100-year GWP**	**Additional EGU Emissions (MMT)**		
		CY 2035	**CY 2045**	**CY 2055**
Carbon Dioxide (CO_2)	1	29.3	14.5	12.9
Methane (CH_4)	28	0.00186	0.00033	0.00026
Nitrous Oxide (N_2O)	265	0.00026	0.00004	0.00003
CO_2 Equivalent (CO_2e)	---	*29.4*	*14.5*	*12.9*

Table 4-22 Annual criteria pollutant emission increases from EGUs from the final standards in calendar years (CYs) 2035, 2045, and 2055

Pollutant	**Increase in EGU Emissions (U.S. Tons)**		
	CY 2035	**CY 2045**	**CY 2055**
Nitrogen Oxides (NO_X)	9,719	1,588	1,520
Primary $PM_{2.5}$	1,418	596	513
Volatile Organic Compounds (VOC)	467	347	196
Sulfur Dioxide (SO_2)	11,726	648	69

In 2055, we estimate the final standards will increase EGU emissions of CO_2 by 12.9 million metric tons, compared to 29.3 million metric tons in 2035. There are similar trends for all other pollutants. EGU impacts decrease over time because of changes in the projected power generation mix as electricity generation uses less fossil fuels.

We expect the final standards to lead to a decrease in refinery emissions. Table 4-23 presents the estimated impacts of the final standards on refinery GHG emissions (in metric tons) from refineries and Table 4-24 presents the estimated impacts on refinery criteria pollutant emissions (in U.S. tons), both relative to the reference case.

Table 4-23 Annual GHG emission reductions from refineries from the final standards in calendar years (CYs) 2035, 2045, and 2055

Pollutant	**100-year GWP**	**Refinery Emission Reductions (Metric Tons)**		
		CY 2035	**CY 2045**	**CY 2055**
Carbon Dioxide (CO_2)	1	331,008	649,943	690,477
Methane (CH_4)	28	17	32	34
Nitrous Oxide (N_2O)	265	3	6	6
CO_2 Equivalent (CO_2e)	---	*332,240*	*652,343*	*693,016*

Table 4-24 Annual criteria pollutant emission reductions from refineries from the final standards in calendar years (CYs) 2035, 2045, and 2055

Pollutant	**Refinery Emission Reductions (U.S. Tons)**		
	CY 2035	**CY 2045**	**CY 2055**
Nitrogen Oxides (NO_X)	148	288	304
Primary $PM_{2.5}$	34	66	70
Volatile Organic Compounds (VOC)	112	216	226
Sulfur Dioxide (SO_2)	46	89	94

4.4.2 Year-over-year Impacts

We estimated emission impacts for two upstream sectors – electricity generation and fuel refining. In general, the year-over-year emission impact of the final standards on either sector depends on two factors. The first factor is how each sector would be impacted by an increase in HD ZEVs from our potential compliance pathway in modeling the final standards, and the second is how the emissions of each sector are expected to change in the future independent of the final standards. The two factors lead to different trends for EGUs and refineries.

We expect the increase in HD ZEV adoption to cause greater electricity demand and a lower demand for refined fuels, therefore causing an increase in EGU emissions and a decrease in refinery emissions. MOVES models a monotonic increase in the number of HD ZEVs in the vehicle fleet from 2027 through 2055, so we should expect the emission impacts for both sectors to grow in magnitude over time.

Simultaneous with these impacts, the power sector is expected to shift the power generation mix away from fossil fuel combustion in favor of renewable energy sources, therefore leading to a decrease in emissions per unit of energy demand overall. This can be seen in Table 4-11from Chapter 4.2.4.2. Fuel refining, on the other hand, has much more stable emission factors, as can be seen in Table 4-14 and Table 4-15 from Chapter 4.2.5.

Because of these differences, we expect to see EGU emission impacts that show both a trend of increasing electrification and a decrease in emissions as renewable adoption increases. Refinery emission impacts, on the other hand, are much more closely correlated with the trend of increasing electrification.

Our estimates of year-over-year emission impacts of the final standards on GHG emissions from EGUs are presented in Table 4-25, Table 4-26, and Figure 4-15. Table 4-25 presents the impacts on methane and nitrous oxide emissions in metric tons, Table 4-26 presents the impacts on CO_2 and total CO_2e emissions in million metric tons. Figure 4-15 presents the impacts graphically, with emission reductions of all three GHGs presented in terms of CO_2 equivalency.

Table 4-25 Year-over-year EGU emission increases from the final standards for CH_4 and N_2O

Calendar Year	EGU Emissions Increase (Metric Tons)	
	Methane (CH_4)	**Nitrous Oxide (N_2O)**
2027	16	2
2028	42	6
2029	79	11
2030	170	23
2031	372	51
2032	751	103
2033	1,127	155
2034	1,499	206
2035	1,863	256
2036	1,869	257
2037	1,753	241
2038	1,523	210
2039	1,190	164
2040	768	106
2041	713	97
2042	640	86
2043	550	72
2044	448	56
2045	334	38
2046	322	36
2047	307	34
2048	291	32
2049	273	29
2050	256	27
2051	258	27
2052	259	27
2053	260	27
2054	260	27
2055	261	27

Table 4-26 Year-over-year EGU emission increases from the final standards for CO_2 and CO_2e

Calendar Year	EGU Emissions Increase (Million Metric Tons)	
	Carbon Dioxide (CO_2)	CO_2 Equivalent (CO_2e)
2027	0.3	0.3
2028	0.7	0.7
2029	1.2	1.2
2030	2.7	2.7
2031	5.8	5.9
2032	11.8	11.8
2033	17.7	17.8
2034	23.5	23.6
2035	29.3	29.4
2036	29.0	29.1
2037	26.7	26.8
2038	22.5	22.6
2039	16.6	16.7
2040	9.3	9.4
2041	10.4	10.5
2042	11.5	11.6
2043	12.6	12.6
2044	13.6	13.6
2045	14.5	14.5
2046	14.2	14.3
2047	13.9	13.9
2048	13.5	13.5
2049	13.1	13.1
2050	12.7	12.7
2051	12.8	12.8
2052	12.8	12.8
2053	12.9	12.9
2054	12.9	12.9
2055	12.9	12.9

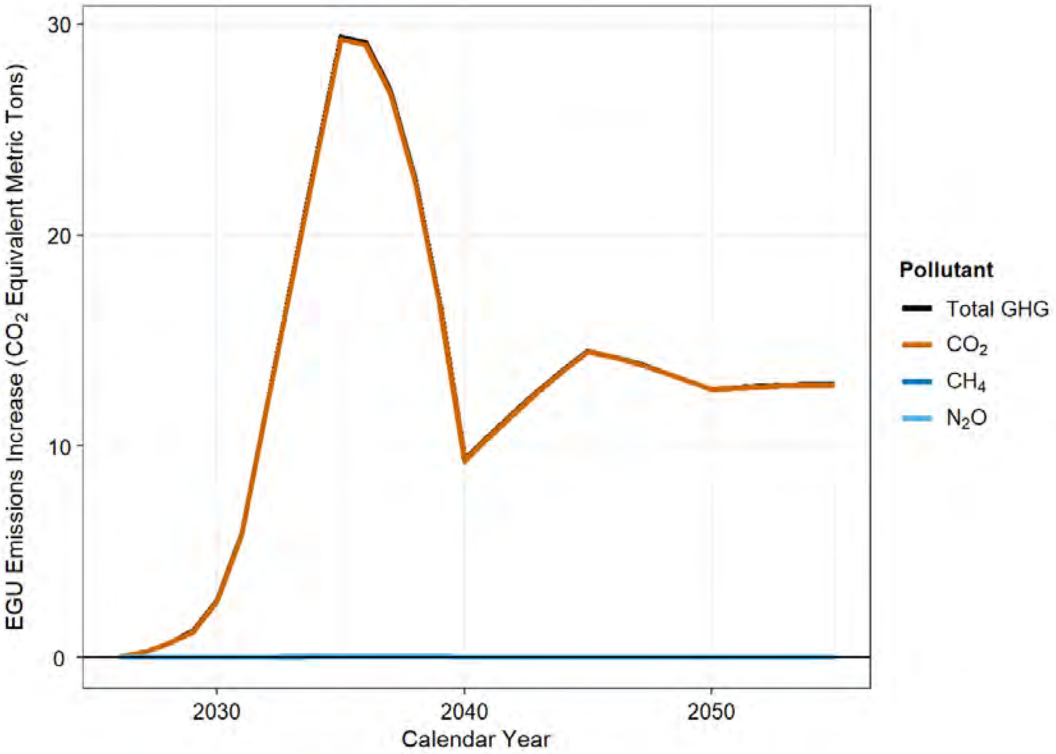

Figure 4-15 Yearly GHG emissions increase from EGUs from the final standards from 2027 through 2055

Almost all GHG emission increases from EGUs are driven by increases in CO_2 specifically, which represents more than 99 percent of the total increase in total GHG emissions.

Our estimates of year-over-year emission impacts of the final standards on criteria pollutant emissions from EGUs are presented in Table 4-27 and Figure 4-16.

Table 4-27 Year-over-year EGU emission inventory increases for criteria pollutants from the final standards

Calendar Year	EGU Emissions Increase (U.S. Tons)			
	NO_x	VOC	$PM_{2.5}$	SO_2
2027	83	4	12	100
2028	220	11	32	265
2029	412	20	60	497
2030	887	43	129	1,071
2031	1,941	93	283	2,342
2032	3,915	188	571	4,724
2033	5,876	282	857	7,089
2034	7,818	375	1,140	9,432
2035	9,719	467	1,418	11,726
2036	9,541	463	1,413	11,362
2037	8,661	427	1,312	10,106
2038	7,133	362	1,122	8,030
2039	5,025	269	852	5,220
2040	2,411	153	513	1,771
2041	2,331	190	540	1,623
2042	2,204	229	562	1,431
2043	2,033	269	579	1,200
2044	1,825	308	590	936
2045	1,588	347	596	648
2046	1,582	320	583	542
2047	1,567	290	566	428
2048	1,544	258	546	310
2049	1,518	226	525	190
2050	1,494	193	505	68
2051	1,504	194	508	68
2052	1,511	195	510	68
2053	1,516	196	512	69
2054	1,519	196	513	69
2055	1,520	196	513	69

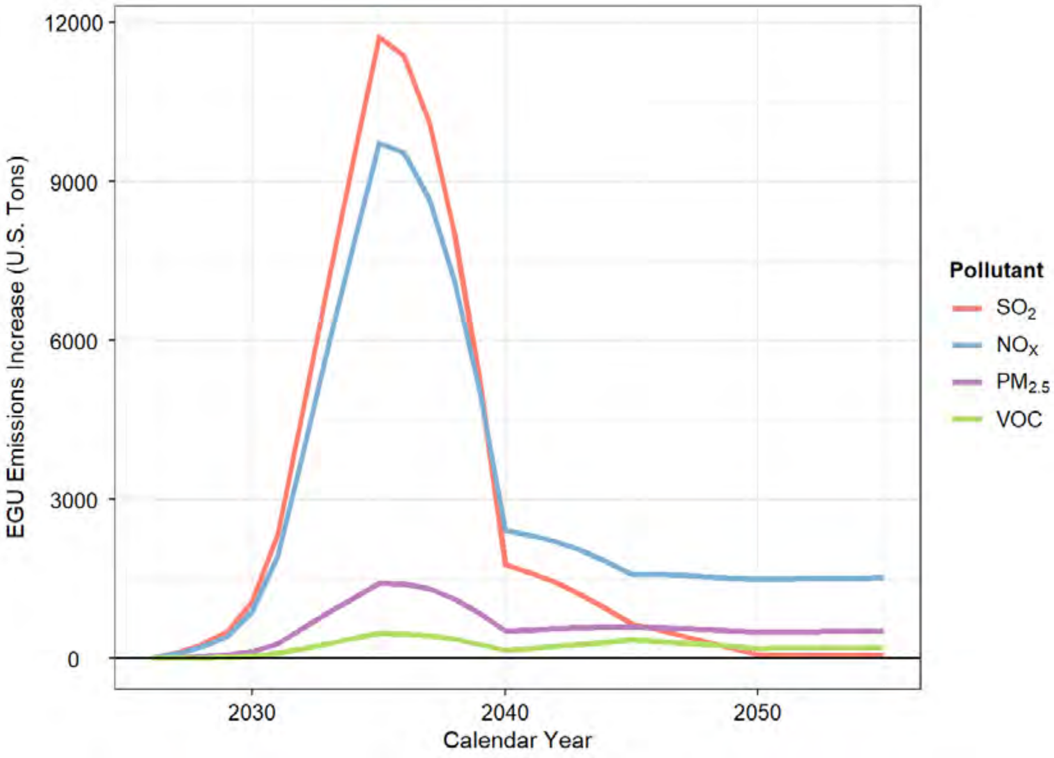

Figure 4-16 Yearly criteria pollutant emissions increase from EGUs from the final standards from 2027 through 2055

From 2027 through the 2030s, EGU emission increases are expected to start small and grow as HD ZEV adoption drives greater increases in energy demand. All four criteria pollutants see their largest increase in EGU emissions in 2035. But through the 2030s and 2040s, a substantial increase in the use of renewable energy sources is expected to take place in the national power generation mix, driven in part by the IRA. This is expected to lead to decreases in EGU emissions at a national level, including a decrease in EGU emissions attributable to HD ZEVs and the final standards.

Table 4-28 and Figure 4-17 present the year-over-year GHG emission reductions from refineries, in metric tons. Figure 4-17 presents all GHG impacts in CO_2 equivalent terms. Similar to EGUs, CO_2 represents over 99 percent of the impact of GHG emissions from refineries from the final standards.

Table 4-28 Year-over-year refinery GHG emission reductions from the final standards

Calendar Year	Refinery Emissions Reduction (Metric Tons)			
	CO_2	CH_4	N_2O	CO_2 Equivalent
2027	9,858	0.5	0.1	9,896
2028	20,579	1.1	0.2	20,657
2029	32,140	1.7	0.3	32,262
2030	48,141	2.6	0.4	48,322
2031	86,429	4.5	0.7	86,753
2032	152,984	7.9	1.3	153,556
2033	216,373	11.2	1.9	217,180
2034	276,137	14.2	2.4	277,166
2035	331,008	16.9	2.9	332,240
2036	381,401	19.5	3.3	382,819
2037	427,812	21.8	3.7	429,402
2038	469,665	23.8	4.1	471,409
2039	507,369	25.7	4.4	509,253
2040	541,395	27.4	4.7	543,403
2041	571,840	28.9	4.9	573,959
2042	598,023	30.1	5.2	600,237
2043	619,458	31.1	5.4	621,749
2044	636,560	31.9	5.5	638,912
2045	649,943	32.5	5.6	652,343
2046	662,267	33.0	5.7	664,710
2047	671,612	33.4	5.8	674,089
2048	677,775	33.6	5.9	680,272
2049	683,220	33.8	5.9	685,736
2050	689,802	34.1	6.0	692,340
2051	692,111	34.2	6.0	694,658
2052	693,247	34.2	6.0	695,797
2053	693,335	34.2	6.0	695,885
2054	692,406	34.2	6.0	694,953
2055	690,477	34.1	6.0	693,016

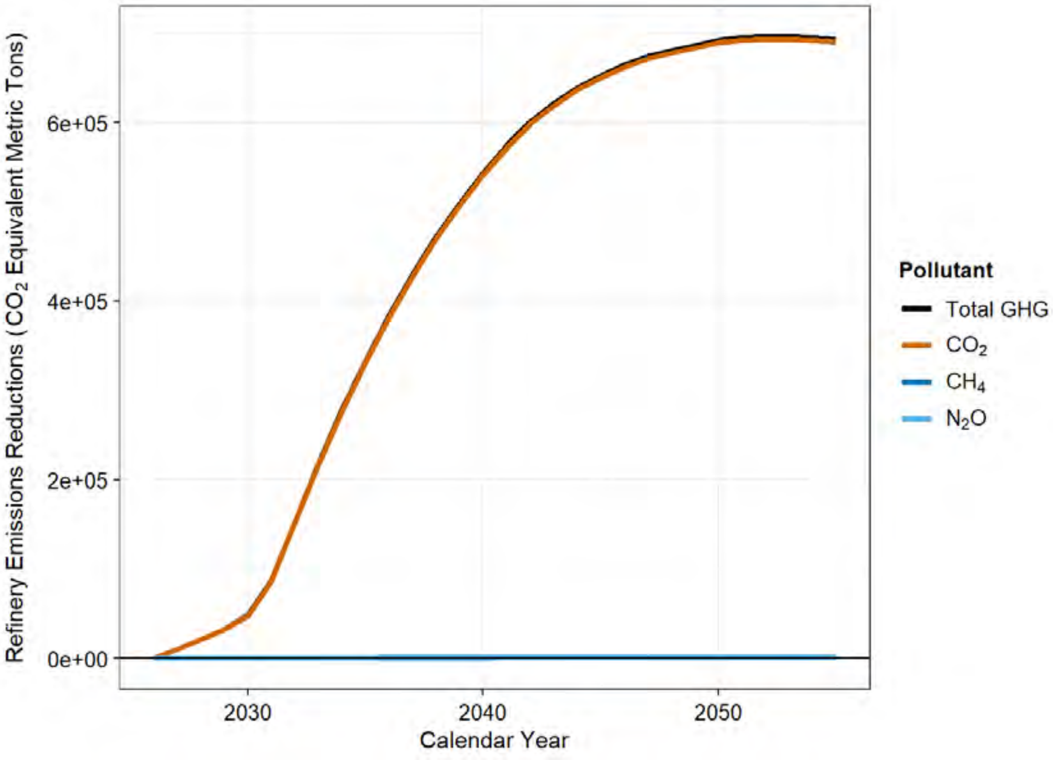

Figure 4-17 Yearly GHG emissions reductions from refineries from the final standards from 2027 through 2055

Table 4-29 and Figure 4-18 present the year-over-year criteria pollutant emission reductions from refineries from the final standards.

Table 4-29 Year-over-year refinery criteria pollutant emission reductions from the final standards

Calendar Year	Refinery Emissions Reductions (U.S. Tons)			
	NO_x	VOC	$PM_{2.5}$	SO_2
2027	5	3	1	1
2028	10	7	2	3
2029	15	11	3	5
2030	22	16	5	7
2031	39	29	9	12
2032	69	52	16	21
2033	97	73	23	30
2034	124	93	29	38
2035	148	112	34	46
2036	170	129	39	53
2037	191	144	44	59
2038	209	158	48	65
2039	226	171	52	70
2040	241	182	56	75
2041	255	192	59	79
2042	266	200	61	82
2043	275	207	64	85
2044	282	212	65	87
2045	288	216	66	89
2046	293	219	68	90
2047	297	222	68	92
2048	299	223	69	92
2049	301	225	69	93
2050	304	226	70	94
2051	305	227	70	94
2052	305	227	70	94
2053	305	227	70	94
2054	305	227	70	94
2055	304	226	70	94

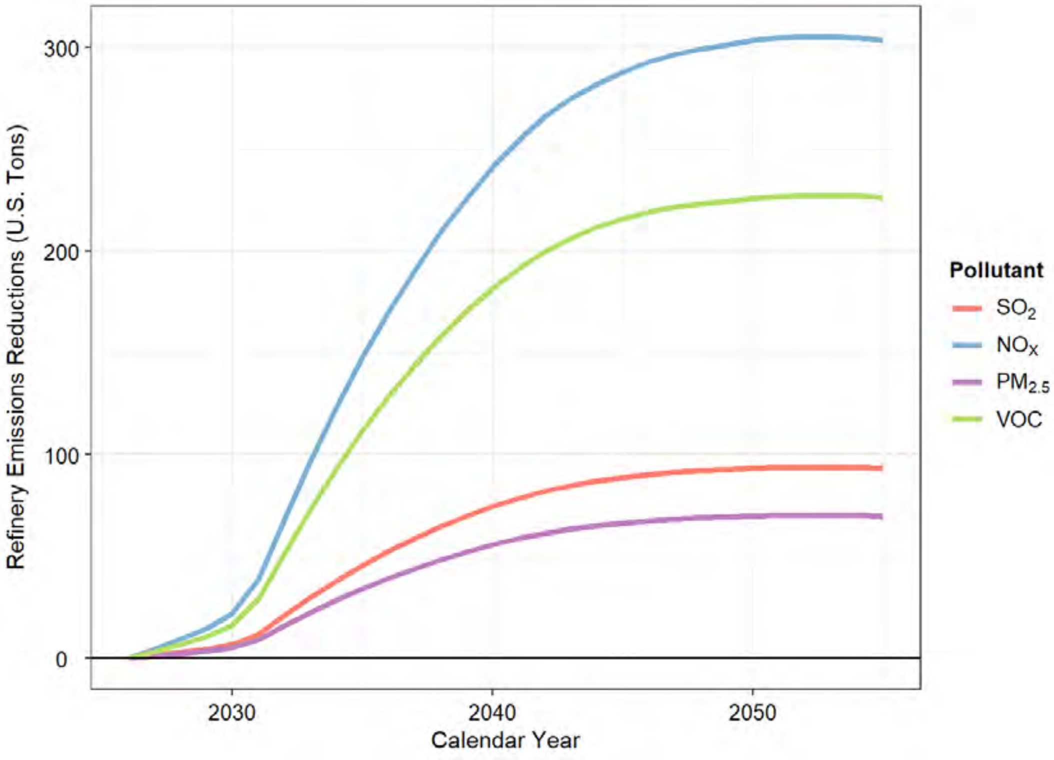

Figure 4-18 Yearly criteria pollutant emissions reductions from refineries from the final standards from 2027 through 2055

We estimate that refinery emission reductions start small in 2027 and grow through 2055. Unlike for EGUs, we do not anticipate a meaningful change in the emission rates related to the refining process, so refinery emission reductions are much more tightly correlated with the modeled drop in liquid fuel demand as HD ZEVs make up an increasing proportion of the national heavy-duty fleet.

4.5 Net Emissions Impacts of the Final Standards

While we present a net emissions impact of the final CO_2 emission standards, it is important to note that some upstream emission sources are not included in the estimates. As discussed in Chapter 4.1, we received several comments on the upstream sources considered in our analysis. Our estimates of upstream EGU and refinery emission impacts also depend on assumptions that we made in our analysis, as discussed in Chapter 4.2.2. Therefore, we present emission impact estimates for various other sensitivity analyses in Chapters 4.8 and 4.9.

4.5.1 Analysis Year Impacts

Table 4-30 shows a summary of our modeled downstream, upstream, and net GHG emission impacts of the final standards relative to the reference case, in million metric tons, for calendar years 2035, 2045, and 2055. Table 4-31 contains a summary of the modeled net impacts of the final standards on criteria pollutant emissions.

Table 4-30 Annual net impacts[A] on GHG emissions from the final standards in calendar years (CYs) 2035, 2045, and 2055

Pollutant	GWP	Calendar Year	Emission Impact (MMT)			
			Downstream	EGU	Refinery	Net
Carbon Dioxide (CO_2)	1	2035	-32.5	29.3	-0.3	-3.5
		2045	-66.3	14.5	-0.6	-52.4
		2055	-70.0	12.9	-0.7	-57.8
Methane (CH_4)	28	2035	-0.002	0.002	0.000	0.000
		2045	-0.006	0.000	0.000	-0.006
		2055	-0.010	0.000	0.000	-0.009
Nitrous Oxide (N_2O)	265	2035	-0.005	0.000	0.000	-0.005
		2045	-0.010	0.000	0.000	-0.010
		2055	-0.010	0.000	0.000	-0.010
CO_2 Equivalent (CO_2e)	---	*2035*	*-33.8*	*29.4*	*-0.3*	*-4.7*
		2045	*-69.1*	*14.5*	*-0.7*	*-55.2*
		2055	*-73.0*	*12.9*	*-0.7*	*-60.8*

[A] We present emissions reductions as negative numbers and emission increases as positive numbers.

Table 4-31 Annual net impacts[A] on criteria pollutant emissions from the final standards in calendar years (CYs) 2035, 2045, and 2055

Pollutant	Calendar Year	Emission Impact (U.S. Tons)			
		Downstream	EGU	Refinery	Net
Nitrogen Oxides (NO_X)	2035	-10,801	9,719	-148	-1,230
	2045	-47,027	1,588	-288	-45,728
	2055	-54,268	1,520	-304	-53,051
Particulate Matter ($PM_{2.5}$)	2035	-126	1,418	-34	1,258
	2045	-302	596	-66	227
	2055	-331	513	-70	113
Volatile Organic Compounds (VOC)	2035	-3,014	467	-112	-2,659
	2045	-6,426	347	-216	-6,295
	2055	-7,242	196	-226	-7,272
Sulfur Dioxide (SO_2)	2035	-126	11,726	-46	11,554
	2045	-256	648	-89	304
	2055	-270	69	-94	-295

[A] We present emissions reductions as negative numbers and emission increases as positive numbers.

In 2055, we estimate the final standards will result in a net decrease of 61 million metric tons of GHG emissions. We also estimate net decreases in emissions of NO_X, VOC, and SO_2 in 2055. However, we estimate a net increase in $PM_{2.5}$ emissions.

In general, net emission impacts are determined by the interaction of two effects. First, HD ZEV adoption increases over time, thus reducing downstream and refinery emissions. Second, the increase in EGU emissions declines over time as the electricity grid becomes cleaner due to EGU regulations and the future power generation mix changes, in part driven by the IRA. These effects can balance differently for different pollutants.

Downstream emissions are a more significant source of GHG, NO_X, and VOC emissions, so net reductions grow over time. However, EGUs are a more significant source of SO_2 emissions (largely driven by coal combustion) and $PM_{2.5}$ emissions (largely driven by coal and natural gas combustion). We estimate a net increase in SO_2 emissions in 2035 and 2045 but a net decrease in 2055 as coal is phased out of the electricity sector. Natural gas remains an important fuel for electricity generation, which is why we estimate a net increase in $PM_{2.5}$ in all years. However, consistent with the trends for other pollutants, the magnitude of the $PM_{2.5}$ emission increases diminish over time.

4.5.2 Year-over-year Impacts

Table 4-32 and Table 4-33 show our estimated year-over-year net GHG emission impacts from the final standards. Table 4-32 presents estimates for methane and nitrous oxide in metric tons and Table 4-33 presents the estimates for carbon dioxide and total GHG emission, in terms of CO_2 equivalency, in million metric tons. Figure 4-19 shows the net GHG impacts for CO_2 equivalent total GHG emissions.

Table 4-32 Year-over-year net emission impacts[A] of the final standards on emissions of CH_4 and N_2O, in metric tons

Calendar Year	**CH_4 Impacts (Metric Tons)**				**N_2O Impacts (Metric Tons)**			
	Downstream	**EGU**	**Refinery**	***Net***	**Downstream**	**EGU**	**Refinery**	***Net***
2027	-22	16	-1	*-6*	-57	2	0	*-55*
2028	-85	42	-1	*-44*	-147	6	0	*-142*
2029	-152	79	-2	*-75*	-269	11	0	*-259*
2030	-238	170	-3	*-70*	-508	23	0	*-485*
2031	-432	372	-5	*-65*	-1,038	51	-1	*-987*
2032	-763	751	-8	*-20*	-1,995	103	-1	*-1,893*
2033	-1,088	1,127	-11	*28*	-2,938	155	-2	*-2,785*
2034	-1,451	1,499	-14	*33*	-3,860	206	-2	*-3,656*
2035	-1,803	1,863	-17	*44*	-4,741	256	-3	*-4,488*
2036	-2,156	1,869	-19	*-306*	-5,552	257	-3	*-5,298*
2037	-2,584	1,753	-22	*-853*	-6,299	241	-4	*-6,062*
2038	-3,094	1,523	-24	*-1,595*	-6,973	210	-4	*-6,767*
2039	-3,577	1,190	-26	*-2,413*	-7,578	164	-4	*-7,419*
2040	-4,033	768	-27	*-3,292*	-8,123	106	-5	*-8,022*
2041	-4,461	713	-29	*-3,777*	-8,610	97	-5	*-8,518*
2042	-4,873	640	-30	*-4,263*	-9,030	86	-5	*-8,949*
2043	-5,264	550	-31	*-4,745*	-9,375	72	-5	*-9,308*
2044	-5,637	448	-32	*-5,221*	-9,646	56	-6	*-9,596*
2045	-5,992	334	-32	*-5,690*	-9,849	38	-6	*-9,816*
2046	-6,345	322	-33	*-6,056*	-10,009	36	-6	*-9,978*
2047	-6,688	307	-33	*-6,415*	-10,118	34	-6	*-10,090*
2048	-7,024	291	-34	*-6,767*	-10,181	32	-6	*-10,155*
2049	-7,371	273	-34	*-7,132*	-10,229	29	-6	*-10,206*
2050	-7,735	256	-34	*-7,513*	-10,295	27	-6	*-10,274*
2051	-8,085	258	-34	*-7,861*	-10,345	27	-6	*-10,324*
2052	-8,432	259	-34	*-8,208*	-10,383	27	-6	*-10,362*
2053	-8,783	260	-34	*-8,558*	-10,409	27	-6	*-10,387*
2054	-9,139	260	-34	*-8,912*	-10,421	27	-6	*-10,400*
2055	-9,497	261	-34	*-9,271*	-10,422	27	-6	*-10,401*

[A] We present emissions reductions as negative numbers and emission increases as positive numbers.

Table 4-33 Year-over-year net emission impacts[A] of the final standards on CO_2 emissions and CO_2e emissions, in million metric tons (MMT)

Calendar Year	CO_2 Impacts (MMT)				CO_2e Impacts (MMT)			
	Downstream	**EGU**	**Refinery**	***Net***	**Downstream**	**EGU**	**Refinery**	***Net***
2027	-0.5	0.2	0.0	*-0.3*	-0.5	0.2	0.0	*-0.3*
2028	-1.2	0.7	0.0	*-0.6*	-1.3	0.7	0.0	*-0.6*
2029	-2.1	1.2	0.0	*-0.9*	-2.2	1.2	0.0	*-1.0*
2030	-3.8	2.7	0.0	*-1.1*	-3.9	2.7	0.0	*-1.3*
2031	-7.4	5.8	-0.1	*-1.7*	-7.7	5.9	-0.1	*-1.9*
2032	-14.0	11.8	-0.2	*-2.4*	-14.5	11.8	-0.2	*-2.9*
2033	-20.4	17.7	-0.2	*-2.9*	-21.2	17.8	-0.2	*-3.7*
2034	-26.6	23.5	-0.3	*-3.3*	-27.7	23.6	-0.3	*-4.3*
2035	-32.5	29.3	-0.3	*-3.5*	-33.8	29.4	-0.3	*-4.7*
2036	-37.9	29.0	-0.4	*-9.2*	-39.4	29.1	-0.4	*-10.6*
2037	-42.8	26.7	-0.4	*-16.5*	-44.6	26.8	-0.4	*-18.2*
2038	-47.3	22.5	-0.5	*-25.2*	-49.2	22.6	-0.5	*-27.1*
2039	-51.3	16.6	-0.5	*-35.2*	-53.4	16.7	-0.5	*-37.2*
2040	-54.9	9.3	-0.5	*-46.1*	-57.2	9.4	-0.5	*-48.4*
2041	-58.1	10.4	-0.6	*-48.3*	-60.5	10.5	-0.6	*-50.6*
2042	-60.9	11.5	-0.6	*-50.0*	-63.4	11.6	-0.6	*-52.5*
2043	-63.2	12.6	-0.6	*-51.2*	-65.8	12.6	-0.6	*-53.8*
2044	-64.9	13.6	-0.6	*-52.0*	-67.7	13.6	-0.6	*-54.7*
2045	-66.3	14.5	-0.6	*-52.4*	-69.1	14.5	-0.7	*-55.2*
2046	-67.3	14.2	-0.7	*-53.7*	-70.2	14.3	-0.7	*-56.6*
2047	-68.1	13.9	-0.7	*-54.8*	-70.9	13.9	-0.7	*-57.7*
2048	-68.5	13.5	-0.7	*-55.6*	-71.4	13.5	-0.7	*-58.5*
2049	-68.8	13.1	-0.7	*-56.4*	-71.7	13.1	-0.7	*-59.3*
2050	-69.2	12.7	-0.7	*-57.2*	-72.2	12.7	-0.7	*-60.2*
2051	-69.5	12.8	-0.7	*-57.5*	-72.5	12.8	-0.7	*-60.4*
2052	-69.8	12.8	-0.7	*-57.7*	-72.8	12.8	-0.7	*-60.6*
2053	-69.9	12.9	-0.7	*-57.8*	-73.0	12.9	-0.7	*-60.8*
2054	-70.0	12.9	-0.7	*-57.8*	-73.0	12.9	-0.7	*-60.8*
2055	-70.0	12.9	-0.7	*-57.8*	-73.0	12.9	-0.7	*-60.8*

[A] We present emissions reductions as negative numbers and emission increases as positive numbers.

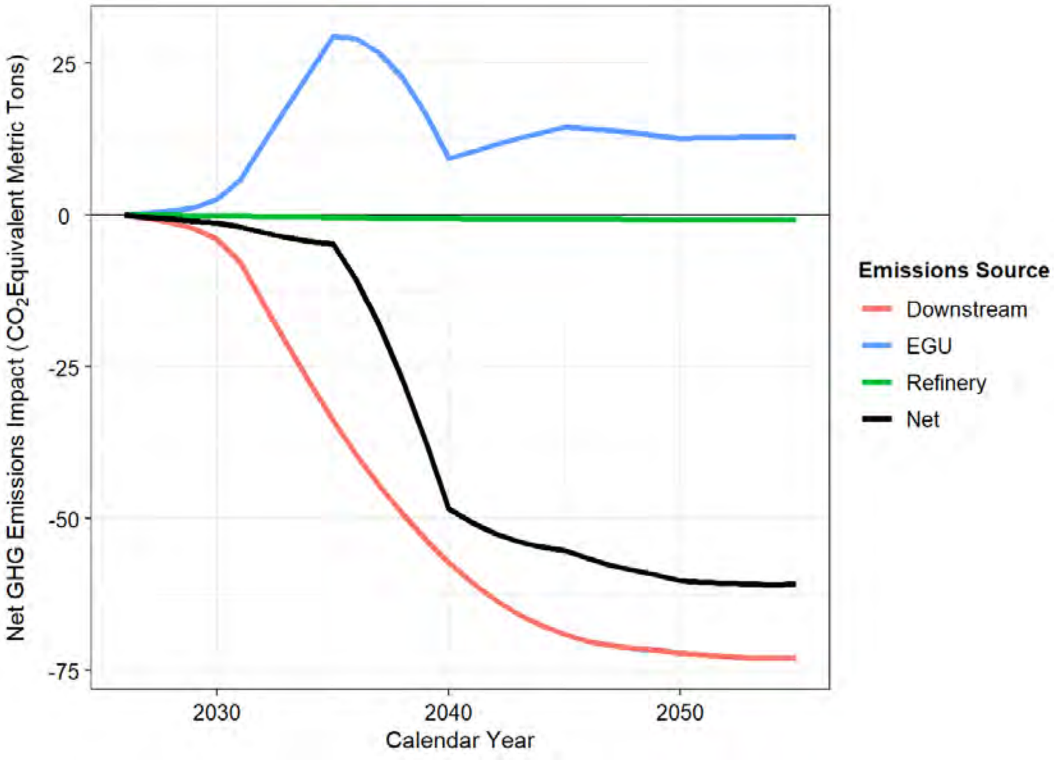

Figure 4-19 Year-over-year net CO_2 emission impacts of the final standards from 2027 through 2055

In terms of GHG emissions, refinery emission impacts are small compared to EGUs and downstream emissions impacts. The downstream emission reductions are larger than the increase in EGU emissions in all years.

Table 4-34, Figure 4-20, and Figure 4-21 show our estimates for the net impact of the final standards on emissions of nitrogen oxides and volatile organic compounds.

Table 4-34 Year-over-year net emission impacts[A] of the final standards on NO_X and VOC emissions, in U.S. tons

Calendar Year	**NO_X Impacts (U.S. Tons)**				**VOC Impacts (U.S. Tons)**			
	Downstream	**EGU**	**Refinery**	***Net***	**Downstream**	**EGU**	**Refinery**	***Net***
2027	-146	83	-5	*-68*	-87	4	-3	*-87*
2028	-361	220	-10	*-151*	-189	11	-7	*-186*
2029	-632	412	-15	*-235*	-302	20	-11	*-293*
2030	-1,096	887	-22	*-230*	-452	43	-16	*-426*
2031	-2,151	1,941	-39	*-249*	-798	93	-29	*-734*
2032	-4,060	3,915	-69	*-214*	-1,380	188	-52	*-1,243*
2033	-5,984	5,876	-97	*-206*	-1,956	282	-73	*-1,747*
2034	-8,156	7,818	-124	*-462*	-2,502	375	-93	*-2,220*
2035	-10,801	9,719	-148	*-1,230*	-3,014	467	-112	*-2,659*
2036	-14,190	9,541	-170	*-4,819*	-3,497	463	-129	*-3,162*
2037	-18,253	8,661	-191	*-9,783*	-3,975	427	-144	*-3,692*
2038	-23,298	7,133	-209	*-16,374*	-4,444	362	-158	*-4,240*
2039	-27,990	5,025	-226	*-23,192*	-4,858	269	-171	*-4,760*
2040	-32,356	2,411	-241	*-30,186*	-5,222	153	-182	*-5,251*
2041	-36,284	2,331	-255	*-34,208*	-5,543	190	-192	*-5,544*
2042	-39,794	2,204	-266	*-37,856*	-5,830	229	-200	*-5,801*
2043	-42,704	2,033	-275	*-40,946*	-6,069	269	-207	*-6,007*
2044	-45,101	1,825	-282	*-43,558*	-6,268	308	-212	*-6,171*
2045	-47,027	1,588	-288	*-45,728*	-6,426	347	-216	*-6,295*
2046	-48,634	1,582	-293	*-47,345*	-6,562	320	-219	*-6,462*
2047	-49,890	1,567	-297	*-48,619*	-6,689	290	-222	*-6,621*
2048	-50,809	1,544	-299	*-49,564*	-6,782	258	-223	*-6,747*
2049	-51,597	1,518	-301	*-50,380*	-6,861	226	-225	*-6,860*
2050	-52,379	1,494	-304	*-51,188*	-6,935	193	-226	*-6,969*
2051	-53,003	1,504	-305	*-51,804*	-7,016	194	-227	*-7,049*
2052	-53,490	1,511	-305	*-52,284*	-7,101	195	-227	*-7,133*
2053	-53,857	1,516	-305	*-52,646*	-7,166	196	-227	*-7,198*
2054	-54,120	1,519	-305	*-52,906*	-7,213	196	-227	*-7,244*
2055	-54,268	1,520	-304	*-53,051*	-7,242	196	-226	*-7,272*

[A] We present emissions reductions as negative numbers and emission increases as positive numbers.

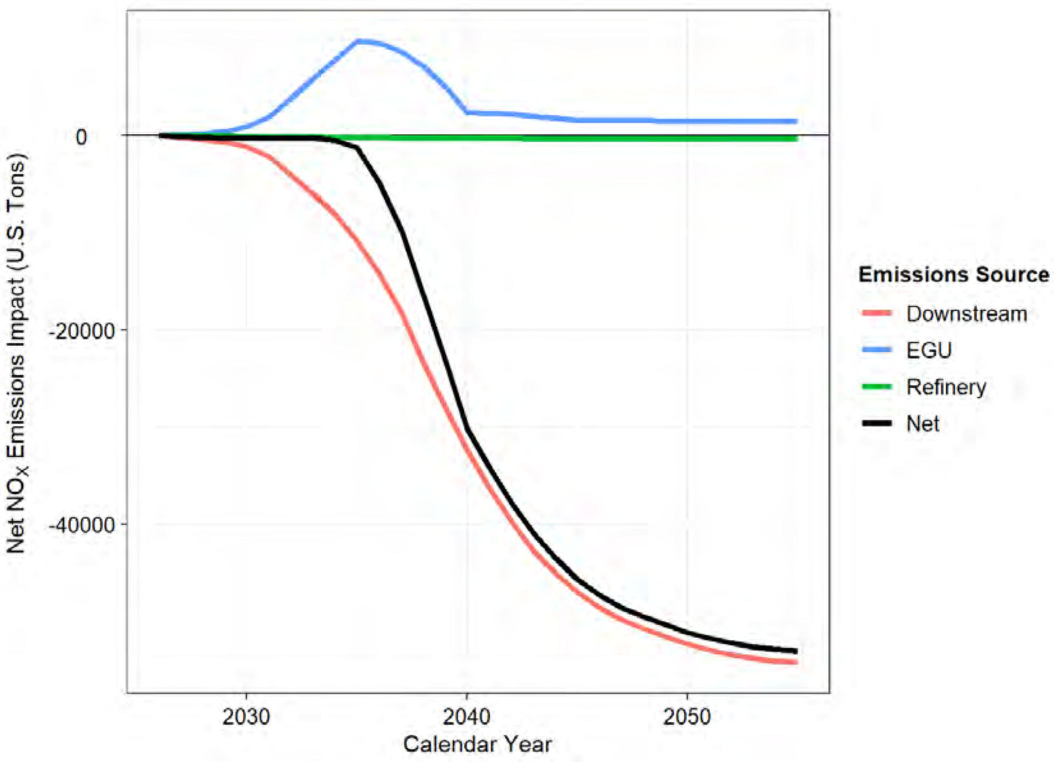

Figure 4-20 Year-over-year net NO$_X$ emission impacts of the final standards from 2027 through 2055

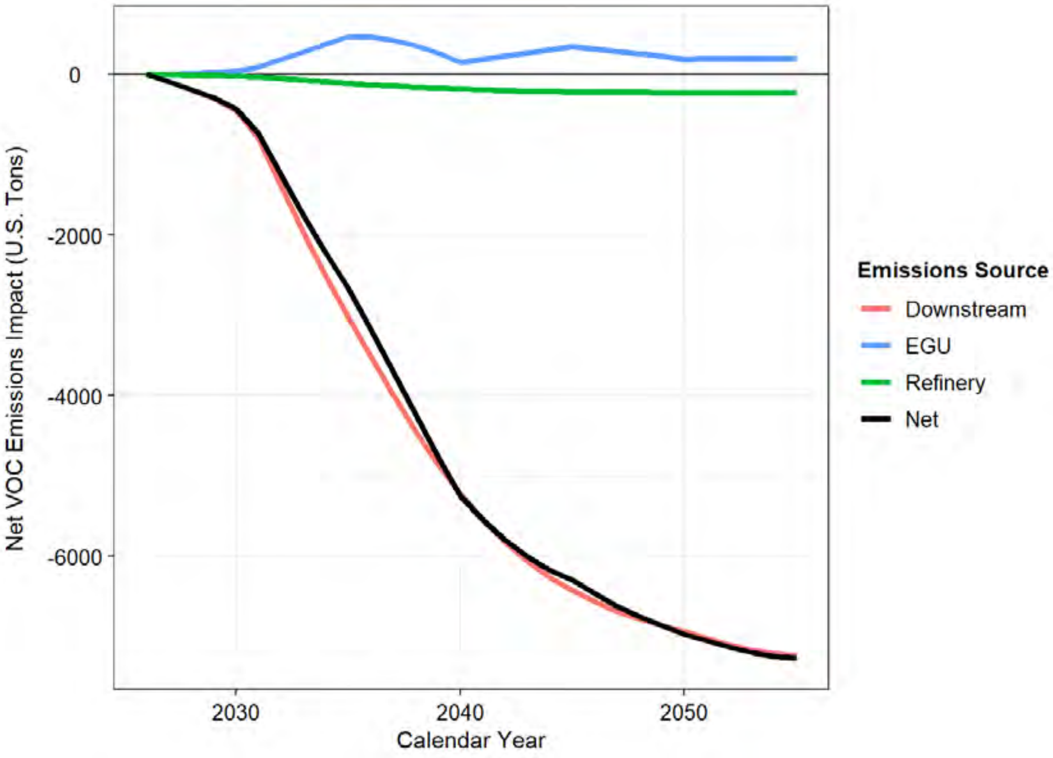

Figure 4-21 Year-over-year net VOC emission impacts of the final standards from 2027 through 2055

Like greenhouse gases, the refinery emission impacts of the final standards on NO_X and VOC emissions are small compared to the EGU and downstream impacts. Downstream emission reductions are greater than the increase in EGU emissions for all years.

Table 4-35, Figure 4-22, and Figure 4-23 show our estimates for the net impact of the final standards on emissions of particulate matter and sulfur dioxide.

Table 4-35 Year-over-year net emission impacts[A] of the final standards on emissions of particulate matter and SO_2 in U.S. tons

Calendar Year	**$PM_{2.5}$ Impacts (U.S. Tons)**				**SO_2 Impacts (U.S. Tons)**			
	Downstream	**EGU**	**Refinery**	***Net***	**Downstream**	**EGU**	**Refinery**	***Net***
2027	-4	12	-1	*7*	-2	100	-1	*96*
2028	-8	32	-2	*22*	-5	265	-3	*257*
2029	-12	60	-3	*44*	-9	497	-5	*483*
2030	-18	129	-5	*106*	-15	1,071	-7	*1,049*
2031	-33	283	-9	*241*	-30	2,342	-12	*2,300*
2032	-57	571	-16	*498*	-55	4,724	-21	*4,647*
2033	-80	857	-23	*754*	-80	7,089	-30	*6,980*
2034	-103	1,140	-29	*1,009*	-104	9,432	-38	*9,290*
2035	-126	1,418	-34	*1,258*	-126	11,726	-46	*11,554*
2036	-150	1,413	-39	*1,224*	-147	11,362	-53	*11,162*
2037	-173	1,312	-44	*1,095*	-166	10,106	-59	*9,881*
2038	-196	1,122	-48	*878*	-183	8,030	-65	*7,782*
2039	-217	852	-52	*583*	-199	5,220	-70	*4,951*
2040	-236	513	-56	*221*	-212	1,771	-75	*1,484*
2041	-254	540	-59	*227*	-225	1,623	-79	*1,320*
2042	-270	562	-61	*230*	-235	1,431	-82	*1,114*
2043	-283	579	-64	*232*	-244	1,200	-85	*871*
2044	-294	590	-65	*230*	-251	936	-87	*598*
2045	-302	596	-66	*227*	-256	648	-89	*304*
2046	-309	583	-68	*206*	-260	542	-90	*191*
2047	-315	566	-68	*183*	-263	428	-92	*74*
2048	-319	546	-69	*158*	-264	310	-92	*-47*
2049	-322	525	-69	*134*	-266	190	-93	*-169*
2050	-325	505	-70	*110*	-267	68	-94	*-293*
2051	-327	508	-70	*111*	-269	68	-94	*-294*
2052	-329	510	-70	*111*	-269	68	-94	*-295*
2053	-330	512	-70	*111*	-270	69	-94	*-296*
2054	-331	513	-70	*112*	-270	69	-94	*-295*
2055	-331	513	-70	*113*	-270	69	-94	*-295*

[A] We present emissions reductions as negative numbers and emission increases as positive numbers.

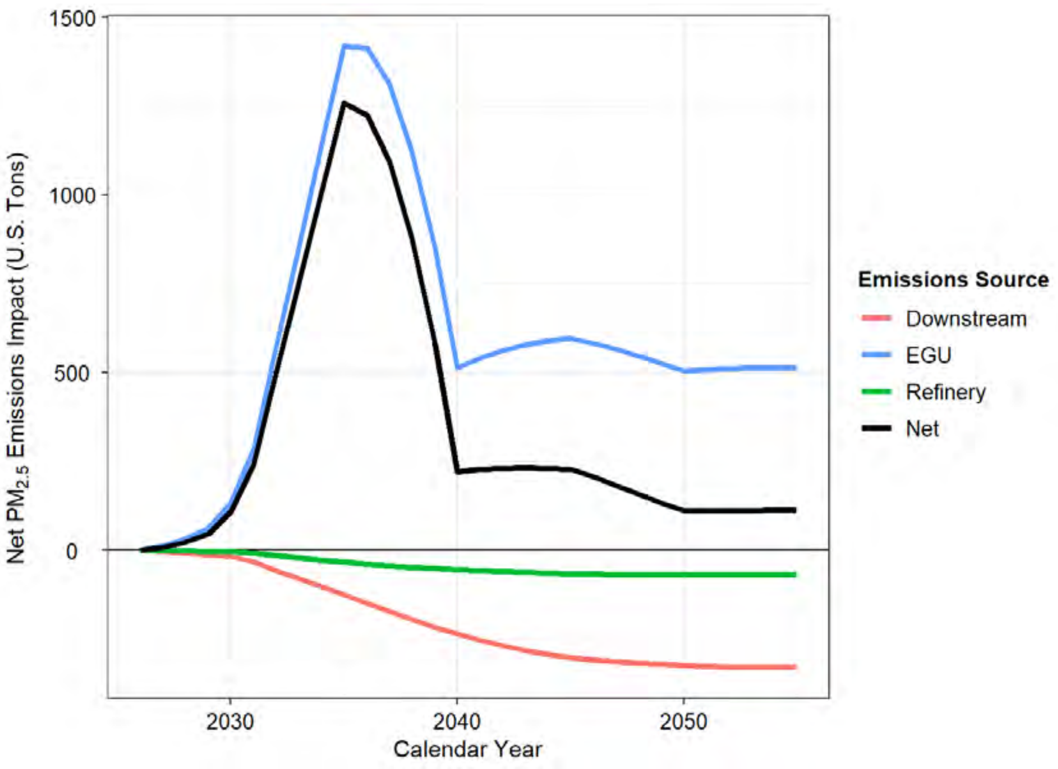

Figure 4-22 Year-over-year net $PM_{2.5}$ emission impacts of the final standards from 2027 through 2055

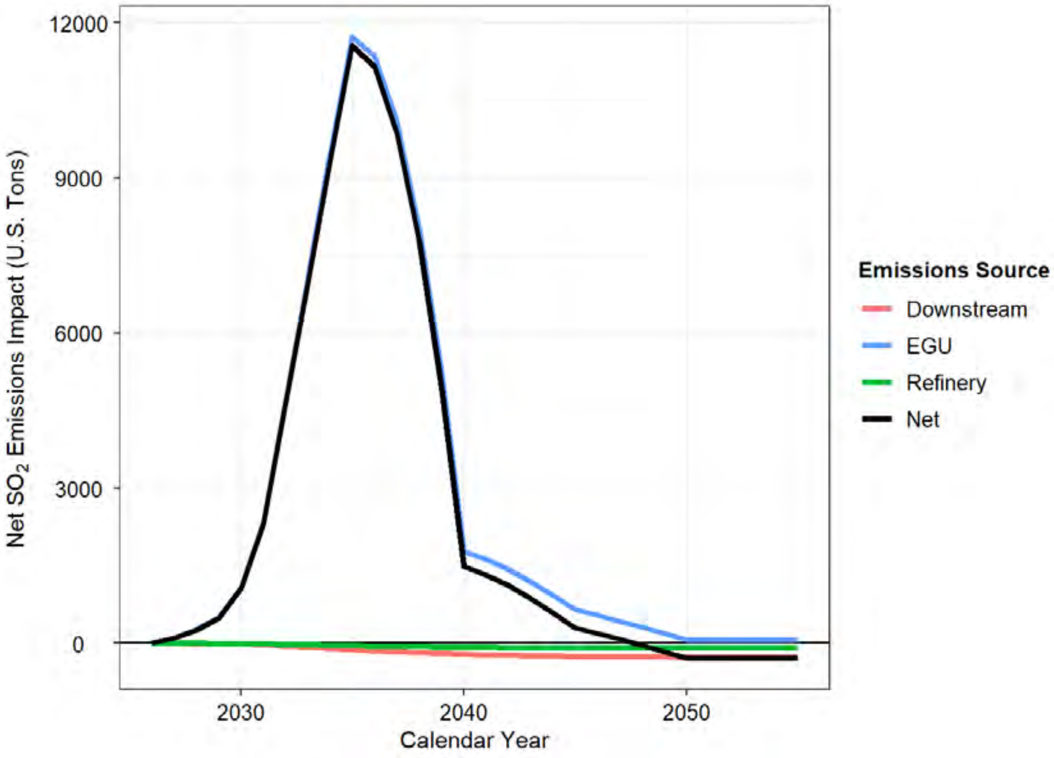

Figure 4-23 Year-over-year net SO_2 emission impacts of the final standards from 2027 through 2055

While particulate matter and sulfur dioxide emissions are the most impacted by refineries than all pollutants we consider here, the net emission impacts of $PM_{2.5}$ and SO_2 are nonetheless dominated by EGU impacts. Because the power generation mix continues to rely on fossil fuel combustion, especially coal, until the 2040s, we estimate that the increase in EGU emissions exceeds the downstream and refinery emission reductions in those initial years. As HD ZEVs represent a growing proportion of the heavy-duty fleet through the 2040s, net emission increases decline. We estimate a net increase in $PM_{2.5}$ emissions in all years and a net reduction of SO_2 emissions beginning in 2048.

4.6 Cumulative GHG Impacts of the Final Standards

The climate warming impacts of GHGs are cumulative. Table 4-36, Table 4-37, and Table 4-38 present the cumulative GHG impacts that we model will result from the final standards between 2027 and 2055 for downstream emissions, EGU emissions, and refinery emissions, respectively, relative to the reference case.

Table 4-36 Cumulative 2027-2055 downstream heavy-duty GHG emission reductions from the final standards

Pollutant	Reduction in MMT	Percent
Carbon Dioxide (CO_2)	1,347	13%
Methane (CH_4)	0.127	7%
Nitrous Oxide (N_2O)	0.199	13%
CO_2 Equivalent (CO_2e)	*1,404*	*13%*

Table 4-37 Cumulative 2027-2055 GHG emission increases from EGUs from the final standards

Pollutant	Increase in MMT
Carbon Dioxide (CO_2)	391.4
Methane (CH_4)	0.018
Nitrous Oxide (N_2O)	0.002
CO_2 Equivalent (CO_2e)	392.5

Table 4-38 Cumulative 2027-2055 GHG emission reductions from refineries from the final standards

Pollutant	Reduction in MMT
Carbon Dioxide (CO_2)	13.4
Methane (CH_4)	0.0007
Nitrous Oxide (N_2O)	0.0001
CO_2 Equivalent (CO_2e)	*13.5*

Overall, we estimate the final standards will reduce net GHG emissions by just over 1 billion metric tons between 2027 and 2055, relative to the reference case, as is presented in Table 4-39.

Table 4-39 Cumulative 2027–2055 net GHG emission impacts[A] (in MMT) reflecting the final standards

Pollutant	Downstream	EGU	Refineries	Net
Carbon Dioxide (CO_2)	-1,347	391	-13	-969
Methane (CH_4)	-0.127	0.018	-0.001	-0.109
Nitrous Oxide (N_2O)	-0.199	0.002	0.000	-0.197
CO_2 Equivalent (CO_2e)	*-1,404*	*393*	*-13*	*-1,025*

[A] We present emissions reductions as negative numbers and emission increases as positive numbers.

4.7 Comparison Between the Final Standards and the Alternative

The alternative has both a less aggressive phase-in of emissions standards from 2027 through 2031 and a less stringent ending standard for model years 2032 and beyond. Both the final standards and alternative were modeled in MOVES4.R3 by increasing ZEV adoption of HD vehicles, which means we model the alternative as displacing fewer ICE vehicles with ZEVs as compared to the final standards (under their respective potential compliance pathways). In general, we expect the alternative to have lower downstream emission reductions, lower upstream EGU emission increases, and lower refinery emission reductions when compared to the final standards.

4.7.1 Downstream Emission Inventory Comparison

Our estimates of the downstream emission reductions of GHGs that would result from the alternative relative to the reference case are presented in Table 4-40 for calendar years 2035, 2045, and 2055.

Table 4-40 Annual downstream HD GHG emission reductions from the alternative in calendar years (CY) 2035, 2045, and 2055

Pollutant	**100-year GWP**	**CY 2035 Reductions**		**CY 2045 Reductions**		**CY 2055 Reductions**	
		Million Metric Tons	**Percent**	**Million Metric Tons**	**Percent**	**Million Metric Tons**	**Percent**
Carbon Dioxide (CO_2)	1	12.9	3%	21.9	6%	20.7	6%
Methane (CH_4)	28	0.001	1%	0.001	2%	0.002	3%
Nitrous Oxide (N_2O)	265	0.002	4%	0.003	7%	0.003	6%
CO_2 Equivalent (CO_2e)	—	*13.4*	*3%*	*22.8*	*6%*	*21.6*	*6%*

Our estimated GHG emission reductions for the alternative are lower than for the final standards (see Table 4-16). In 2055, we estimate that the alternative would reduce emissions of CO_2 by 6 percent (the final standards estimate is 20 percent), methane by 3 percent (the final standards estimate is 12 percent), and N_2O by 6 percent (the final standards estimate is 20 percent). The resulting total GHG reduction, in CO_2e, is 6 percent for the alternative versus 20 percent for the final standards.

We modeled an increase in the use of zero-emission technologies to meet the CO_2 emission standards for both the final standards and the alternative under their respective potential compliance pathways. Therefore, we also project that downstream emission reductions of criteria pollutants and air toxics would result from the alternative, as presented in Table 4-41.

Table 4-41 Annual downstream HD criteria pollutant and air toxic emission reductions from the alternative in calendar years (CYs) 2035, 2045, and 2055

Pollutant	**CY 2035 Reductions**		**CY 2045 Reductions**		**CY 2055 Reductions**	
	U.S. Tons	**Percent**	**U.S. Tons**	**Percent**	**U.S. Tons**	**Percent**
Nitrogen Oxides (NO_X)	4,491	1%	17,310	6%	18,107	7%
Particulate Matter ($PM_{2.5}$)^A	46	1%	74	1%	62	1%
Volatile Organic Compounds (VOC)	1,118	2%	1,557	4%	1,398	4%
Sulfur Dioxide (SO_2)	49	3%	82	6%	77	6%
Carbon Monoxide (CO)	18,388	2%	31,733	5%	29,995	4%
1,3-Butadiene	2	4%	2	3%	0	1%
Acetaldehyde	22	2%	31	4%	29	3%
Benzene	13	3%	10	3%	3	1%
Formaldehyde	14	1%	23	3%	25	3%
Naphthalene^B	1	2%	1	4%	1	3%

^{A} $PM_{2.5}$ estimates include both exhaust and non-exhaust emissions.
^{B} Naphthalene includes both gas and particle phase emissions.

Once again, the estimated emission reductions in criteria pollutants and air toxics that would result from the alternative are smaller than those estimated to result from the final standards (see

Table 4-17). For example, in 2055, we estimate the alternative would reduce NO_X emissions by 7 percent, $PM_{2.5}$ emissions by 1 percent, and VOC emissions by 4 percent. This is compared to reductions of NO_X by 20 percent, $PM_{2.5}$ by 5 percent, and VOC by 20 percent for the final standards. Estimated reductions in emissions for air toxics from the alternative range from 1 percent for benzene (the final standards estimate is 25 percent) to 3 percent for formaldehyde (the final standards estimate is 15 percent).

The year-over-year downstream emission trends of the alternative would be similar to the trends presented for the final standards in Chapter 4.3.2. The detailed discussion of the impacts of the final standards presented in Chapter 4.3.3, including the detailed breakdowns of emission reductions by fuel type, source type, regulatory class, and emissions process also applies to the alternative. However, in all cases, the magnitude of the emission impacts would be smaller for the alternative than for the final standards. Therefore, we do not present this detailed information and discussion for the alternative here.

Figure 4-24 shows the year-over-year inventory of total HD GHG emissions (CO_2e) in the reference case as well as for the final standards and alternative. It shows that the slower phase-in and lower ending standards of the alternative would result in lower overall GHG reductions compared to the final standards.

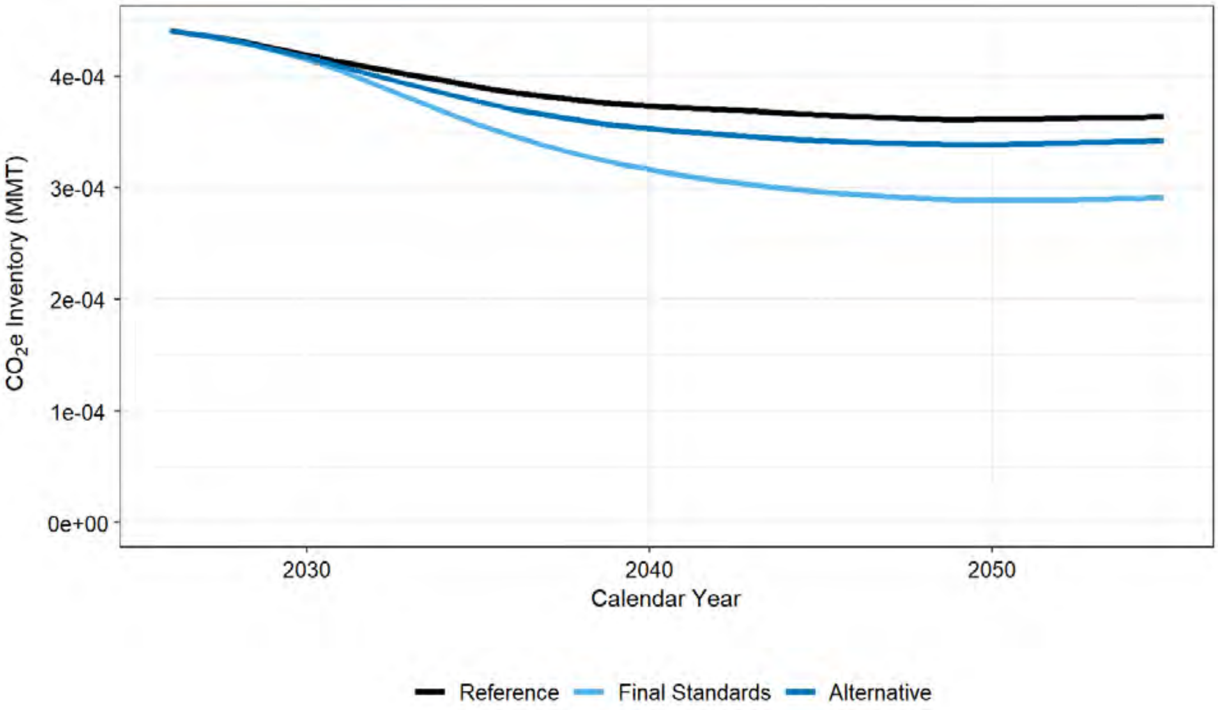

Figure 4-24 Yearly downstream CO_2e inventory for the reference case, final standards, and alternative from 2027 through 2055

4.7.2 Upstream Emission Inventory Comparison

Our estimates of the additional GHG emissions from EGUs due to the alternative, relative to the reference case, are presented in Table 4-42 for calendar years 2035, 2045, and 2055, in million metric tons (MMT). Our estimates for additional criteria pollutant emissions from the alternative are presented in Table 4-43.

Table 4-42 Annual GHG emission increases from EGUs from the alternative in calendar years (CY) 2035, 2045, and 2055

Pollutant	**100-year GWP**	**Additional EGU Emissions (MMT)**		
		CY 2035	**CY 2045**	**CY 2055**
Carbon Dioxide (CO_2)	1	12.4	5.4	4.4
Methane (CH_4)	28	0.00079	0.00013	0.00009
Nitrous Oxide (N_2O)	265	0.00011	0.00001	0.00001
CO_2 Equivalent (CO_2e)	---	*12.5*	*5.4*	*4.4*

Table 4-43 Annual criteria pollutant emission increases from EGUs from the alternative in calendar years (CYs) 2035, 2045, and 2055

Pollutant	Additional EGU Emissions (U.S. Tons)		
	CY 2035	**CY 2045**	**CY 2055**
Nitrogen Oxides (NO_X)	4,131	594	520
Primary $PM_{2.5}$	603	223	176
Volatile Organic Compounds (VOC)	198	130	67
Sulfur Dioxide (SO_2)	4,984	243	24

Because the alternative has lower ZEV adoption rates under its potential compliance pathway, we project smaller increases in emissions from EGUs than the final standards (see Table 4-21 and Table 4-22). In 2055, we estimate the alternative would increase EGU emissions of CO_2 by 4.4 million metric tons (compared to 12.9 million metric tons from the final standards), with similar trends for all other pollutants. The EGU impacts decrease over time because of projected changes in the power generation mix.

Table 4-44 presents the estimated impact of the alternative on GHG emissions from refineries and Table 4-45 presents the estimated impact of the alternative on criteria pollutant emissions from refineries, both relative to the reference case.

Table 4-44 Annual GHG emission reductions from refineries due to the alternative in calendar years (CY) 2035, 2045, and 2055

Pollutant	**100-year GWP**	**Refinery Emission Reductions (Metric Tons)**		
		CY 2035	**CY 2045**	**CY 2055**
Carbon Dioxide (CO_2)	1	118,269	163,781	147,787
Methane (CH_4)	28	6	8	7
Nitrous Oxide (N_2O)	265	1	1	1
CO_2 Equivalent (CO_2e)	---	*118,707*	*164,377*	*148,320*

Table 4-45 Annual criteria pollutant emission reductions from refineries due to the alternative in calendar years (CYs) 2035, 2045, and 2055

Pollutant	**Refinery Emission Reductions (U.S. Tons)**		
	CY 2035	**CY 2045**	**CY 2055**
Nitrogen Oxides (NO_X)	52	70	63
Particulate Matter ($PM_{2.5}$)	12	16	14
Volatile Organic Compounds (VOC)	40	54	48
Sulfur Dioxide (SO_2)	16	22	20

We project smaller reductions in refinery emissions for the alternative than for the final standards (see Table 4-23and Table 4-24), consistent with our projected impacts for downstream emissions. We project a reduction of 147,787 metric tons of CO_2 for the alternative versus 690,477 metric tons for the final standards. The general comparison of CO_2 reductions is representative of other GHG and criteria pollutants.

As was the case for downstream emissions, the year-over-year emissions impacts trends of the alternative on both EGUs and refineries would be similar to the impacts presented in Chapter 4.4.2 for the final standards, but smaller in magnitude. Thus, we do not present information specific to the alternative here.

4.7.3 Net Emission Inventory Comparison

Table 4-46 shows a summary of our modeled downstream, upstream, and net GHG emission impacts of the alternative relative to the reference case (i.e., the emissions inventory without the final standards), in million metric tons, for calendar years 2035, 2045, and 2055. Table 4-47 contains a summary of the modeled net impacts of the alternative on criteria pollutant emissions.

Table 4-46 Annual net impacts[A] on GHG emissions from the alternative in calendar years (CYs) 2035, 2045, and 2055

Pollutant	**GWP**	**Calendar Year**	**Emission Impact (MMT)**			
			Downstream	**EGU**	**Refinery**	**Net**
Carbon Dioxide (CO_2)	1	2035	-12.9	12.4	-0.1	-0.5
		2045	-21.9	5.4	-0.2	-16.6
		2055	-20.7	4.4	-0.1	-16.4
Methane (CH_4)	28	2035	-0.001	0.001	0.000	0.000
		2045	-0.001	0.000	0.000	-0.001
		2055	-0.002	0.000	0.000	-0.002
Nitrous Oxide (N_2O)	265	2035	-0.002	0.000	0.000	-0.002
		2045	-0.003	0.000	0.000	-0.003
		2055	-0.003	0.000	0.000	-0.003
CO_2 Equivalent (CO_2e)	---	*2035*	*-13.4*	*12.5*	*-0.1*	*-1.0*
		2045	*-22.8*	*5.4*	*-0.2*	*-17.6*
		2055	*-21.6*	*4.4*	*-0.1*	*-17.3*

[A] We present emissions reductions as negative numbers and emission increases as positive numbers.

Table 4-47 Annual net impacts[A] on criteria pollutant emissions from the alternative in calendar years (CYs) 2035, 2045, and 2055

Pollutant	Calendar Year	Emission Impact (U.S. Tons)			
		Downstream	EGU	Refinery	Net
Nitrogen Oxides (NO_X)	2035	-4,491	4,131	-52	-413
	2045	-17,310	594	-70	-16,786
	2055	-18,107	520	-63	-17,650
Particulate Matter ($PM_{2.5}$)	2035	-46	603	-12	545
	2045	-74	223	-16	133
	2055	-62	176	-14	99
Volatile Organic Compounds (VOC)	2035	-1,118	198	-40	-960
	2045	-1,557	130	-54	-1,481
	2055	-1,398	67	-48	-1,379
Sulfur Dioxide (SO_2)	2035	-49	4,984	-16	4,918
	2045	-82	243	-22	139
	2055	-77	24	-20	-73

[A] We present emissions reductions as negative numbers and emission increases as positive numbers.

In 2055, we estimate the alternative would result in a net decrease of 17 million metric tons of GHG emissions, compared to 61 million metric tons for the final standards (see Table 4-30). Like the final standards, we project net decreases in emissions of NO_X, VOC, and SO_2 in 2055 but a net increase in $PM_{2.5}$ emissions (see Table 4-31). Consistent with other emissions impacts trends discussed for the alternative, the magnitude of these net impacts would be smaller for the alternative than for the final standards.

Finally, Figure 4-25 shows the net year-over-year GHG emissions impacts, measured in CO_2e emissions, for the final standards and alternative. The net GHG impacts of the alternative would be significantly smaller than the final standards, especially in the further future years beyond 2040 as the total number of HD ICE vehicles displaced by ZEVs is much smaller than in the final standards under their respective potential compliance pathways.

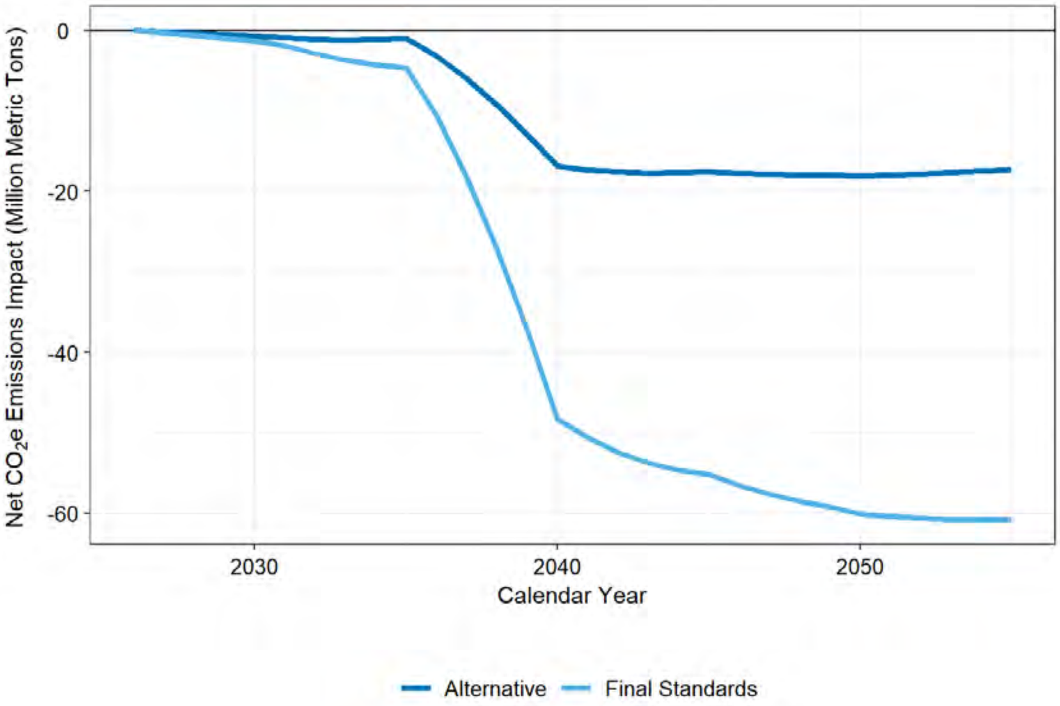

Figure 4-25 Comparison of net CO_2e emission impacts of the final standards and alternative from 2027 through 2055

4.7.4 Cumulative GHG Reduction Comparison

Table 4-48, Table 4-49, and Table 4-50 present the cumulative GHG impacts that we project would result from both the final standards and the alternative from 2027 through 2055 for downstream emissions, EGU emissions, and refinery emissions, respectively, relative to the reference case.

Table 4-48 Cumulative 2027-2055 downstream HD GHG emission reductions from the final standards and the alternative

Pollutant	**Final Standards**		**Alternative**	
	Reduction in MMT	**Percent**	**Reduction in MMT**	**Percent**
Carbon Dioxide (CO_2)	1,347	13%	454	4%
Methane (CH_4)	0.127	7%	0.030	2%
Nitrous Oxide (N_2O)	0.199	13%	0.071	5%
CO_2 Equivalent (CO_2e)	*1,404*	*13%*	*473*	*4%*

Table 4-49 Cumulative 2027-2055 GHG emission increases from EGUs from the final standards and the alternative

Pollutant	Increase in MMT	
	Final Standards	**Alternative**
Carbon Dioxide (CO_2)	391.4	155.3
Methane (CH_4)	0.018	0.008
Nitrous Oxide (N_2O)	0.002	0.001
CO_2 Equivalent (CO_2e)	*392.5*	*155.7*

Table 4-50 Cumulative 2027-2055 GHG emission reductions from refineries from the final standards and alternative

Pollutant	Reduction in MMT	
	Final Standards	**Alternative**
Carbon Dioxide (CO_2)	13.4	3.6
Methane (CH_4)	0.0007	0.0000
Nitrous Oxide (N_2O)	0.0001	0.0000
CO_2 Equivalent (CO_2e)	*13.5*	*3.6*

Overall, we estimate the alternative would reduce net GHG emissions by 321 million metric tons between 2027 and 2055, relative to the reference case, as is presented in Table 4-51. This is less than one third the total reduction from the final standards, which is more than 1 billion metric tons.

Table 4-51 Cumulative 2027–2055 net GHG emission impacts[A] (in MMT) of the alternative

Pollutant	Downstream	EGU	Refineries	Net
Carbon Dioxide (CO_2)	-454	155	-4	-302
Methane (CH_4)	-0.030	0.008	0.000	-0.023
Nitrous Oxide (N_2O)	-0.071	0.001	0.000	-0.070
CO_2 Equivalent (CO_2e)	*-473*	*156*	*-4*	*-321*

[A] We present emissions reductions as negative numbers and emission increases as positive numbers.

4.8 Hydrogen Production Comparative Analysis

As mentioned in Chapter 4.3, for the purposes of emissions inventory modeling, we assumed hydrogen fuel produced for the HD FCEVs in our potential compliance pathway would be produced via grid electrolysis. IPM allowed us to represent the estimated emission impacts of grid electrolysis-derived hydrogen fuel over the timeframe of this analysis, embedding projected changes to electricity capacity and generation that also apply to projected emissions from hydrogen produced via grid electrolysis.

In this section, we conduct a comparative analysis to assess how lifecycle emissions outcomes between multiple alternative hydrogen production pathways could compare on a relative basis. We use data from Argonne’s Greenhouse Gases, Regulated Emissions, and Energy Use in

Transportation (GREET)[1403] model to show relative comparisons between estimated well-to-wheel emission outcomes from different hydrogen production pathways per kilogram of hydrogen. GREET is a lifecycle analysis model based on supply chains of technologies and products. It provides lifecycle energy, water, GHG, and other air emission results intended to evaluate the impacts of various vehicle and fuel combinations. GREET is developed by Argonne National Laboratory (ANL) and sponsored by the U.S. Department of Energy (DOE).[1404]

GREET is not a dynamic model like IPM in which projections of future time periods depend on the simulation of prior time periods.[1405] However, it does include projected background data, using projections from sources such as EIA. GREET users can estimate supply chain-related lifecycle emissions for any target year between 1990 and 2050 but it is not an economic model that can account for categories of indirect emission impacts that vary based on magnitudes of fuels used or produced in a scenario. Thus, GREET can demonstrate how the estimated emissions of a produced fuel may change over time based on various factors, such as changes in technological efficiency, so long as available data and projections exist.[1406]

There are multiple potential pathways for hydrogen fuel production. Though hydrogen today in the U.S. is predominantly produced through steam methane reforming (SMR),[1407] hydrogen production modes are expected to shift to other pathways given BIL and IRA provisions that meaningfully incentivize reducing the emissions and carbon intensity of the fuel. Therefore, we compare lifecycle emission estimates associated with several pathways with commercialized technologies expected to be possible in the timeframe of the rule. This evaluation demonstrates a range of estimated emission outcomes associated with hydrogen produced for HD FCEVs in the potential compliance pathway.

Steam methane reforming is a process that reacts natural gas with high-pressure steam to produce hydrogen fuel. The steam is channeled through reforming tubes that contain catalysts that separate hydrogen molecules from the steam. Most SMR facilities in the U.S. currently produce hydrogen for industrial processes, such as fertilizer production or petroleum refining, and are often co-located with refineries that can make use of the excess steam generated from the SMR to displace some natural gas usage. Future SMR facilities built to supply hydrogen fuel for transportation purposes are unlikely to be co-located with such refineries and we do not include a co-product credit for excess steam generated by SMR in GREET. GREET provides multiple

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[1403] Wang, Michael et al. Greenhouse gases, Regulated Emissions, and Energy use in Technologies Model ® (2021 Excel). Computer Software. U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy (EERE). 11 Oct. 2021. Web. doi:10.11578/GREET-Excel-2021/dc.20210902.1.

[1404] Elgowainy, A. and Wang, M. (2019) ‘Overview of Life Cycle Analysis (LCA) with the GREET Model’, p. 21. Available online: https://greet.es.anl.gov/files/workshop_2019_overview

[1405] This is one reason we decided to represent hydrogen produced via grid electrolysis using the dynamic model, IPM, rather than extrapolating GREET’s per-unit hydrogen emissions to represent hydrogen production in this rulemaking.

[1406] Many data sources GREET relies on do not project out to 2050 and have assumptions that flatline after a certain year such as 2030 or 2035.

[1407] U.S. Department of Energy. “Hydrogen Production: Natural Gas Reforming.” Available online: https://www.energy.gov/eere/fuelcells/hydrogen-production-natural-gas-reforming options for representing SMR and we present it both produced centrally and distributed[1408], as well as with and without carbon capture and sequestration (CCS).

Another hydrogen production process is autothermal reforming (ATR), which is similar to SMR but adds high purity oxygen as part of the process. When natural gas, steam (water), and oxygen are combined in the ATR, the results are partial combustion of the natural gas and an output stream that is low in nitrogen gas. ATR's ability to keep nitrogen gas output lower than SMR makes this pathway especially well-suited for connecting to CCS.[1409] GREET provides one hydrogen production pathway for ATR that includes CCS.

Table 4-52 presents GREET lifecycle CO_2e emission estimates for four hydrogen production pathways that include SMR and ATR. We present pathways with and without CCS based on the model's estimates of the technologies in 2030. SMR is considered a mature and advanced technology that, absent use of CCS, is not expected to become significantly more efficient or lower in carbon intensity over time.[1407]

Table 4-52 Lifecycle CO_2e emissions for hydrogen fuel production pathways from GREET in calendar year 2030

Production Pathway	Infrastructure	CCS	kgCO_2e/kg H_2
Steam Methane Reforming (SMR)	Distributed	No	13.07
Steam Methane Reforming (SMR)	Centralized	No	13.01
Steam Methane Reforming (SMR)	Centralized	Yes	4.65
Autothermal Reforming (ATR)	Centralized	Yes	5.41

Our IPM modeling shows emissions from EGUs are expected to decline as the mixture of electricity generating sources becomes less emitting over time.[1410] We expect emissions for producing hydrogen fuel from grid electrolysis are to be directly correlated with these trends, so we can use IPM output to project emissions from hydrogen generated via grid electrolysis compared to from the alternative production pathways provided by GREET. However, GREET estimates supply chain-related lifecycle GHG emissions while IPM only estimates combustion emissions from EGUs and does not include emissions upstream of the EGU, such as the extraction and refining of the fossil fuel feedstocks that are combusted in EGUs. Using GREET, we derived multiplicative factors that represent these upstream feedstock emissions for each mode of electricity generation that has these emissions. We then applied these factors to the specific EGU generation mix for each output year in IPM to calculate average annual lifecycle CO_2e emission factors, per kilowatt-hour of electricity generated, which are shown in Table 4-53.[1411]

[1408] Central refers to a larger-scale facility that produces hydrogen offsite from a refueling station and delivers the fuel to a refueling station either via pipeline or truck delivery. Distributed (or forecourt) refers to fuel produced at the refueling station itself, usually produced from small-scale equipment onsite. Production efficiencies are usually higher for centrally generated fuels but can incur greater transportation related emissions from needing to deliver the finished fuel to refueling stations.

[1409] Khojasteh Salkuyeh, Yaser, et al. "Techno-Economic Analysis and Life Cycle Assessment of Hydrogen Production from Natural Gas Using Current and Emerging Technologies." International Journal of Hydrogen Energy, vol. 42, no. 30, July 2017, pp. 18894–909., https://doi.org/10.1016/j.ijhydene.2017.05.219.

[1410] This can be seen in Table 4-11, for example.

[1411] These CO_2e values combine CO_2, CH_4, and N_2O emissions represented by IPM using IPCC Assessment Report 5 (AR5) the 100-year global warming potential (GWP) values as shown in Table 4-55.

Table 4-53 Calculated average annual lifecycle CO_2e per kWh generated from EGUs (kgCO_2e/kWh)

Emissions	**2028**	**2030**	**2035**	**2040**	**2045**	**2050**	**2055**
kgCO_2e/kWh Generated	0.30	0.23	0.14	0.09	0.08	0.06	0.06

To calculate the electricity needed to produce hydrogen via electrolysis, we used National Renewable Energy Laboratory's (NREL) Hydrogen Analysis (H2A) modeling. Their modeling shows that the electricity required to produce a kilogram of hydrogen using proton exchange membrane (PEM) electrolysis ranges from 55.8 kWh, using current technology, to 51.4 kWh, based on their assumption for future efficiency improvements. We then used GREET to account for the additional electricity required for compressing and pre-cooling the hydrogen for fueling HD FCEVs. We expect increasing amounts of hydrogen to be produced via electrolysis in the future, and therefore expect hydrogen producers to develop better techniques and efficiencies for producing hydrogen. We assumed a linear learning curve between 2025 and 2055 so that grid electrolysis hydrogen production represented in IPM becomes somewhat more efficient over time.[1412] Table 4-54 presents our assumptions for electricity required to generate hydrogen at a refueling station using PEM electrolysis.

Table 4-54 Electricity required to produce hydrogen using PEM electrolysis (kWh/kg H_2)

	2025	**2055**
PEM Electrolysis Efficiency (kWh/kg H_2)	55.8	51.4
Compression and Pre-Cooling Energy (kWh/kg H_2)	2.6	2.6
Combined Energy Required (kWh/kg H_2)	58.4	54.0

We multiplied the average annual lifecycle CO_2e emission factors from Table 4-53 by the electricity required for hydrogen production via electrolysis in Table 4-54 to derive a projected lifecycle CO_2e intensity estimates per kilogram of hydrogen produced using distributed grid PEM electrolysis.

Figure 4-26 presents these estimates compared to the alternative hydrogen fuel production pathways from GREET. Cases where the yellow line (representing grid electrolysis) drops below one of the dotted lines (representing SMR or ATR) indicate when it is projected that grid electrolysis would become comparatively less carbon intensive than the alternative production pathway.

[1412] We used a linear learning curve in this scenario to interpolate between the two data points NREL provides for PEM electrolysis efficiency. This approximate approach is simplified compared to how industry will likely improve the technology over time.

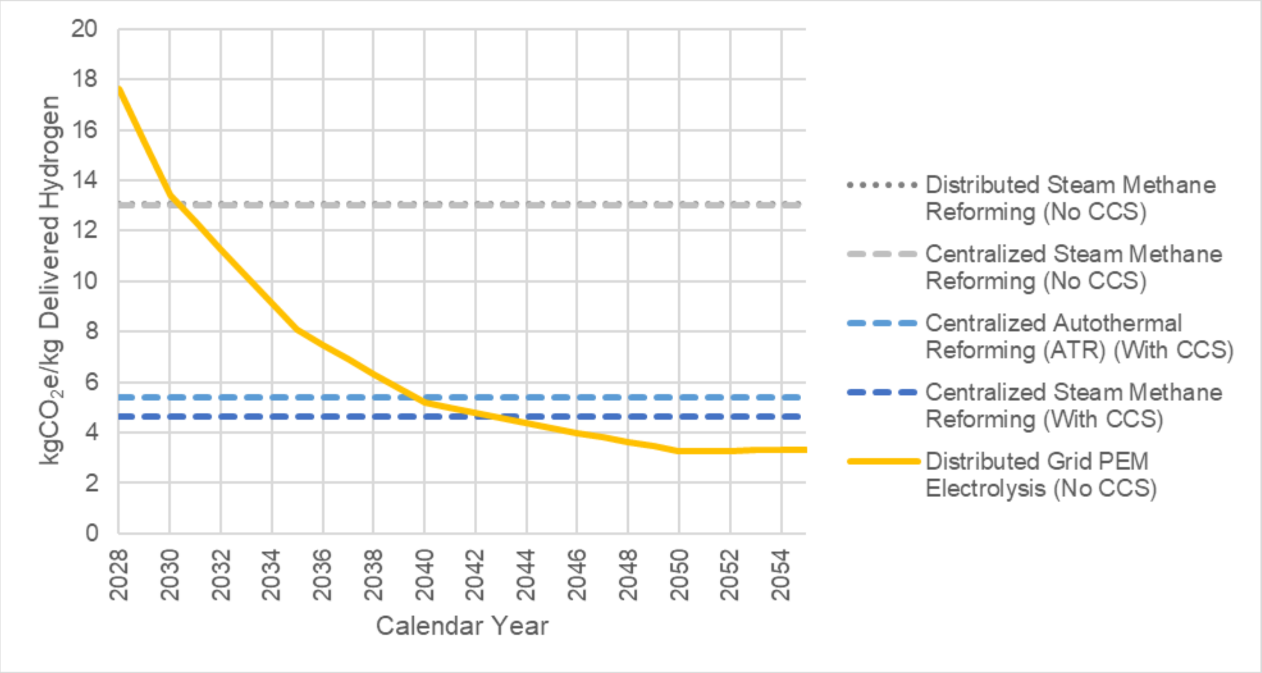

Figure 4-26 Comparison of projected lifecycle CO_2e/kg of delivered hydrogen from distributed grid PEM electrolysis to alternative hydrogen production pathways from 2028 through 2055

We estimate grid PEM electrolysis will become less carbon intensive on a lifecycle basis than SMR without CCS between 2030 and 2031. This is predominantly due to the decarbonization of electricity generation that IPM projects. [1413,1414] This suggests that conventional SMR would be a less carbon intensive pathway to produce hydrogen fuel before 2030. We estimate that SMR and ATR coupled with CCS will continue to be lower emitting options for producing hydrogen until the early to mid-2040s, at which point EGU emissions become low enough that grid PEM electrolysis could be expected to be lower emitting than these alternatives as well.

This is an illustrative analysis comparing relative lifecycle GHG emissions across multiple hydrogen production pathways that are already mature or are expected to become more prominent. Other pathways exist for producing hydrogen at scale, such as coupling PEM electrolyzers with incremental zero-emitting energy sources. Similarly, competing technologies may replace PEM electrolysis, such as alkaline or solid oxide electrolyzers. Ultimately, emissions from grid-derived PEM electrolysis hydrogen used in HD FCEVs, similar to electricity used to charge HD BEVs, are sensitive to the source of the electricity.

Relative to the emission inventory impacts presented earlier in this chapter (see Chapters 4.4, 4.5, and 4.6, for example), we therefore expect that an emission inventory impacts analysis which assumes more hydrogen produced via SMR to estimate decreased upstream GHG emissions in earlier years and increased upstream GHG emissions in further out years. Given that

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[1413] Our results aligned closely with work by Tao, Meng et al. (2022) that found electrolysis using electricity from the grid became lower emitting on a CO_2 basis compared to SMR from natural gas once average electricity grid emissions reached 0.22 $kgCO_2/kWh$.

[1414] Tao, Meng, et al. “Review—Engineering Challenges in Green Hydrogen Production Systems.” Journal of The Electrochemical Society, vol. 169, no. 5, May 2022, p. 054503. Institute of Physics, https://doi.org/10.1149/1945-7111/ac6983.

these are offsetting trends and given the uncertainty inherent in projecting how the hydrogen needed to fuel FCEVs will be produced,[1415, 1416] we feel that our modeling assumption that all hydrogen will be produced via grid electrolysis does not meaningfully skew the overall GHG emission inventory impacts attributable to the final standards.

4.9 Refined Fuels Export Sensitivity Analysis

This chapter presents our sensitivity analysis of refinery emissions should U.S. refineries offset the drop in domestic fuel demand from the final standards using exports to a greater extent than we assumed in our main analysis. As discussed in RIA Chapter 4.2.5, we assumed that refineries would offset 50 percent of the drop in domestic demand by increasing net exports in our main analysis. Some commenters noted that refineries could increase exports more than that, so this sensitivity analysis presents emission impacts should U.S. refineries increase exports even more.

We evaluated the change in refinery inventory should only 20 percent of the drop in domestic demand be reflected in decreased refinery activity, which is less than half of what we assumed for our main modeling case. Therefore, we expect the refinery emission reductions in this sensitivity case to be smaller than we presented in RIA Chapter 4.4 As shown in RIA Chapter 4.5 and RIA Chapter 4.6, the refinery emission impacts from the final standards tend to be much smaller than either the downstream or EGU emission impacts. Therefore, we expect to see little change in the net emissions impact from the final standards in the case that U.S. refineries increase net exports more than in our final standards modeling.

Table 4-55 and Table 4-56 present the sensitivity case refinery emission reductions for GHGs and criteria pollutants in calendar year 2055, respectively, compared to our main final standards modeling. The reductions are about 60% smaller in our sensitivity case than the main case.

Table 4-55 Annual GHG emission reductions from refineries from the final standards in calendar year 2055 for our main modeling case and fuel export sensitivity case

Pollutant	**100-year GWP**	**CY 2055 Refinery Emission Reductions (Metric Tons)**	
		Main Case	**Sensitivity Case**
Carbon Dioxide (CO_2)	1	690,477	276,191
Methane (CH_4)	28	34	14
Nitrous Oxide (N_2O)	265	6	2
CO_2 Equivalent (CO_2e)	---	*693,016*	*277,206*

[1415] The hydrogen production tax credit (described further in RIA Chapter 1.3.2.4), designed to incentivize the production of qualified clean hydrogen at a qualified clean hydrogen production facility, has significant potential to reduce overall greenhouse gas emissions associated with hydrogen production in the coming years, as the value of the credit is based on lifecycle GHG emissions associated with the hydrogen production process. The comment period for the proposed rule by the Internal Revenue Service ended in February 2024. See 88 FR 89220.

[1416] 88 FR 89220. Available online: https://www.federalregister.gov/documents/2023/12/26/2023-28359/section-45v-credit-for-production-of-clean-hydrogen-section-48a15-election-to-treat-clean-hydrogen

Table 4-56 Annual criteria pollutant emission reductions from refineries from the final standards in calendar year 2055 for our main modeling case and fuel export sensitivity case

Pollutant	CY 2055 Refinery Emission Reductions (U.S. Tons)	
	Main Case	Sensitivity Case
Nitrogen Oxides (NO_X)	304	122
Primary $PM_{2.5}$	70	28
Volatile Organic Compounds (VOC)	226	91
Sulfur Dioxide (SO_2)	94	37

Table 4-57 presents the net impacts of the final standards in our sensitivity case for GHGs and Table 4-58 presents the same for criteria pollutants.

Table 4-57 Annual net impacts[A] on GHG emissions from the final standards in calendar years (CYs) 2035, 2045, and 2055, analyzed with our fuel exports sensitivity case

Pollutant	GWP	Calendar Year	Emission Impact (MMT)			
			Downstream	EGU	Refinery	Net
Carbon Dioxide (CO_2)	1	2035	-32.5	29.3	-0.1	-3.3
		2045	-66.3	14.5	-0.3	-52.1
		2055	-70.0	12.9	-0.3	-57.4
Methane (CH_4)	28	2035	-0.002	0.002	0.000	0.000
		2045	-0.006	0.000	0.000	-0.006
		2055	-0.010	0.000	0.000	-0.009
Nitrous Oxide (N_2O)	265	2035	-0.005	0.000	0.000	-0.005
		2045	-0.010	0.000	0.000	-0.010
		2055	-0.010	0.000	0.000	-0.010
CO_2 Equivalent (CO_2e)	---	*2035*	*-33.8*	*29.4*	-0.1	-4.5
		2045	*-69.1*	*14.5*	-0.3	-54.8
		2055	*-73.0*	*12.9*	-0.3	-60.4

[A] We present emissions reductions as negative numbers and emission increases as positive numbers.

We can see little change in the net GHG emission impacts. Compared to our main modeling (see Table 4-30), the net emission impacts are about the same. Our main modeling estimates a net reduction of 60.8 million metric tons of GHG emissions in 2055 versus 60.4 million metric tons in our sensitivity modeling.

Table 4-58 Annual net impacts[A] on criteria pollutant emissions from the final standards in calendar years (CYs) 2035, 2045, and 2055, analyzed with our fuel exports sensitivity case

Pollutant	Calendar Year	Emission Impact (U.S. Tons)			
		Downstream	EGU	Refinery	Net
Nitrogen Oxides (NO_X)	2035	-10,801	9,719	-59	-1,141
	2045	-47,027	1,588	-115	-45,555
	2055	-54,268	1,520	-122	-52,869
Particulate Matter ($PM_{2.5}$)	2035	-126	1,418	-14	1,278
	2045	-302	596	-27	267
	2055	-331	513	-28	155
Volatile Organic Compounds (VOC)	2035	-3,014	467	-45	-2,592
	2045	-6,426	347	-86	-6,166
	2055	-7,242	196	-91	-7,137
Sulfur Dioxide (SO_2)	2035	-126	11,726	-18	11,582
	2045	-256	648	-36	357
	2055	-270	69	-37	-239

[A] We present emissions reductions as negative numbers and emission increases as positive numbers.

In 2055, we estimate net reduction in VOC, NO_X, and SO_2 emissions of 7,137 tons, 52,869 tons, and 239 tons respectively. This is compared with our main case net emission reduction estimates (see Table 4-31) of 7,272 tons of VOC emissions, 53,151 tons of NO_X emissions, and 295 tons of SO_2 emissions. Because we are projecting a smaller emission reduction from refineries in our sensitivity case, we project a larger net increase in $PM_{2.5}$ emissions than in our main case. Our estimated net $PM_{2.5}$ emissions increase in the sensitivity case is 155 tons versus 113 tons in the main case.

Table 4-59 shows the net cumulative GHG impacts of the final standards evaluated with the refinery sensitivity case. The net GHG impacts of the final standards are determined more by downstream emission reductions versus increased EGU emissions than by the refinery emission reductions and, by extension, the extent to which U.S. refineries offset the drop in domestic fuel demand by increasing net exports. In our main modeling, we estimated that net GHG emissions would decrease by 1.025 billion metric tons (see Table 4-39) versus 1.016 billion metric tons for the sensitivity case.

Table 4-59 Cumulative 2027–2055 net GHG emission impacts[A] (in MMT), reflecting the final standards analyzed with our fuel exports sensitivity case

Pollutant	Downstream	EGU	Refineries	Net
Carbon Dioxide (CO_2)	-1,347	391	-5	-961
Methane (CH_4)	-0.127	0.018	0.000	-0.109
Nitrous Oxide (N_2O)	-0.199	0.002	0.000	-0.197
CO_2 Equivalent (CO_2e)	*-1,404*	*393*	-5	*-1,016*

[A] We present emissions reductions as negative numbers and emission increases as positive numbers.

Because the difference between our sensitivity case and main modeling cases is small, the monetized benefits of the rule should U.S. refineries increase net exports more than we assume would be minimally impacted. The net benefits of the rule, therefore, are not very sensitive to the amount that U.S. refineries may increase net exports in the future.

4.10 Reference Case ZEV Adoption Sensitivity Analysis

We performed a sensitivity analysis to evaluate the emissions impact of the final standards for a different reference case than the one described in Chapter 4.2.2. We chose to evaluate a sensitivity reference that has reduced HD ZEV adoption compared to the reference case, in part because we expected such a scenario may result in a greater magnitude of costs. We model differing HD ZEV adoption rates in the sensitivity analysis for both the reference case and final standards case, described in Chapter 4.10.1. Chapter 4.10.2 discusses changes in manufacturer costs.

We modeled the downstream emission inventory for the sensitivity reference case and sensitivity final standards case using MOVES4.R3.[1417] Due to the lead times necessary to run IPM, we did not perform upstream emissions modeling for this sensitivity case. Downstream emission inventory impacts in the sensitivity case are discussed in Chapter 4.10.3.

4.10.1 ZEV Adoption Rate Calculations

To evaluate a reference case with lower ZEV adoption, we calculated ZEV adoption rates in the sensitivity reference case using a methodology conceptually similar to the one we used in the NPRM. When we performed our inventory analysis for the NPRM, CARB’s ACT rule had not yet been granted its waiver and our NPRM reference case approach to HD ZEV adoption was thus based on other considerations (like the IRA and BIL) and did not include ACT as an enforceable rule. However, because it represented the best quantitative data source on which to base our HD ZEV adoption rates absent the final standards (among other reasons noted in DRIA Chapter 4.3.1), we used it as our primary source to calculate a projected national level of reference case ZEV adoption based on the other considerations.

To estimate the adoption of HD ZEVs in the sensitivity reference case, we assumed a national level of ZEV sales equivalent to combined volumes using the NPRM approach with updated data (i.e. national level ZEV adoption expected from ACT in California and the other states that had adopted ACT under CAA Section 177 at the time of our analysis).[1418] We used those volumes as the numeric basis for a projection of the number of ZEVs nationwide in model years 2024 and beyond. While we calculated the national ZEV sales percentages based on those volumes applied to the states that have adopted ACT, we do not explicitly model ACT (or compliance with ACT) in those states in this sensitivity reference case; the ZEV adoption is meaningfully lower than inclusion of ACT in our reference case. Instead, we model ZEV adoption as homogeneous across the United States.

[1417] The only difference between the sensitivity cases and our main inventory modeling is the ZEV adoption rates. We used the same MOVES run specification files to model the sensitivity cases as those described in the beginning of Chapter 4.3.

[1418] At the time we performed the inventory modeling analysis, seven states had adopted ACT in addition to California. Oregon, Washington, New York, New Jersey, and Massachusetts adopted ACT beginning in MY 2025 while Vermont adopted ACT beginning in MY 2026 and Colorado in MY 2027. Three other states, New Mexico, Maryland, and Rhode Island adopted ACT (beginning in MY 2027) in November and December of 2023, but there was not sufficient time for us to incorporate them as ACT states in our modeling.

We made several assumptions to calculate HD ZEV adoption rates by vehicle type for the sensitivity reference case. As we did in the NPRM, we assume, for the purposes of calculating national HD ZEV adoption, the proportion of national HD sales in the states that adopted the ACT program remains the same in the future as they were for MYs 2019 and 2020.[1419] We maintain the modeling of differential adoption rates within the vehicle groups defined by ACT from the FRM reference case based on our technology assessment in HD TRUCS. This is described in Chapter 4.2.2.[1420] Our method for apportioning ZEVs between BEVs and FCEVs also matches the algorithm described in Chapter 4.2.2 and Appendix B to this RIA.

Table 4-60 shows the sensitivity reference case ZEV adoption rates from model years 2027 through 2035. Model years 2036 and beyond have the same adoption rates as MY 2035.

Table 4-60 National heavy-duty ZEV adoption in the sensitivity reference case

Model Year	LHD Vocational	MHD Vocational	HHD Vocational	Short-Haul Tractors	Long-Haul Tractors
2024	2.9%	1.8%	1.7%	1.0%	0.0%
2025	3.5%	2.2%	2.0%	1.4%	0.0%
2026	4.2%	2.6%	2.4%	2.0%	0.0%
2027	6.4%	4.0%	3.7%	2.9%	0.2%
2028	9.7%	6.0%	5.6%	3.8%	0.4%
2029	12.9%	8.0%	7.4%	4.6%	0.7%
2030	16.0%	9.9%	9.2%	5.4%	1.0%
2031	17.6%	10.9%	10.1%	5.8%	2.0%
2032	19.1%	11.9%	11.0%	6.5%	2.5%
2033	20.7%	12.8%	12.0%	6.5%	2.5%
2034	22.3%	13.8%	12.9%	6.5%	2.5%
2035 and beyond	23.9%	14.8%	13.8%	6.5%	2.5%

In this sensitivity analysis, we model the final standards, i.e., the sensitivity control case, using the same stringency level, compliance pathway, and HD ZEV adoption algorithm outlined in Chapter 4.2.3. In the HD ZEV adoption algorithm, the calculation of HD ZEV adoption rates in the modeled compliance pathway for the final standards is not independent of the reference case,[1421] so we model a sensitivity control case that is different from the FRM final standards control case described in Chapter 4.2.3, referred to here as the FRM control case, despite the identical numeric level of the standards and same algorithm.

[1419] We based the proportion of national HD sales in the states that have adopted ACT on vehicle registration data in IHS2020. We used MY 2020 registrations because it was the most recent MY data available. However, the data set encompassed a partial year of registrations, so we also included MY 2019 registrations.

[1420] We model greater ZEV adoption rates in LHD vocational vehicles than MHD vocational vehicles, which have greater ZEV adoption rates than HHD vocational vehicles. Likewise, we model greater adoption of ZEVs for short-haul tractors than long-haul tractors.

[1421] There may be some HD vehicle types in which reference case HD ZEV adoption exceeds what is needed to comply with the final standards. In these cases, we set the HD ZEV adoption rate in our modeling of the final standards to match the reference case. Because the sensitivity reference case has lower HD ZEV adoption rates than the FRM reference case, there are fewer cases where sensitivity reference case ZEV adoption exceeds what is needed to comply with the final standards than the main reference case. Therefore, the sensitivity final standards case has slightly lower overall HD ZEV adoption than the FRM final standards case. It is important to note that the differences are small and have minimal impact on the HD downstream emission inventories.

Table 4-61 shows the HD ZEV adoption rates modeled in our sensitivity control case. The differences in HD ZEV adoption in the sensitivity control case versus the FRM control case (see Table 4-9) are small and have a minimal impact on the estimated HD downstream emission inventories estimated in either final standards case.

Table 4-61 National heavy-duty ZEV adoption in the sensitivity analysis for the final standards

Model Year	LHD Vocational	MHD Vocational	HHD Vocational[a]	Short-Haul Tractors	Long-Haul Tractors[b]
2027	18.0%	13.2%	3.7%	4.9%	0.2%
2028	22.9%	16.3%	9.0%	8.4%	0.4%
2029	27.8%	19.4%	11.4%	11.9%	0.7%
2030	32.7%	22.5%	13.8%	16.3%	6.2%
2031	46.2%	31.1%	19.4%	27.7%	12.5%
2032 and beyond	59.8%	39.8%	25.0%	39.9%	25.0%

[a] For HHD vocational vehicles, the final standards do not include revisions to MY 2027 standards. ZEV adoption for these vehicles in this model year was set to be equal to the reference case.

[b] For sleeper cab tractors, which are represented by long-haul tractors (source type 62) in MOVES, the final standards do not include revisions to the MY 2027 standards or new standards for MYs 2028 or 2029. ZEV adoption for this source type in these model years was set to be equal to the reference case.

4.10.2 Heavy-Duty Vehicle Manufacturer Costs

We do not model a change in the cost of HD ZEV costs for purchasers as part of this sensitivity analysis. We expect the additional cost of a HD ZEV and its payback period, relative to a comparable ICE vehicle, to remain the same regardless of how we model the reference case. HD ZEV purchaser costs and payback periods are discussed in RIA Chapter 2.10.6.

Manufacturer costs depend on the incremental ZEV adoption rate: the difference between the ZEV adoption rates in the technology packages that support the final standards and reference case.[1422] Because the sensitivity reference case has a lower overall level of HD ZEV adoption, we model greater incremental ZEV adoption rates and manufacturer costs change accordingly. More detailed discussions of manufacturer costs can be found in RIA Chapter 2.10.6.

Table 4-62 through Table 4-64 show the ZEV technology costs for manufacturers relative to the sensitivity reference case for MYs 2027, 2030, and 2032, respectively. These cost estimates include the direct manufacturing costs that reflect learning effects, the indirect costs, and the IRA section 13502 Advanced Manufacturing Production Credit, on average aggregated by regulatory group.

[1422] We note that the ZEV adoption rates used in this RIA Chapter 4.10.2 are consistent with the technology packages shown in RIA Chapter 2.10.1 and the sensitivity reference case shown in Table 4-60. Due to the lead time required for MOVES modeling, we were not able to incorporate some changes to the final standards that occurred late in the rulemaking process into MOVES. Thus, for the analysis shown in this RIA Chapter 4.10.2, we use the ZEV adoption rates from RIA Chapter 2.10.1. For other program analyses which depend on data from MOVES, the differences between the final standards and MOVES modeling are negligible because of the timescale of the analyses, which analyze impacts out to 2055.

Table 4-62 Manufacturer costs to meet the final MY 2027 standards through the potential compliance pathway relative to the sensitivity reference case (2022$)

Regulatory Group	Incremental ZEV Adoption Rate in Technology Package	Per-ZEV Manufacturer RPE on Average	Fleet-Average Per-Vehicle Manufacturer RPE
LHD Vocational Vehicles	11%	-$4,100	-$435
MHD Vocational Vehicles	6%	$3,959	$356
HHD Vocational Vehicles	0%	N/A	$0
Day Cab Tractors	0%	N/A	$0
Sleeper Cab Tractors	0%	N/A	$0

Note: The average costs represent the average across the regulatory group. For example the first row represents the average across all LHD vocational vehicles

Table 4-63 Manufacturer costs to meet the final MY 2030 standards through the potential compliance pathway relative to the sensitivity reference case (2022$)

Regulatory Group	Incremental ZEV Adoption Rate in Technology Package	Per-ZEV Manufacturer RPE on Average	Fleet-Average Per-Vehicle Manufacturer RPE
LHD Vocational Vehicles	16%	-$10,637	-$1,702
MHD Vocational Vehicles	12%	-$6,164	-$746
HHD Vocational Vehicles	6%	-$7,582	-$440
Day Cab Tractors	11%	$32	$3
Sleeper Cab Tractors	5%	$41,877	$2,094

Note: The average costs represent the average across the regulatory group. For example the first row represents the average across all LHD vocational vehicles

Table 4-64 Manufacturer costs to meet the final MY 2032 standards through the potential compliance pathway relative to the sensitivity reference case (2022$)

Regulatory Group	Incremental ZEV Adoption Rate in Technology Package	Per-ZEV Manufacturer RPE on Average	Fleet-Average Per-Vehicle Manufacturer RPE
LHD Vocational Vehicles	41%	-$9,776	-$3,998
MHD Vocational Vehicles	28%	-$5,033	-$1,414
HHD Vocational Vehicles	19%	-$3,989	-$758
Day Cab Tractors	34%	$10,816	$3,623
Sleeper Cab Tractors	23%	$53,295	$11,991

Note: The average costs represent the average across the regulatory group. For example the first row represents the average across all LHD vocational vehicles

These manufacturer costs are greater in magnitude than those in the main analysis shown in RIA Chapter 2.10.6. This is true both when costs are projected to be positive (i.e., costs resulting from our projection that certain HD ZEVs will be more expensive than comparable ICE vehicles)) and negative (i.e., savings resulting from our projection that certain HD ZEVs will be cheaper than a comparable ICE vehicle). For example, the MY 2032 fleet-average per-vehicle cost for medium heavy-duty vocational vehicles is -$1,414 here and -$981 in the main analysis. Conversely, the MY 2032 fleet-average per-vehicle cost for sleeper cab tractors is $11,991 here and $10,819 in the main analysis. This is because we model an increase in ZEV adoption and no change in the per-ZEV manufacturer cost. Consistent with our discussion in preamble Section II.G.2 for the main analysis, the fleet-average per-vehicle manufacturer costs in this reference case sensitivity analysis are lower than those we projected for the HD GHG Phase 2 rule that we considered to be reasonable.

4.10.3 Downstream Emission Inventory Impacts

In general, we model greater downstream emission reductions in this sensitivity analysis than in our main modeling of the final standards. Because the sensitivity reference case has lower HD ZEV adoption rates than the FRM reference case, we model greater incremental HD ZEV adoption in our potential compliance pathway for the final standards and therefore greater downstream emission reductions. The greater emission reductions do not result from us modeling a different level of stringency of the final standards themselves.

Our estimates of the downstream emission reductions of GHGs that would result from the final standards relative to the sensitivity reference case are presented in Table 4-65 for calendar years 2035, 2045, and 2055.

Table 4-65 Annual downstream heavy-duty GHG emission reductions from the final standards in calendar years (CYs) 2035, 2045, and 2055, relative to the sensitivity reference case

Pollutant	**100-year GWP**	**CY 2035 Reductions**		**CY 2045 Reductions**		**CY 2055 Reductions**	
		Million Metric Tons	**Percent**	**Million Metric Tons**	**Percent**	**Million Metric Tons**	**Percent**
Carbon Dioxide (CO_2)	1	44.7	12%	96.9	25%	115.0	29%
Methane (CH_4)	28	0.002	4%	0.008	13%	0.014	17%
Nitrous Oxide (N_2O)	265	0.006	12%	0.014	25%	0.017	28%
CO_2 Equivalent (CO_2e)	—	46.5	12%	100.8	25%	119.8	29%

Our estimated GHG emission reductions from the final standards relative to the sensitivity reference case are greater than the reductions relative to the FRM reference case (see Table 4-16). In 2055, we estimate that emission reductions of CO_2 by 29 percent (the main analysis estimate is 20 percent), methane by 17 percent (the main analysis estimate is 12 percent), and N_2O by 28 percent (the main analysis estimate is 20 percent). The resulting total GHG reduction, in CO_2e, is 29 percent for the sensitivity analysis versus 20 percent for the main analysis.

We also project that downstream emission reductions of criteria pollutants and air toxics would result from the final standards in the sensitivity case, as presented in Table 4-66.

Table 4-66 Annual downstream heavy-duty criteria pollutant and air toxic emission reductions from the final standards in calendar years (CYs) 2035, 2045, and 2055, relative to the sensitivity reference case

Pollutant	CY 2035 Reductions		CY 2045 Reductions		CY 2055 Reductions	
	U.S. Tons	Percent	U.S. Tons	Percent	U.S. Tons	Percent
Nitrogen Oxides (NO_X)	15,351	4%	65,923	21%	82,943	28%
Particulate Matter ($PM_{2.5}$)[A]	181	2%	475	7%	619	9%
Volatile Organic Compounds (VOC)	4,293	9%	10,137	24%	13,534	31%
Sulfur Dioxide (SO_2)	173	12%	374	26%	448	29%
Carbon Monoxide (CO)	68,496	8%	175,468	23%	228,506	29%
1,3-Butadiene	10	15%	24	39%	31	45%
Acetaldehyde	88	9%	216	24%	290	27%
Benzene	57	11%	141	33%	189	42%
Formaldehyde	58	6%	150	20%	212	23%
Naphthalene[B]	4	7%	10	31%	12	38%

[A] $PM_{2.5}$ estimates include both exhaust and non-exhaust emissions.
[B] Naphthalene includes both gas and particle phase emissions.

Once again, the estimated emission reductions in criteria pollutants and air toxics that would result from the final standards are greater in the sensitivity case than our main modeling of the final standards (see Table 4-17). For example, in 2055, we estimate the final standards would reduce NO_X emissions by 28 percent, $PM_{2.5}$ emissions by 9 percent, and VOC emissions by 31 percent relative to the sensitivity reference case. This is compared to reductions of NO_X by 20 percent, $PM_{2.5}$ by 5 percent, and VOC by 20 percent for the main analysis. Estimated reductions in emissions of air toxics range from 23 percent for formaldehyde (the main analysis estimate is 15 percent) to 45 percent for 1,3-butadiene (the main analysis estimate is 27 percent).

The year-over-year downstream emission trends in this sensitivity analysis are similar to the trends presented in our main modeling of the final standards in Chapter 4.3.2. The detailed discussion of the impacts of the final standards presented in Chapter 4.3.3, including the detailed breakdowns of emission reductions by fuel type, source type, regulatory class, and emissions process also broadly apply to the sensitivity analysis. However, in all cases, the magnitude of the emission impacts would be greater in this sensitivity analysis than in our modeling of the final standards. Therefore, we do not present this detailed information and discussion of the downstream emission impacts of this sensitivity analysis here.

Figure 4-27 shows the year-over-year inventory of total HD GHG emissions (CO_2e) for both the reference case and final standards, including both our main modeling and our sensitivity analysis.

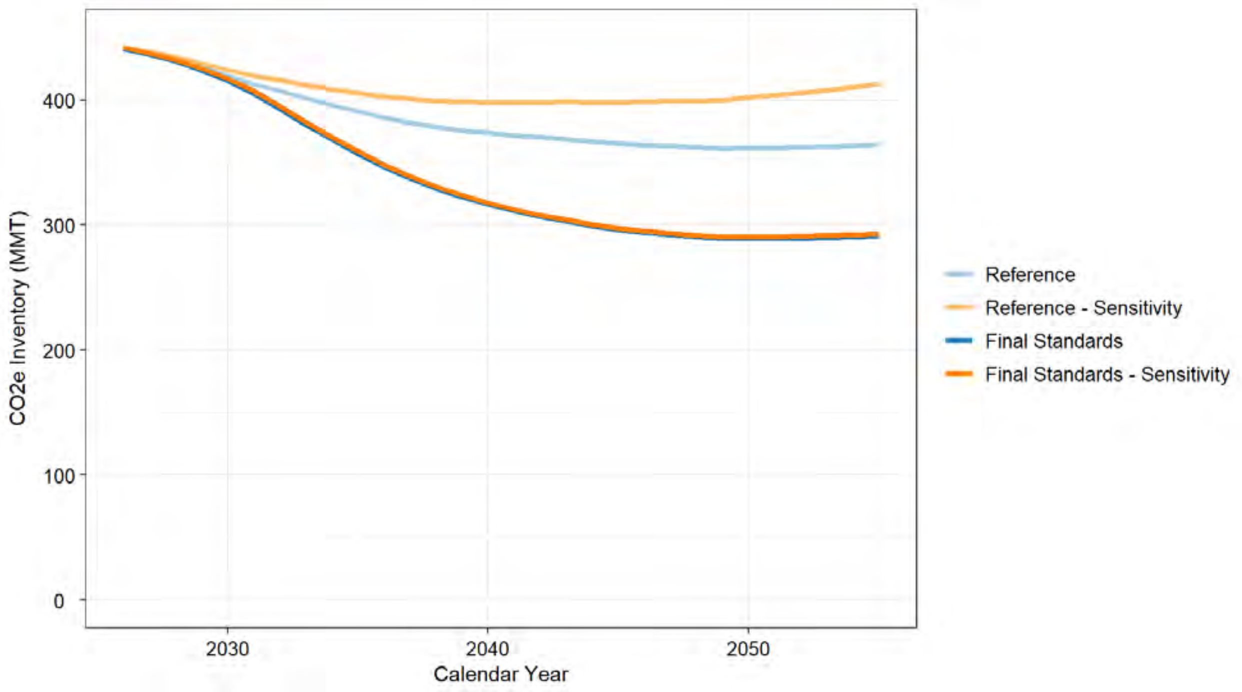

Figure 4-27 Yearly downstream CO_2e inventory for the reference case and final standards from 2027 through 2055, including both our main modeling and reference case sensitivity analysis

As discussed in Chapter 4.10.1, our modeling of the final standards is different between our main modeling and sensitivity analysis, but the differences have a very small impact on the total downstream HD GHG inventory. Because the sensitivity reference case has lower overall HD ZEV adoption, it also has a greater downstream GHG inventory. As a result, we model greater GHG emission reductions from the final standards relative to the sensitivity reference case than the main reference case.

The warming impacts of GHGs are cumulative. Table 4-67 presents the cumulative downstream GHG impacts that we project would result from the final standards from 2027 through 2055, relative to both the main reference case and the sensitivity reference case.

Table 4-67 Cumulative 2027-2055 downstream HD GHG emission reductions from the final standards relative to the main reference case and sensitivity reference case

Pollutant	**Main Modeling**		**Sensitivity Analysis**	
	Reduction in MMT	**Percent**	**Reduction in MMT**	**Percent**
Carbon Dioxide (CO_2)	1,347	13%	2,007	18%
Methane (CH_4)	0.127	7%	0.172	10%
Nitrous Oxide (N_2O)	0.199	13%	0.291	18%
CO_2 Equivalent (CO_2e)	*1,404*	*13%*	*2,089*	*18%*

Consistent with Figure 4-27, the cumulative GHG emission reductions attributable to the final standards are greater relative to the sensitivity reference case than the main reference case.

4.11 Comparison Between the Final Standards and Proposed Standards

As discussed in Chapter 4.6, we estimate that the final standards will reduce cumulative greenhouse gas emissions, from 2027 through 2055, by approximately 1 billion metric tons. In our analysis for the NPRM, our modeling showed cumulative CO_2 emission reductions of 1.8 billion metric tons.[1423] This difference (approximately 0.8 billion metric tons) is explained largely by a change in the modeled downstream emission reductions. In the NPRM, we modeled a reduction of downstream CO_2 emissions of 2.2 billion metric tons, compared to downstream GHG reductions of 1.4 billion metric tons that we estimate for the final standards.

To better understand the difference in downstream emission reductions, we remodeled the proposed standards using our updated FRM modeling tools, which are discussed throughout Chapter 4.2. This includes using MOVES4.R3, updated upstream emissions modeling methodologies, and an updated technology assessment based on HD TRUCS. Here, we present updated HD ZEV adoption estimates and downstream emissions modeling results for the proposed standards. This modeling demonstrates that the differences in the emissions estimates between the NPRM and FRM are attributable to our updated reference case (this is also discussed in Chapter 4.10) and modeling methodologies as opposed to any substantial changes in the overall stringency of the standards themselves. More detailed discussion of the FRM modeling of the proposed standards can be found in a memorandum to the docket.[1424]

In the NRPM, we presented HD ZEV adoption rates for three vehicle groups – vocational vehicles, short-haul tractors, and long-haul tractors. In this FRM, we present HD ZEV adoption rates identically for tractors, but split vocational vehicles into three subgroups – light heavy-duty (LHD), medium heavy-duty (MHD), and heavy heavy-duty (HHD) vocational vehicles. Table 4-68 presents the ZEV adoption rates for modeled compliance pathway for the proposed standards, as they appear in Table 4-7 of DRIA Chapter 4.3.2.

Table 4-68 HD ZEV adoption rates for the proposed standards as presented in the NPRM

HD Vehicle Group	MY 2027	MY 2028	MY 2029	MY 2030	MY 2031	MY 2032 and later
Vocational	20%	25%	30%	35%	40%	50%
Short-Haul Tractors	10%	12%	15%	20%	30%	35%
Long-Haul Tractors	0%	0%	0%	10%	20%	25%

The NPRM adoption rates, presented in this way, are not directly comparable to the adoption rates we used to model the final standards (presented in Table 4-9). We reanalyzed the proposed standards by taking the ZEV adoption rates (i.e., the sum of BEV and FCEV adoption rates) by MOVES source type and regulatory class combination from the NPRM (see DRIA Chapter 4.3.2) and applying the same two constraints to ZEV adoption noted in Chapter 4.2.3. The updated HD ZEV adoption rates we used to model the proposed standards in MOVES4.R3 are presented in Table 4-69.

[1423] In the NRPM, we estimated net emission impacts only for CO_2, instead of all greenhouse gases, because our modeling of emissions from EGUs and refineries did not include the same set of GHGs as our downstream modeling. See DRIA Chapter 4.6 for more details.

[1424] Murray, Evan. Memorandum to Docket EPA-HQ-OAR-2022-0985. “FRM Modeling of the Proposed Standards”. March 2024.

Table 4-69 National heavy-duty ZEV adoption in the control case for the FRM modeling of the proposed standards

Model Year	LHD Vocational	MHD Vocational	HHD Vocational	Short-Haul Tractors	Long-Haul Tractors
2027	18.8%	19.0%	14.4%	9.5%	0.4%
2028	25.8%	22.1%	16.6%	11.6%	0.7%
2029	32.8%	25.2%	18.9%	14.6%	1.3%
2030	39.8%	28.3%	29.4%	19.6%	10.0%
2031	46.5%	31.3%	32.5%	29.5%	20.0%
2032	59.4%	37.5%	38.5%	34.5%	25.0%

The HD ZEV adoption rates resulting from our modeled potential compliance pathway for the proposed and final standards are similar. Where they differ, the proposed standards tend to have greater ZEV adoption in the early years of the rule (2027–2029) and greater ZEV adoption for HHD vocational vehicles. On the other hand, the final standards tend to have greater ZEV adoption later in the rule (2030–2032) for LHD and MHD vocational vehicles as well as for short-haul tractors.

Aside from the differing HD ZEV adoption rates, we used identical methods to model the emissions impact of the proposed standards as we did for the final standards. This includes using the same algorithm to apportion ZEVs between BEVs and FCEVs[1425] and an identical MOVES version (MOVES4.R3) and run specification.

Our estimates of the downstream vehicle emission reductions of GHGs that would result from the proposed standards, relative to the FRM reference case, are presented in Table 4-70 for calendar years 2035, 2045, and 2055.

Table 4-70 Annual downstream heavy-duty GHG emission reductions from the proposed standards in calendar years (CYs) 2035, 2045, and 2055

Pollutant	100-year GWP	CY 2035 Reductions		CY 2045 Reductions		CY 2055 Reductions	
		Million Metric Tons	Percent	Million Metric Tons	Percent	Million Metric Tons	Percent
Carbon Dioxide (CO_2)	1	35.3	9%	64.5	18%	67.5	19%
Methane (CH_4)	28	0.004	7%	0.013	23%	0.024	30%
Nitrous Oxide (N_2O)	265	0.005	10%	0.010	19%	0.010	20%
CO_2 Equivalent (CO_2e)	—	*36.8*	*9%*	*67.4*	*19%*	*70.9*	*20%*

Consistent with the differences in modeled HD ZEV adoption between the proposed and final standards, we estimate the proposed standards have greater GHG emission reductions in earlier years. For example, total GHG emission reductions are 36.8 MMT in 2035 for the proposed standards versus 33.8 MMT for the final standards. In 2055, the final standards have greater GHG emission reductions than the proposed standards (73 MMT versus 70.9 MMT).

Table 4-71 presents the cumulative downstream GHG impacts that we project would result from both the final standards and the proposed standards from 2027 through 2055.

[1425] This algorithm is discussed in Chapter 4.2.3 and Appendix B to this RIA.

Table 4-71 Cumulative 2027-2055 downstream HD GHG emission reductions from the final standards and the proposed standards

Pollutant	Final Standards		Proposed Standards	
	Reduction in MMT	**Percent**	**Reduction in MMT**	**Percent**
Carbon Dioxide (CO_2)	1,347	13%	1,352	13%
Methane (CH_4)	0.127	7%	0.295	17%
Nitrous Oxide (N_2O)	0.199	13%	0.202	13%
CO_2 Equivalent (CO_2e)	*1,404*	*13%*	*1,414*	*13%*

While we model greater emission reductions for proposed standards in early years and greater reductions for the final standards in later years, the cumulative emission reductions are almost identical between the proposed and final standards.

We discuss the emission impacts of the proposed standards on other pollutants in a memorandum to the docket. We also present the emission impacts of the proposed standards from upstream EGUs and refineries, according to our updated modeling.[1426] Table 4-72 presents our net cumulative GHG impact estimates for the proposed standards.

Table 4-72 Cumulative 2027–2055 net GHG emission impacts[A] (in MMT) reflecting the proposed standards

Pollutant	Downstream	EGU	Refineries	Net
Carbon Dioxide (CO_2)	-1,352	428	-13	-937
Methane (CH_4)	-0.295	0.021	-0.001	-0.275
Nitrous Oxide (N_2O)	-0.202	0.003	0.000	-0.199
CO_2 Equivalent (CO_2e)	*-1,414*	*429*	-13	-998

[A] We present emissions reductions as negative numbers and emission increases as positive numbers.

We estimate the net GHG emission reductions from the proposed standards would be 0.998 billion metric tons. This is close to, but smaller than, our estimated GHG emission reductions for the final standards (1.025 billion metric tons). We model the proposed standards to have a greater impact on EGU emissions than the final standards, driven largely by the greater ZEV adoption for HHD vocational vehicles.

When analyzing each scenario using our updated FRM modeling methodology and reference case, the emission impacts of the proposed and final standards are nearly identical despite their differences in modeled HD ZEV adoption rates. The change in estimated net emission impacts from the NPRM to the FRM is therefore attributable to our updated modeling methodologies and updated reference case rather than to a substantial change in the standards themselves.

[1426] Like the downstream emissions modeling methodology, we used identical modeling methodologies to estimate the upstream impacts from the proposed standards as we used for the final standards.

Chapter 5 Health and Environmental Impacts

5.1 Climate Change Impacts from GHG emissions

Elevated concentrations of greenhouse gases (GHGs) have been warming the planet, leading to changes in the Earth's climate that are occuring at a pace and in a way that threatens human health, society, and the natural environment. While EPA is not making any new scientific or factual findings with regard to the well-documented impact of GHG emissions on public health and welfare in support of this rule, EPA is providing in this section a brief scientific background on climate change to offer additional context for this rulemaking and to help the public understand the environmental impacts of GHGs.

Extensive information on climate change is available in the scientific assessments and the EPA documents that are briefly described in this section, as well as in the technical and scientific information supporting them. One of those documents is EPA's 2009 Endangerment and Cause or Contribute Findings for Greenhouse Gases Under section 202(a) of the CAA (74 FR 66496, December 15, 2009). In the 2009 Endangerment Finding, the Administrator found under section 202(a) of the CAA that elevated atmospheric concentrations of six key well-mixed GHGs – CO_2, methane (CH_4), nitrous oxide (N_2O), HFCs, perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6) – "may reasonably be anticipated to endanger the public health and welfare of current and future generations" (74 FR at 66523). The 2009 Endangerment Finding, together with the extensive scientific and technical evidence in the supporting record, documented that climate change caused by human emissions of GHGs threatens the public health of the U.S. population. It explained that by raising average temperatures, climate change increases the likelihood of heat waves, which are associated with increased deaths and illnesses (74 FR 66497). While climate change also increases the likelihood of reductions in cold-related mortality, evidence indicates that the increases in heat mortality will be larger than the decreases in cold mortality in the U.S. (74 FR 66525). The 2009 Endangerment Finding further explained that compared with a future without climate change, climate change is expected to increase tropospheric ozone pollution over broad areas of the U.S., including in the largest metropolitan areas with the worst tropospheric ozone problems, and thereby increase the risk of adverse effects on public health (74 FR 66525). Climate change is also expected to cause more intense hurricanes and more frequent and intense storms of other types and heavy precipitation, with impacts on other areas of public health, such as the potential for increased deaths, injuries, infectious and waterborne diseases, and stress-related disorders (74 FR 66525). Children, the elderly, and the poor are among the most vulnerable to these climate-related health effects (74 FR 66498).

The 2009 Endangerment Finding also documented, together with the extensive scientific and technical evidence in the supporting record, that climate change touches nearly every aspect of public welfare[1427] in the U.S., including: Changes in water supply and quality due to changes in drought and extreme rainfall events; increased risk of storm surge and flooding in coastal areas and land loss due to inundation; increases in peak electricity demand and risks to electricity

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[1427] The CAA states in section 302(h) that "[a]ll language referring to effects on welfare includes, but is not limited to, effects on soils, water, crops, vegetation, manmade materials, animals, wildlife, weather, visibility, and climate, damage to and deterioration of property, and hazards to transportation, as well as effects on economic values and on personal comfort and well-being, whether caused by transformation, conversion, or combination with other air pollutants." 42 U.S.C. 7602(h).

infrastructure; and the potential for significant agricultural disruptions and crop failures (though offset to some extent by carbon fertilization). These impacts are also global and may exacerbate problems outside the U.S. that raise humanitarian, trade, and national security issues for the U.S. (74 FR 66530).

In 2016, the Administrator issued a similar finding for GHG emissions from aircraft under section 231(a)(2)(A) of the CAA.[1428] In the 2016 Endangerment Finding, the Administrator found that the body of scientific evidence amassed in the record for the 2009 Endangerment Finding compellingly supported a similar endangerment finding under CAA section 231(a)(2)(A), and also found that the science assessments released between the 2009 and the 2016 Findings “strengthen and further support the judgment that GHGs in the atmosphere may reasonably be anticipated to endanger the public health and welfare of current and future generations” (81 FR 54424).

Since the 2016 Endangerment Finding, the climate has continued to change, with new observational records being set for several climate indicators such as global average surface temperatures, GHG concentrations, and sea level rise. Additionally, major scientific assessments continue to be released that further advance our understanding of the climate system and the impacts that GHGs have on public health and welfare both for current and future generations.

[1428] "Finding that Greenhouse Gas Emissions From Aircraft Cause or Contribute to Air Pollution That May Reasonably Be Anticipated To Endanger Public Health and Welfare." 81 FR 54422, August 15, 2016. ("2016 Endangerment Finding").

These updated observations and projections document the rapid rate of current and future climate change both globally and in the U.S.[1429,1430,1431,1432,1433,1434,1435,1436,1437,1438,1439,1440,1441]

The most recent information demonstrates that the climate is continuing to change in response to the human-induced buildup of GHGs in the atmosphere. These recent assessments show that atmospheric concentrations of GHGs have risen to a level that has no precedent in human history

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[1429] USGCRP, 2017: *Climate Science Special Report: Fourth National Climate Assessment*, Volume I [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, 470 pp, doi: 10.7930/J0J964J6.

[1430] USGCRP, 2016: *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment.* Crimmins, A., J. Balbus, J.L. Gamble, C.B. Beard, J.E. Bell, D. Dodgen, R.J. Eisen, N. Fann, M.D. Hawkins, S.C. Herring, L. Jantarasami, D.M. Mills, S. Saha, M.C.

[1431] USGCRP, 2018: Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, 1515 pp. doi:10.7930/NCA4.2018.

[1432] IPCC, 2018: *Global Warming of 1.5 °C.* An IPCC Special Report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)].

[1433] IPCC, 2019: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems [P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. Malley, (eds.)].

[1434] IPCC, 2019: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)].

[1434] IPCC, 2023: Summary for Policymakers. In: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, pp. 1–34, doi:10.59327/IPCC/AR6-9789291691647.001.

[1435] National Academies of Sciences, Engineering, and Medicine. 2016. Attribution of Extreme Weather Events in the Context of Climate Change. Washington, DC: The National Academies Press. https://dio.org/10.17226/21852.

[1436] National Academies of Sciences, Engineering, and Medicine. 2017. *Valuing Climate Damages: Updating Estimation of the Social Cost of Carbon Dioxide*. Washington, DC: The National Academies Press. *https://doi.org/10.17226/24651.*

[1437] National Academies of Sciences, Engineering, and Medicine. 2019. *Climate Change and Ecosystems.* Washington, DC: The National Academies Press. *https://doi.org/10.17226/25504.*

[1438] Blunden, J. and T. Boyer, Eds., 2022: “State of the Climate in 2021”. Bull. Amer. Meteor. Soc., 103 (8), Si–S465, *https://doi.org/10.1175/2022BAMSStateoftheClimate.1.*

[1439] EPA. 2021. Climate Change and Social Vulnerability in the United States: A Focus on Six Impacts. U.S. Environmental Protection Agency, EPA 430-R-21-003.

[1440] Jay, A.K., A.R. Crimmins, C.W. Avery, T.A. Dahl, R.S. Dodder, B.D. Hamlington, A. Lustig, K. Marvel, P.A. Méndez-Lazaro, M.S. Osler, A. Terando, E.S. Weeks, and A. Zycherman, 2023: Ch. 1. Overview: Understanding risks, impacts, and responses. In: Fifth National Climate Assessment. Crimmins, A.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA. https://doi.org/10.7930/NCA5.2023.CH1

[1441] Jay, A.K., A.R. Crimmins, C.W. Avery, T.A. Dahl, R.S. Dodder, B.D. Hamlington, A. Lustig, K. Marvel, P.A. Méndez-Lazaro, M.S. Osler, A. Terando, E.S. Weeks, and A. Zycherman, 2023: Ch. 1. Overview: Understanding risks, impacts, and responses. In: Fifth National Climate Assessment. Crimmins, A.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA. https://doi.org/10.7930/NCA5.2023.CH1 and that they continue to climb, primarily because of both historical and current anthropogenic emissions, and that these elevated concentrations endanger our health by affecting our food and water sources, the air we breathe, the weather we experience, and our interactions with the natural and built environments. For example, atmospheric concentrations of one of these GHGs, CO_2, measured at Mauna Loa in Hawaii and at other sites around the world reached 419 parts per million (ppm) in 2022 (nearly 50 percent higher than preindustrial levels)[1442] and have continued to rise at a rapid rate. Global average temperature has increased by about 1.1 °C (2.0 °F) in the 2011–2020 decade relative to 1850–1900.[1443] The years 2015–2021 were the warmest 7 years in the 1880–2021 record, contributing to the warmest decade on record with a decadal temperature of 0.82 °C (1.48 °F) above the 20th century.[1444,1445] The IPCC determined (with medium confidence) that this past decade was warmer than any multi-century period in at least the past 100,000 years.[1446] Global average sea level has risen by about 8 inches (about 21 centimeters (cm)) from 1901 to 2018, with the rate from 2006 to 2018 (0.15 inches/year or 3.7 millimeters (mm)/year) almost twice the rate over the 1971 to 2006 period, and three times the rate of the 1901 to 2018 period.[1447] The rate of sea level rise over the 20th century was higher than in any other century in at least the last 2,800 years.[1448] Higher CO_2 concentrations have led to acidification of the surface ocean in recent decades to an extent unusual in the past 65 million years, with negative impacts on marine organisms that use calcium carbonate to build shells or skeletons.[1449] Arctic sea ice extent continues to decline in all months of the year; the most rapid reductions occur in September (very likely almost a 13 percent decrease per decade between 1979 and 2018) and are unprecedented in at least 1,000 years.[1450] Human-induced climate change has led to heatwaves and heavy precipitation becoming more frequent and more intense, along with increases in agricultural and ecological droughts[1451] in many regions.[1452]

The assessment literature demonstrates that modest additional amounts of warming may lead to a climate different from anything humans have ever experienced. The 2022 CO_2 concentration of 419 ppm is already higher than at any time in the last 2 million years.[1453] If concentrations exceed 450 ppm, they would likely be higher than any time in the past 23 million years:[1454] at the

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[1442] *https://gml.noaa.gov/webdata/ccgg/trends/co2/co2_annmean_mlo.txt*.

[1443] IPCC, 2021: Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 3−32, doi:10.1017/9781009157896.001.

[1444] NOAA National Centers for Environmental Information, State of the Climate 2021 retrieved on August 3, 2023, from *https://www.ncei.noaa.gov/bams-state-of-climate*.

[1445] Blunden, *et al.* 2022.

[1446] IPCC, 2021.

[1447] IPCC, 2021.

[1448] USGCRP, 2018: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II* [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, 1515 pp. doi:10.7930/NCA4.2018.

[1449] IPCC, 2018.

[27] IPCC, 2021.

[1451] These are drought measures based on soil moisture.

[1452] IPCC, 2021.

[1453] Annual Mauna Loa CO_2 concentration data from *https://gml.noaa.gov/webdata/ccgg/trends/co2/co2_annmean_mlo.txt*, accessed September 9, 2023.

[1454] IPCC, 2013.

current rate of increase of more than 2 ppm a year, this would occur in about 15 years. While GHGs are not the only factor that controls climate, it is illustrative that 3 million years ago (the last time CO_2 concentrations were above 400 ppm) Greenland was not yet completely covered by ice and still supported forests, while 23 million years ago (the last time concentrations were above 450 ppm) the West Antarctic ice sheet was not yet developed, indicating the possibility that high GHG concentrations could lead to a world that looks very different from today and from the conditions in which human civilization has developed. If the Greenland and Antarctic ice sheets were to melt substantially, sea levels would rise dramatically—the IPCC estimated that over the next 2,000 years, sea level will rise by 7 to 10 feet even if warming is limited to 1.5 °C (2.7 °F), from 7 to 20 feet if limited to 2 °C (3.6 °F), and by 60 to 70 feet if warming is allowed to reach 5 °C (9 °F) above preindustrial levels.[1455] For context, almost all of the city of Miami is less than 25 feet above sea level, and the 4th National Climate Assessment (NCA4) stated that 13 million Americans would be at risk of migration due to 6 feet of sea level rise.

The NCA4 found that it is very likely (greater than 90 percent likelihood) that by mid-century, the Arctic Ocean will be almost entirely free of sea ice by late summer for the first time in about 2 million years.[1456] Coral reefs will be at risk for almost complete (99 percent) losses with 1 °C (1.8 °F) of additional warming from today (2 °C or 3.6 °F since preindustrial). At this temperature, between 8 and 18 percent of animal, plant, and insect species could lose over half of the geographic area with suitable climate for their survival, and 7 to 10 percent of rangeland livestock would be projected to be lost.[1457] The IPCC similarly found that climate change has caused substantial damages and increasingly irreversible losses in terrestrial, freshwater, and coastal and open ocean marine ecosystems.

Every additional increment of temperature comes with consequences. For example, the half degree of warming from 1.5 to 2°C (0.9°F of warming from 2.7°F to 3.6°F) above preindustrial temperatures is projected on a global scale to expose 420 million more people to frequent extreme heatwaves, and 62 million more people to frequent exceptional heatwaves (where heatwaves are defined based on a heat wave magnitude index which takes into account duration and intensity—using this index, the 2003 French heat wave that led to almost 15,000 deaths would be classified as an “extreme heatwave” and the 2010 Russian heatwave which led to thousands of deaths and extensive wildfires would be classified as “exceptional”). It would increase the frequency of sea-ice-free Arctic summers from once in 100 years to once in a decade. It could lead to 4 inches of additional sea level rise by the end of the century, exposing an additional 10 million people to risks of inundation as well as increasing the probability of triggering instabilities in either the Greenland or Antarctic ice sheets. Between half a million and a million additional square miles of permafrost would thaw over several centuries. Risks to food security would increase from medium to high for several lower-income regions in the Sahel, southern Africa, the Mediterranean, central Europe, and the Amazon. In addition to food security issues, this temperature increase would have implications for human health in terms of increasing ozone concentrations, heatwaves, and vector-borne diseases (for example, expanding the range of the mosquitoes which carry dengue fever, chikungunya, yellow fever, and the Zika virus, or the ticks which carry Lyme, babesiosis, or Rocky Mountain Spotted Fever).[1458] Moreover, every

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[1455] IPCC, 2021.

[1456] USGCRP, 2018.

[1457] IPCC, 2018.

[1458] IPCC, 2018.

additional increment in warming leads to larger changes in extremes, including the potential for events unprecedented in the observational record. Every additional degree will intensify extreme precipitation events by about 7 percent. The peak winds of the most intense tropical cyclones (hurricanes) are projected to increase with warming. In addition to a higher intensity, the IPCC found that precipitation and frequency of rapid intensification of these storms has already increased, the movement speed has decreased, and elevated sea levels have increased coastal flooding, all of which make these tropical cyclones more damaging.[1459]

The NCA4 also evaluated a number of impacts specific to the U.S. Severe drought and outbreaks of insects like the mountain pine beetle have killed hundreds of millions of trees in the western U.S. Wildfires have burned more than 3.7 million acres in 14 of the 17 years between 2000 and 2016, and Federal wildfire suppression costs were about a billion dollars annually.[1460] The National Interagency Fire Center has documented U.S. wildfires since 1983, and the 10 years with the largest acreage burned have all occurred since 2004.[1461] Wildfire smoke degrades air quality, increasing health risks, and more frequent and severe wildfires due to climate change would further diminish air quality, increase incidences of respiratory illness, impair visibility, and disrupt outdoor activities, sometimes thousands of miles from the location of the fire. Meanwhile, sea level rise has amplified coastal flooding and erosion impacts, requiring the installation of costly pump stations, flooding streets, and increasing storm surge damages. Tens of billions of dollars of U.S. real estate could be below sea level by 2050 under some scenarios. Increased frequency and duration of drought will reduce agricultural productivity in some regions, accelerate depletion of water supplies for irrigation, and expand the distribution and incidence of pests and diseases for crops and livestock. The NCA4 also recognized that climate change can increase risks to national security, both through direct impacts on military infrastructure and by affecting factors such as food and water availability that can exacerbate conflict outside U.S. borders. Droughts, floods, storm surges, wildfires, and other extreme events stress nations and people through loss of life, displacement of populations, and impacts on livelihoods.[1462]

EPA modeling efforts can further illustrate how these impacts from climate change may be experienced across the U.S. EPA's Framework for Evaluating Damages and Impacts (FrEDI)[1463] uses information from over 30 peer-reviewed climate change impact studies to project the physical and economic impacts of climate change to the U.S. resulting from future temperature changes. These impacts are projected for specific regions within the U.S. and for more than 20

[1459] IPCC, 2021.

[1460] USGCRP, 2018.

[1461] NIFC (National Interagency Fire Center). 2021. Total wildland fires and acres (1983–2020). Accessed August 2021. *www.nifc.gov/fireInfo/fireInfo_stats_totalFires.html.*

[1462] USGCRP, 2018.

[1463] (1) Hartin, C., *et al.* (2023). Advancing the estimation of future climate impacts within the United States. Earth Syst. Dynam., 14, 1015-1037, https://dio.org/10.5194/esd-14-1015-2023. (2) *Supplementary Material for the Regulatory Impact Analysis for the Supplemental Proposed Rulemaking, "Standards of Performance for New, Reconstructed, and Modified Sources and Emissions Guidelines for Existing Sources: Oil and Natural Gas Sector Climate Review,"* Docket ID No. EPA-HQ-OAR-2021-0317, September 2022, (3) *The Long-Term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050.* Published by the U.S. Department of State and the U.S. Executive Office of the President, Washington DC. November 2021, (4) *Climate Risk Exposure: An Assessment of the Federal Government's Financial Risks to Climate Change,* White Paper, Office of Management and Budget, April 2022.

impact categories, which span a large number of sectors of the U.S. economy.[1464] Using this framework, the EPA estimates that global emission projections, with no additional mitigation, will result in significant climate-related damages to the U.S.[1465] These damages to the U.S. would mainly be from increases in lives lost due to increases in temperatures, as well as impacts to human health from increases in climate-driven changes in air quality, dust and wildfire smoke exposure, and incidence of suicide. Additional major climate-related damages would occur to U.S. infrastructure such as roads and rail, as well as transportation impacts and coastal flooding from sea level rise, increases in property damage from tropical cyclones, and reductions in labor hours worked in outdoor settings and buildings without air conditioning. These impacts are also projected to vary from region to region with the Southeast, for example, projected to see some of the largest damages from sea level rise, the West Coast projected to experience damages from wildfire smoke more than other parts of the country, and the Northern Plains states projected to see a higher proportion of damages to rail and road infrastructure. While information on the distribution of climate impacts helps to better understand the ways in which climate change may impact the U.S., recent analyses are still only a partial assessment of climate impacts relevant to U.S. interests and in addition do not reflect increased damages that occur due to interactions between different sectors impacted by climate change or all the ways in which physical impacts of climate change occurring abroad have spillover effects in different regions of the U.S.

Some GHGs also have impacts beyond those mediated through climate change. For example, elevated concentrations of CO_2 stimulate plant growth (which can be positive in the case of beneficial species, but negative in terms of weeds and invasive species, and can also lead to a reduction in plant micronutrients[1466]) and cause ocean acidification. Nitrous oxide depletes the levels of protective stratospheric ozone.[1467]

Transportation is the largest U.S. source of GHG emissions, representing 27 percent of total GHG emissions. Within the transportation sector, heavy-duty vehicles are the second largest contributor to GHG emissions and are responsible for 25 percent of GHG emissions in the sector. The GHG emission reductions resulting from compliance with this final rule will significantly reduce the volume of GHG emissions from this sector. Chapter 5.4.2 of this RIA discusses impacts of GHG emissions on individuals living in socially and economically vulnerable communities. While EPA did not conduct modeling to specifically quantify changes in climate impacts resulting from this rule in terms of avoided temperature change or sea-level rise, we did quantify climate benefits by monetizing the emission reductions through the application of the social cost of greenhouse gases (SC-GHGs), as described in Chapter 7.1 of this RIA.

[1464] EPA (2021). Technical Documentation on the Framework for Evaluating Damages and Impacts (FrEDI). U.S. Environmental Protection Agency, EPA 430–R–21–004, available at *https://www.epa.gov/cira/fredi.* Documentation has been subject to both a public review comment period and an independent expert peer review, following EPA peer-review guidelines.

[1465] Compared to a world with no additional warming after the model baseline (1986–2005)

[1466] Ziska, L., A. Crimmins, A. Auclair, S. DeGrasse, J.F. Garofalo, A.S. Khan, I. Loladze, A.A. Pérez de León, A. Showler, J. Thurston, and I. Walls, 2016: Ch. 7: *Food Safety, Nutrition, and Distribution. The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment*. U.S. Global Change Research Program, Washington, DC, 189–216. *https://health2016.globalchange.gov/low/ClimateHealth2016_07_Food_small.pdf.*

[1467] WMO (World Meteorological Organization), *Scientific Assessment of Ozone Depletion: 2018, Global Ozone Research and Monitoring Project* – Report No. 58, 588 pp., Geneva, Switzerland, 2018.

These scientific assessments, the EPA analyses, and documented observed changes in the climate of the planet and of the U.S. present clear support regarding the current and future dangers of climate change and the importance of GHG emissions mitigation.

5.2 Climate Benefits

The EPA estimates the climate benefits of GHG emissions reductions expected from the final rule using estimates of the social cost of greenhouse gases (SC-GHG) that reflect recent advances in the scientific literature on climate change and its economic impacts and incorporate recommendations made by the National Academies of Science, Engineering, and Medicine (National Academies 2017).[1468] The EPA published and used these estimates in the RIA for the December 2023 Final Oil and Gas NSPS/EG Rulemaking, "Standards of Performance for New, Reconstructed, and Modified Sources and Emissions Guidelines for Existing Sources: Oil and Natural Gas Sector Climate Review" (EPA 2023f).[1469] The EPA solicited public comment on the methodology and use of these estimates in the RIA for the agency's December 2022 Oil and Gas NSPS/EG Supplemental Proposal[1470] and has conducted an external peer review of these estimates, as described further below.

The SC-GHG is the monetary value of the net harm to society associated with a marginal increase in GHG emissions in a given year, or the benefit of avoiding that increase. In principle, SC-GHG includes the value of all climate change impacts (both negative and positive), including (but not limited to) changes in net agricultural productivity, human health effects, property damage from increased flood risk and natural disasters, disruption of energy systems, risk of conflict, environmental migration, and the value of ecosystem services. The SC-GHG, therefore, reflects the societal value of reducing emissions of the gas in question by one metric ton and is the theoretically appropriate value to use in conducting benefit-cost analyses of policies that affect GHG emissions. In practice, data and modeling limitations restrain the ability of SC-GHG estimates to include all physical, ecological, and economic impacts of climate change, implicitly assigning a value of zero to the omitted climate damages. The estimates are, therefore, a partial accounting of climate change impacts and likely underestimate the marginal benefits of abatement.

Since 2008, the EPA has used estimates of the social cost of various greenhouse gases (i.e., SC-CO_2, SC-CH_4, and SC-N_2O), collectively referred to as the "social cost of greenhouse gases" (SC-GHG), in analyses of actions that affect GHG emissions. The values used by the EPA from 2009 to 2016, and since 2021 – including in the proposal for this rulemaking – have been consistent with those developed and recommended by the IWG on the SC-GHG; and the values used from 2017 to 2020 were consistent with those required by E.O. 13783, which disbanded the IWG. During 2015-2017, the National Academies conducted a comprehensive review of the SC-CO_2 and issued a final report in 2017 recommending specific criteria for future updates to the

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[1468] National Academies 2017. "Valuing Climate Damages: Updating Estimation of the Social Cost of Carbon Dioxide." Washington, D.C.: National Academies of Sciences, Engineering, and Medicine, The National Academies Press. https://doi.org/10.17226/24651.

[1469] EPA 2023f. "Supplementary Material for the Regulatory Impact Analysis for the Final Rulemaking: Standards of Performance for New, Reconstructed, and Modified Sources and Emissions Guidelines for Existing Sources: Oil and Natural Gas Sector Climate Review." EPA Report on the Social Cost of Greenhouse Gases: Estimates Incorporating Recent Scientific Advances, Washington, DC. doi:Docket ID No. EPA-HQ-OAR-2021-0317.

[1470] See https://www.epa.gov/environmental-economics/scghg for a copy of the final report and other related materials.

$SC-CO_2$ estimates, a modeling framework to satisfy the specified criteria, and both near-term updates and longer-term research needs pertaining to various components of the estimation process.[1471]. The IWG was reconstituted in 2021 and E.O. 13990 directed it to develop a comprehensive update of its SC-GHG estimates, recommendations regarding areas of decision-making to which SC-GHG should be applied, and a standardized review and updating process to ensure that the recommended estimates continue to be based on the best available economics and science going forward.

The EPA is a member of the IWG and is participating in the IWG's work under E.O. 13990., As noted in previous EPA RIAs, while that process continues, the EPA is continuously reviewing developments in the scientific literature on the SC-GHG, including more robust methodologies for estimating damages from emissions, and looking for opportunities to further improve SC-GHG estimation [1472]. In the December 2022 Oil and Gas NSPS/EG Supplemental Proposal RIA, the Agency included a sensitivity analysis of the climate benefits of the Supplemental Proposal using a new set of SC-GHG estimates that incorporates recent research addressing recommendations of the National Academies[1473] in addition to using the interim SC-GHG estimates presented in the Technical Support Document: Social Cost of Carbon, Methane, and Nitrous Oxide Interim Estimates under Executive Order 13990[1474] that the IWG recommended for use until updated estimates that address the National Academies' recommendations are available.

The EPA solicited public comment on the sensitivity analysis and the accompanying draft technical report, External Review Draft of Report on the Social Cost of Greenhouse Gases: Estimates Incorporating Recent Scientific Advances, which explains the methodology underlying the new set of estimates, in the December 2022 Supplemental Oil and Gas Proposal. The response to comments document can be found in the docket for that action.

To ensure that the methodological updates adopted in the technical report are consistent with economic theory and reflect the latest science, the EPA also initiated an external peer review panel to conduct a high-quality review of the technical report, completed in May 2023. See 88 FR at 26075/2 noting this peer review process. The peer reviewers commended the agency on its development of the draft update, calling it a much-needed improvement in estimating the SC-GHG and a significant step towards addressing the National Academies' recommendations with defensible modeling choices based on current science. The peer reviewers provided numerous recommendations for refining the presentation and for future modeling improvements, especially with respect to climate change impacts and associated damages that are not currently included in the analysis. Additional discussion of omitted impacts and other updates have been incorporated in the technical report to address peer reviewer recommendations. Complete information about

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[1471] National Academies 2017. "Valuing Climate Damages: Updating Estimation of the Social Cost of Carbon Dioxide." Washington, D.C.: National Academies of Sciences, Engineering, and Medicine, The National Academies Press. https://doi.org/10.17226/24651.

[1472] EPA strives to base its analyses on the best available science and economics, consistent with its responsibilities, for example, under the Information Quality Act.

[1473] National Academies 2017. "Valuing Climate Damages: Updating Estimation of the Social Cost of Carbon Dioxide." Washington, D.C.: National Academies of Sciences, Engineering, and Medicine, The National Academies Press. https://doi.org/10.17226/24651.

[1474] IWG. 2021. Social Cost of Carbon, Methane, and Nitrous Oxide: Interim Estimates under Executive Order 13990. Technical Support Government, Interagency Working Group on Social Cost of Carbon, United States Government.

the external peer review, including the peer reviewer selection process, the final report with individual recommendations from peer reviewers, and the EPA's response to each recommendation is available on EPA's website.[1475]

The remainder of this section provides an overview of the methodological updates incorporated into the SC-GHG estimates used in this final RIA. A more detailed explanation of each input and the modeling process is provided in the final technical report, EPA Report on the Social Cost of Greenhouse Gases: Estimates Incorporating Recent Scientific Advances. Appendix C to this RIA shows the benefits of the final rule using the interim SC-GHG estimates presented in the proposal.[1476]

The steps necessary to estimate the SC-GHG with a climate change integrated assessment model (IAM) can generally be grouped into four modules: socioeconomics and emissions, climate, damages, and discounting. The emissions trajectories from the socioeconomic module are used to project future temperatures in the climate module. The damage module then translates the temperature and other climate endpoints (along with the projections of socioeconomic variables) into physical impacts and associated monetized economic damages, where the damages are calculated as the amount of money the individuals experiencing the climate change impacts would be willing to pay to avoid them. To calculate the marginal effect of emissions, i.e., the SC-GHG in year t, the entire model is run twice – first as a baseline and second with an additional pulse of emissions in year t. After recalculating the temperature effects and damages expected in all years beyond t resulting from the adjusted path of emissions, the losses are discounted to a present value in the discounting module. Many sources of uncertainty in the estimation process are incorporated using Monte Carlo techniques by taking draws from probability distributions that reflect the uncertainty in parameters.

The SC-GHG estimates used by the EPA and many other federal agencies since 2009 have relied on an ensemble of three widely used IAMs: Dynamic Integrated Climate and Economy (DICE)[1477] Climate Framework for Uncertainty, Negotiation, and Distribution (FUND)[1478,1479] and Policy Analysis of the Greenhouse Gas Effect (PAGE)[1480]. In 2010, the IWG harmonized key inputs across the IAMs, but all other model features were left unchanged, relying on the model developers' best estimates and judgments. That is, the representation of climate dynamics

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[1475] EPA. 2023f. "Supplementary Material for the Regulatory Impact Analysis for the Final Rulemaking: Standards of Performance for New, Reconstructed, and Modified Sources and Emissions Guidelines for Existing Sources: Oil and Natural Gas Sector Climate Review." EPA Report on the Social Cost of Greenhouse Gases: Estimates Incorporating Recent Scientific Advances, Washington, DC. doi:Docket ID No. EPA-HQ-OAR-2021-0317.

[1476] IWG. 2021. Social Cost of Carbon, Methane, and Nitrous Oxide: Interim Estimates under Executive Order 13990. Technical Support Government, Interagency Working Group on Social Cost of Carbon, United States Government.

[1477] Nordhaus, W.D. 2010. "Economic aspects of global warming in a post-Copenhagen environment." Proceedings of the National Academy of Sciences of the United States of America 107(26), 11721-11726.

[1478] Anthoff, D, and R.S.J Tol. 2013. "Erratum to: The uncertainty about the social cost of carbon: A decomposition analysis using FUND." Climatic Change 121(2), 413.

[1479] Anthoff, D, and R. S. J. Tol. 2013b. "The uncertainty about the social cost of carbon: A decomposition analysis using FUND." Climate Change 117(3), 515-530. doi:https://doi.org/10.1007/s10584-013-0706-7.

[1480] Hope, C. 2013. "Critical issues for the calculation of the social cost of CO2: why the estimates from PAGE09 are higher than those from PAGE2002." Climate Change 117(3), 531-543. doi:https://doi.org/10.1007/s10584-012-0633-z.

and damage functions included in the default version of each IAM as used in the published literature was retained.

The SC-GHG estimates in this RIA no longer rely on the three IAMs (i.e., DICE, FUND, and PAGE) used in previous SC-GHG estimates. As explained previously, EPA uses a modular approach to estimate the SC-GHG, consistent with the National Academies' near-term recommendations.[1481] That is, the methodology underlying each component, or module, of the SC-GHG estimation process is developed by drawing on the latest research and expertise from the scientific disciplines relevant to that component. Under this approach, each step in the SC-GHG estimation improves consistency with the current state of scientific knowledge, enhances transparency, and allows for more explicit representation of uncertainty.

The socioeconomic and emissions module relies on a new set of probabilistic projections for population, income, and GHG emissions developed under the Resources for the Future (RFF) Social Cost of Carbon Initiative (K. P. Rennert 2021) (Rennert, Prest, et al. 2022a).[1482,1483] These socioeconomic projections (hereafter collectively referred to as the RFF-SPs) are an internally consistent set of probabilistic projections of population, GDP, and GHG emissions (CO_2, CH_4, and N_2O) to 2300. Based on a review of available sources of long-run projections necessary for damage calculations, the RFF-SPs stand out as being most consistent with the National Academies' recommendations. Consistent with the National Academies' recommendation, the RFF-SPs were developed using a mix of statistical and expert elicitation techniques to capture uncertainty in a single probabilistic approach, taking into account the likelihood of future emissions mitigation policies and technological developments, and provide the level of disaggregation necessary for damage calculations. Unlike other sources of projections, they provide inputs for estimation out to 2300 without further extrapolation assumptions. Conditional on the modeling conducted for the SC-GHG estimates, this time horizon is far enough in the future to capture the majority of discounted climate damages. Including damages beyond 2300 would increase the estimates of the SC-GHG. As discussed in EPA 2023f the use of the RFF-SPs allows for capturing economic growth uncertainty within the discounting module.[1484]

The climate module relies on the Finite Amplitude Impulse Response (FaIR) model (Smith, et al. 2018, IPCC, Climate Change 2021 - The Physical Science Basis 2021, Millar, et al.

[1481] National Academies 2017. "Valuing Climate Damages: Updating Estimation of the Social Cost of Carbon Dioxide." Washington, D.C.: National Academies of Sciences, Engineering, and Medicine, The National Academies Press. https://doi.org/10.17226/24651.

[1482] Rennert, K., Prest, B.C., Pizer, W.A., Newell, R.G., Anthoff, D., Kingdon, C., Rennels, L., Cooke, R., Raftery, A.E., Ševčíková, H. and Errickson, F. 2021. "The social cost of carbon: Advances in long-term probablisitic projections of poulation, GDP, emissions, and discount rates." Brookings Papers on Economic Activity 223-305.

[1483] Rennert, K, F Errickson, BC Prest, L Rennels, R Newell, W Pizer, C Kingdon, J Wingenroth, and R Cooke. 2022. "Comprehensive evidence implies a higher social cost of CO2." Nature 610(7933): 687-692.

[1484] EPA 2023f. "Supplementary Material for the Regulatory Impact Analysis for the Final Rulemaking: Standards of Performance for New, Reconstructed, and Modified Sources and Emissions Guidelines for Existing Sources: Oil and Natural Gas Sector Climate Review." EPA Report on the Social Cost of Greenhouse Gases: Estimates Incorporating Recent Scientific Advances, Washington, DC. doi:Docket ID No. EPA-HQ-OAR-2021-0317.

2017)[1485,1486,1487], a widely used Earth system model which captures the relationships between GHG emissions, atmospheric GHG concentrations, and global mean surface temperature. The FaIR model was originally developed by Richard Millar, Zeb Nicholls, and Myles Allen at Oxford University, as a modification of the approach used in IPCC AR5 to assess the GWP and GTP (Global Temperature Potential) of different gases. It is open source, widely used (e.g., IPCC 2018; IPCC 2021a)[1488,1489] and was highlighted by the National Academies[1490] as a model that satisfies their recommendations for a near-term update of the climate module in SC-GHG estimation. Specifically, it translates GHG emissions into mean surface temperature response and represents the current understanding of the climate and GHG cycle systems and associated uncertainties within a probabilistic framework. The SC-GHG estimates used in this RIA rely on FaIR version 1.6.2 as used by the IPCC[1491]. It provides, with high confidence, an accurate representation of the latest scientific consensus on the relationship between global emissions and global mean surface temperature and offers a code base that is fully transparent and available online. The uncertainty capabilities in FaIR 1.6.2 have been calibrated to the most recent assessment of the IPCC (which importantly narrowed the range of likely climate sensitivities relative to prior assessments). See EPA 2023f for more details.[1492]

The socioeconomic projections and outputs of the climate module are inputs into the damage module to estimate monetized future damages from climate change[1493]. The National Academies' recommendations for the damage module, scientific literature on climate damages,

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[1485] Smith, CJ, PM Forster, M Allen, N Leach, RJ Millar, GA Passerello, and LA Regayre. 2018. "FAIR v1.3: a simple emissions-based impulse response and carbon cycle model." Geosci. Model Dev. 11(6): 2273-2297. doi:https://doi.org/10.5194/gmd-11-2273-2018.

[1486] IPCC. 2021. "Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change." Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press. 3-32. doi:10.1017/9781009157896.001.

[1487] Millar, RJ, ZR Nicholls, P Friedlingstein, and MR Allen. 2017. "A modified impulse-response representation of the global near-surface air temperature and atmospheric concentration response to carbon dioxide emissions." Atmospheric Chemistry and Physics 17(11): 7213-7228.

[1488] IPCC. 2018. "Global Warming of 1.5 °C. An IPCC Special Report on the impacts of global warming of 1.5 °C above pre-industrial levels ..."

[1489] —. 2021a. Climate Change 2021: The Physical Science Basis. Vol. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Online: Cambridge University Press. doi:https://www.ipcc.ch/report/ar6/wg1.

[1490] National Academies 2017. "Valuing Climate Damages: Updating Estimation of the Social Cost of Carbon Dioxide." Washington, D.C.: National Academies of Sciences, Engineering, and Medicine, The National Academies Press. https://doi.org/10.17226/24651.

[1491] IPCC. 2021. Climate Change 2021 - The Physical Science Basis. Online: Cambridge University Press. https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Chapter07.pdf.

[1492] EPA 2023f. "Supplementary Material for the Regulatory Impact Analysis for the Final Rulemaking: Standards of Performance for New, Reconstructed, and Modified Sources and Emissions Guidelines for Existing Sources: Oil and Natural Gas Sector Climate Review." EPA Report on the Social Cost of Greenhouse Gases: Estimates Incorporating Recent Scientific Advances, Washington, DC. doi:Docket ID No. EPA-HQ-OAR-2021-0317.

[1493] In addition to temperature change, two of the three damage modules used in the SC-GHG estimation require global mean sea level (GMSL) projections as an input to estimate coastal damages. Those two damage modules use different models for generating estimates of GMSL. Both are based off reduced complexity models that can use the FaIR temperature outputs as inputs to the model and generate projections of GMSL accounting for the contributions of thermal expansion and glacial and ice sheet melting based on recent scientific research. Absent clear evidence on a preferred model, the SC-GHG estimates presented in this RIA retain both methods used by the damage module developers. See (EPA 2023f) for more details.

updates to models that have been developed since 2010, as well as the public comments received on individual EPA rulemakings and the IWG's February 2021 TSD, have all helped to identify available sources of improved damage functions. The IWG (e.g., (IWG 2010) (IWG 2016a) (IWG 2021) [1494,1495,1496]), the National Academies (2017) [1497], comprehensive studies (e.g., (Rose, et al. 2014)[1498]), and public comments have all recognized that the damages functions underlying the IWG SC-GHG estimates used since 2013 (taken from DICE 2010 (W. Nordhaus 2010)[1499]; FUND 3.8 (Anthoff and Tol 2013b)[1500]; (Anthoff and Tol 2013)[1501]; and PAGE 2009 (Hope 2013)[1502]) do not include all the important physical, ecological, and economic impacts of climate change. The climate change literature and the science underlying the economic damage functions have evolved, and DICE 2010, FUND 3.8, and PAGE 2009 now lag behind the most recent research.

The challenges involved with updating damage functions have been widely recognized. Functional forms and calibrations are constrained by the available literature and need to extrapolate beyond warming levels or locations studied in that literature. Research and public resources focused on understanding how these physical changes translate into economic impacts have been significantly less than the resources focused on modeling and improving our understanding of climate system dynamics and the physical impacts from climate change (Auffhammer 2018).[1503] Even so, there has been a large increase in research on climate impacts and damages in the time since DICE 2010, FUND 3.8, and PAGE 2009 were published. Along with this growth, there continues to be wide variation in methodologies and scope of studies, such that care is required when synthesizing the current understanding of impacts or damages. Based on a review of available studies and approaches to damage function estimation, the EPA uses three separate damage functions to form the damage module. They are:

[1494] IWG 2010. Technical Support Document: Social Cost of Carbon for Regulatory Impact Analysis under Executive Order 12866. Accessed 2023. https://www.epa.gov/sites/default/files/2016-12/documents/scc_tsd_2010.pdf.

[1495] IWG. 2016a. Addendum to Technical Support Document on Social Cost of Carbon for Regulatory Impact Analysis under Executive Order 12866: Application of the Methodology to Estimate the Social Cost of Methane and the Social Cost of Nitrous Oxide. https://www.epa.gov/sites/default/files/2016-12/documents/addendum_to_sc-ghg_tsd_august_2016.pdf.

[1496] IWG. 2021. Social Cost of Carbon, Methane, and Nitrous Oxide: Interim Estimates under Executive Order 13990. Technical Support Government, Interagency Working Group on Social Cost of Carbon, United States Government.

[1497] National Academies 2017. "Valuing Climate Damages: Updating Estimation of the Social Cost of Carbon Dioxide." Washington, D.C.: National Academies of Sciences, Engineering, and Medicine, The National Academies Press. https://doi.org/10.17226/24651.

[1498] Rose, S, D Turner, G Blanford, J Bistline, F de la Chesnaye, and T Wilson. 2014. "Understanding the Social Cost of Carbon: A Technical Assessment." EPRI Technical Update Report, Palo Alto, CA.

[1499] Nordhaus, W.D. 2010. "Economic aspects of global warming in a post-Copenhagen environment. ." Proceedings of the National Academy of Sciences of the United States of America 107(26), 11721-11726

[1500] Anthoff, D, and R. S. J. Tol. 2013b. "The uncertainty about the social cost of carbon: A decomposition analysis using FUND." Climate Change 117(3), 515-530. doi:https://doi.org/10.1007/s10584-013-0706-7.

[1501] Anthoff, D, and R.S.J Tol. 2013. "Erratum to: The uncertainty about the social cost of carbon: A decomposition analysis using FUND." Climatic Change 121(2), 413.

[1502] Hope, C. 2013. "Critical issues for the calculation of the social cost of CO2: why the estimates from PAGE09 are higher than those from PAGE2002." Climate Change 117(3), 531-543. doi:https://doi.org/10.1007/s10584-012-0633-z.

[1503] Auffhammer, M. 2018. "Quantifying economic damages from climate change." Journal of Economic Perspectives 32(4): 33-52.

A subnational-scale, sectoral damage function (based on the Data-driven Spatial Climate Impact Model (DSCIM) developed by the Climate Impact Lab (CIL 2023)[1504] (Carleton 2022)[1505] (Rode, et al. 2021)[1506], a country-scale, sectoral damage function (based on the Greenhouse Gas Impact Value Estimator (GIVE) model developed under RFF's Social Cost of Carbon Initiative (Rennert, Errickson, et al. 2022)[1507] and a meta-analysis-based damage function (based on (Howard and Sterner 2017)[1508]). The damage functions in DSCIM and GIVE represent substantial improvements relative to the damage functions underlying the SC-GHG estimates used by the EPA to date and reflect the forefront of scientific understanding about how temperature change and SLR lead to monetized net (market and nonmarket) damages for several categories of climate impacts. The models' spatially explicit and impact-specific modeling of relevant processes allow for improved understanding and transparency about mechanisms through which climate impacts are occurring and how each damage component contributes to the overall results, consistent with the National Academies' recommendations. DSCIM addresses common criticisms related to the damage functions underlying current SC-GHG estimates (e.g., (Pindyck 2017)[1509]) by developing multi-sector, empirically grounded damage functions. The damage functions in the GIVE model offer a direct implementation of the National Academies' near-term recommendation to develop updated sectoral damage functions that are based on recently published work and reflective of the current state of knowledge about damages in each sector. Specifically, the National Academies noted that "[t]he literature on agriculture, mortality, coastal damages, and energy demand provide immediate opportunities to update the [models]",[1510] which are the four damage categories currently in GIVE. A limitation of both models is that the sectoral coverage is still limited, and even the categories that are represented are incomplete. Neither DSCIM nor GIVE yet accommodate estimation of several categories of temperature driven climate impacts (e.g., morbidity, conflict, migration, biodiversity loss) and only represent a limited subset of damages from changes in precipitation. For example, while precipitation is considered in the agriculture sectors in both DSCIM and GIVE, neither model takes into account impacts of flooding, changes in rainfall from tropical storms, and other precipitation related impacts. As another example, the coastal damage estimates in both models do not fully reflect the consequences of SLR-driven salt-water intrusion and erosion, or SLR damages to coastal tourism and recreation. Other missing elements are damages that result from

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[1504] CIL, Climate Impact Lab. 2023. Documentation for Data-driven Spatial Climate Impact Model (DSCIM). https://impactlab.org/wpcontent/uploads/2023/10/DSCIM_UserManual_Version092023-EPA.pdf.

[1505] Carleton, T., Jina, A., Delgado, M., Greenstone, M., Houser, T., Hsiang, S., Hultgren, A., Kopp, R.E., McCusker, K.E., Nath, I., Rising, J., Ashwin, A., Seo, H., Viaene, A., Yaun, J., and Zhang, A.,. 2022. "Valuing the Global mortality Consequences of Climate Change Accounting for Adaptation Costs and Benefits." The Quarterly Journal of Economics 137(4): 2037-2105.

[1506] Rode, A, T Carleton, M Delgado, M Greenstone, T Houser, S Hsiang, A Hultgren, et al. 2021. "Estimating a social cost of carbon for global energy consumption." Nature 598(7880): 308-314.

[1507] Rennert, K, F Errickson, BC Prest, L Rennels, R Newell, W Pizer, C Kingdon, J Wingenroth, and R Cooke. 2022. "Comprehensive evidence implies a higher social cost of CO2." Nature 610(7933): 687-692.

[1508] Howard, PH, and T Sterner. 2017. "Few and not so far between: a meta-analysis of climate damage estimates." Environmental Resource Economics 68(1): 197-225.

[1509] Pindyck, RS. 2017. "Comments on Proposed Rule and Regulatory Impact Analysis on the Delay and Suspension of Certain Requirements for Waster Prevention and Resource Conservation." Accessed Comment submitted on Nov. 6, 2017. https://downloads.regulations.gov/EPA-HQ-OAR-2018-0283- 6184/attachment_6.pdf.

[1510] National Academies 2017. "Valuing Climate Damages: Updating Estimation of the Social Cost of Carbon Dioxide." Washington, D.C.: National Academies of Sciences, Engineering, and Medicine, The National Academies Press. https://doi.org/10.17226/24651.

other physical impacts (e.g., ocean acidification, non-temperature-related mortality such as diarrheal disease and malaria) and the many feedbacks and interactions across sectors and regions that can lead to additional damages[1511]. See EPA 2023f[1512] for more discussion of omitted damage categories and other modeling limitations. DSCIM and GIVE do account for the most commonly cited benefits associated with CO_2 emissions and climate change – CO2 crop fertilization and declines in cold related mortality. As such, while the GIVE- and DSCIM-based results provide state-of-the-science assessments of key climate change impacts, they remain partial estimates of future climate damages resulting from incremental changes in CO2, CH4, and N2O.[1513]

Finally, given the still relatively narrow sectoral scope of the recently developed DSCIM and GIVE models, the damage module includes a third damage function that reflects a synthesis of the state of knowledge in other published climate damages literature. Studies that employ meta-analytic techniques[1514] offer a tractable and straightforward way to combine the results of multiple studies into a single damage function that represents the body of evidence on climate damages that pre-date CIL and RFF's research initiatives. The first use of meta-analysis to combine multiple climate damage studies was done by (Tol 2009)[1515] and included 14 studies. The studies in (Tol 2009) served as the basis for the global damage function in DICE starting in version 2013R (W. Nordhaus 2014)[1516]. The damage function in the most recent published version of DICE, DICE 2016, is from an updated meta-analysis based on a rereview of existing damage studies and included 26 studies published over 1994-2013. Howard and Sterner provide a more recent published peer-reviewed meta-analysis of existing damage studies (published through 2016) and account for additional features of the underlying studies (Howard and Sterner 2017).[1517] This study address differences in measurement across studies by adjusting estimates such that the data are relative to the same base period. They also eliminate double counting by removing duplicative estimates. Howard and Sterner's final sample is drawn from 20 studies that were published through 2015. Howard and Sterner present results under several specifications and shows that the estimates are somewhat sensitive to defensible alternative modeling choices.

[1511] The one exception is that the agricultural damage function in DSCIM and GIVE reflects the ways that trade can help mitigate damages arising from crop yield impacts.

[1512] EPA 2023f. "Supplementary Material for the Regulatory Impact Analysis for the Final Rulemaking: Standards of Performance for New, Reconstructed, and Modified Sources and Emissions Guidelines for Existing Sources: Oil and Natural Gas Sector Climate Review." EPA Report on the Social Cost of Greenhouse Gases: Estimates Incorporating Recent Scientific Advances, Washington, DC. doi:Docket ID No. EPA-HQ-OAR-2021-0317.

[1513] One advantage of the modular approach used by these models is that future research on new or alternative damage functions can be incorporated in a relatively straightforward way. DSCIM and GIVE developers have work underway on other impact categories that may be ready for consideration in future updates (e.g., morbidity and biodiversity loss).

[1514] Meta-analysis is a statistical method of pooling data and/or results from a set of comparable studies of a problem. Pooling in this way provides a larger sample size for evaluation and allows for a stronger conclusion than can be provided by any single study. Meta-analysis yields a quantitative summary of the combined results and current state of the literature.

[1515] Tol, R. 2009. An analysis of mitigation as a response to climate change. Copenhagen Consensus on Climate, Copenhagen Consensus Center.

[1516] Nordhaus, W. 2014. "Estimates of the social cost of carbon: concepts and results from the DICE 2013R model and alternative approaches." Journal of the Association of Environmental Economists 1(1/2): 273-312.

[1517] Howard, PH, and T Sterner. 2017. "Few and not so far between: a meta-analysis of climate damage estimates." Environmental Resource Economics 68(1): 197-225.

As discussed in detail in EPA 2023f,[1518] the damage module underlying the SC-GHG estimates in this RIA includes the damage function specification (that excludes duplicate studies) from Howard and Sterner that leads to the lowest SC-GHG estimates, all else equal.

The discounting module discounts the stream of future net climate damages to its present value in the year when the additional unit of emissions was released. Given the long-time horizon over which the damages are expected to occur, the discount rate has a large influence on the present value of future damages. Consistent with the findings of National Academies 2017,[1519] the economic literature, OMB Circular A-4's guidance for regulatory analysis, and IWG recommendations to date[1520,1521,1522,1523,1524,] the EPA continues to conclude that the consumption rate of interest is the theoretically appropriate discount rate to discount the future benefits of reducing GHG emissions and that discount rate uncertainty should be accounted for in selecting future discount rates in this intergenerational context. OMB’s Circular A-4 points out that “the analytically preferred method of handling temporal differences between benefits and costs is to adjust all the benefits and costs to reflect their value in equivalent units of consumption and to discount them at the rate consumers and savers would normally use in discounting future consumption benefits” (OMB 2003). The damage module described above calculates future net damages in terms of reduced consumption (or monetary consumption equivalents), and so an application of this guidance is to use the consumption discount rate to calculate the SC-GHG. Thus, EPA concludes that the use of the social rate of return on capital (7 percent under current OMB Circular A-4 guidance), which does not reflect the consumption rate, to discount damages estimated in terms of reduced consumption would inappropriately underestimate the impacts of climate change for the purposes of estimating the SC-GHG.[1525]

[1518] EPA 2023f. "Supplementary Material for the Regulatory Impact Analysis for the Final Rulemaking: Standards of Performance for New, Reconstructed, and Modified Sources and Emissions Guidelines for Existing Sources: Oil and Natural Gas Sector Climate Review." EPA Report on the Social Cost of Greenhouse Gases: Estimates Incorporating Recent Scientific Advances, Washington, DC. doi:Docket ID No. EPA-HQ-OAR-2021-0317.

[1519] National Academies 2017. "Valuing Climate Damages: Updating Estimation of the Social Cost of Carbon Dioxide." Washington, D.C.: National Academies of Sciences, Engineering, and Medicine, The National Academies Press. https://doi.org/10.17226/24651.

[1520] IWG 2010. Technical Support Document: Social Cost of Carbon for Regulatory Impact Analysis under Executive Order 12866. Accessed 2023. https://www.epa.gov/sites/default/files/2016-12/documents/scc_tsd_2010.pdf.

[1521] IWG 2013. Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866. https://www.ourenergypolicy.org/wp-content/uploads/2013/06/social_cost_of_carbon_for_ria_2013_update.pdf.

[1522] IWG. 2016a. Addendum to Technical Support Document on Social Cost of Carbon for Regulatory Impact Analysis under Executive Order 12866: Application of the Methodology to Estimate the Social Cost of Methane and the Social Cost of Nitrous Oxide. https://www.epa.gov/sites/default/files/2016-12/documents/addendum_to_sc-ghg_tsd_august_2016.pdf.

[1523] IWG 2016b. Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866. Accessed 2023. https://www.epa.gov/sites/default/files/2016-12/documents/sc_CO2_tsd_august_2016.pdf.

[1524] IWG. 2021. Social Cost of Carbon, Methane, and Nitrous Oxide: Interim Estimates under Executive Order 13990. Technical Support Government, Interagency Working Group on Social Cost of Carbon, United States Government.

[1525] See also the discussion of the inappropriateness of discounting consumption-equivalent measures of benefits and costs using a rate of return on capital in Circular A-4 (2023) (OMB 2003).

For the SC-GHG estimates used in this RIA, EPA relies on a dynamic discounting approach that more fully captures the role of uncertainty in the discount rate in a manner consistent with the other modules. Based on a review of the literature and data on consumption discount rates, the public comments received on individual EPA rulemakings, and the February 2021 TSD[1526], and the National Academies[1527] recommendations for updating the discounting module, the SC-GHG estimates rely on discount rates that reflect more recent data on the consumption interest rate and uncertainty in future rates. Specifically, rather than using a constant discount rate, the evolution of the discount rate over time is defined following the latest empirical evidence on interest rate uncertainty and using a framework originally developed by Ramsey[1528] that connects economic growth and interest rates. The Ramsey approach explicitly reflects (1) preferences for utility in one period relative to utility in a later period and (2) the value of additional consumption as income changes. The dynamic discount rates used to develop the SC-GHG estimates applied in this RIA have been calibrated following the Newell, Pizer and Prest (2022)[1529] approach, as applied in (Rennert, Errickson, et al. 2022)[1530] (Rennert, Prest, et al. 2022a)[1531]. This approach uses the discounting formula[1532] in which the parameters are calibrated such that (1) the decline in the certainty-equivalent discount rate matches the latest empirical evidence on interest rate uncertainty estimated by (Bauer and Rudebusch 2020)[1533] (Bauer and Rudebusch 2023)[1534] and (2) the average of the certainty-equivalent discount rate over the first decade matches a near-term consumption rate of interest. Uncertainty in the starting rate is addressed by using three near-term target rates (1.5, 2.0, and 2.5 percent) based on multiple lines of evidence on observed market interest rates.

The resulting dynamic discount rate provides a notable improvement over the constant discount rate framework used for SC-GHG estimation in previous EPA RIAs. Specifically, it provides internal consistency within the modeling and a more complete accounting of uncertainty consistent with economic theory (Arrow, et al. 2013)[1535] (Cropper, et al. 2014)[1536]

[1526] IWG. 2021. Social Cost of Carbon, Methane, and Nitrous Oxide: Interim Estimates under Executive Order 13990. Technical Support Government, Interagency Working Group on Social Cost of Carbon, United States Government.

[1527] Similarly, OMB's Circular A-4 (2023) points out that "The analytically preferred method of handling temporal differences between benefits and costs is to adjust all the benefits and costs to reflect their value in equivalent units of consumption before discounting them" (OMB 2003).

[1528] Ramsey, FP. 1928. "A mathematical theory of saving." The Economic Journal 38(152): 543-559.

[1529] Newell, RG, WA Pizer, and BC Prest. 2022. "A discounting rule for the social cost of carbon." Journal of the Association of Environmental and Resource Economists 9(5): 1017-1046.

[1530] Rennert, K, F Errickson, BC Prest, L Rennels, R Newell, W Pizer, C Kingdon, J Wingenroth, and R Cooke. 2022. "Comprehensive evidence implies a higher social cost of CO2." Nature 610(7933): 687-692.

[1531] Rennert, K., Prest, B.C., Pizer, W.A., Newell, R.G., Anthoff, D., Kingdon, C., Rennels, L., Cooke, R., Raftery, A.E., Ševčíková, H. and Errickson, F. 2021. "The social cost of carbon: Advances in long-term probablisitic projections of poulation, GDP, emissions, and discount rates." Brookings Papers on Economic Activity 223-305.

[1532] Ramsey, FP. 1928. "A mathematical theory of saving." The Economic Journal 38(152): 543-559.

[1533] Bauer, MD, and GD Rudebusch. 2020. "Interest rates under falling stars." American Economic Review 110(5): 1316-54.

[1534] Bauer, MD, and GD Rudebusch. 2023. "The rising cost of climate change: evidence from the bond market." The Review of Economics and Statistics 105(5): 1255-1270.

[1535] Arrow, K, M Cropper, C Gollier, B Groom, G Heal, R Newell, W Nordhaus, R Pindyck, W Pizer, and P Portney. 2013. "Determining benefits and costs for future generations." Science 341(6144) : 349-350.

[1536] Cropper, ML, MC Freeman, B Groom, and WA Pizer. 2014. "Declining discount rates." American Economic Review 104(5): 538-43.

and the National Academies[1537] recommendation to employ a more structural, Ramsey-like approach to discounting that explicitly recognizes the relationship between economic growth and discounting uncertainty. This approach is also consistent with the National Academies[1538] recommendation to use three sets of Ramsey parameters that reflect a range of near-term certainty-equivalent discount rates and are consistent with theory and empirical evidence on consumption rate uncertainty. Finally, the value of aversion to risk associated with net damages from GHG emissions is explicitly incorporated into the modeling framework following the economic literature. See EPA 2023f for a more detailed discussion of the entire discounting module and methodology used to value risk aversion in the SC-GHG estimates.[1539]

Taken together, the methodologies adopted in this SC-GHG estimation process allow for a more holistic treatment of uncertainty than past estimates used by the EPA. The updates incorporate a quantitative consideration of uncertainty into all modules and use a Monte Carlo approach that captures the compounding uncertainties across modules. The estimation process generates nine separate distributions of discounted marginal damages per metric ton – the product of using three damage modules and three near-term target discount rates – for each gas in each emissions year. These distributions have long right tails reflecting the extensive evidence in the scientific and economic literature that shows the potential for lower-probability but higher-impact outcomes from climate change, which would be particularly harmful to society. The uncertainty grows over the modeled time horizon. Therefore, under cases with a lower near-term target discount rate – that give relatively more weight to impacts in the future – the distribution of results is wider. To produce a range of estimates that reflects the uncertainty in the estimation exercise while also providing a manageable number of estimates for policy analysis, the EPA combines the multiple lines of evidence on damage modules by averaging the results across the three damage module specifications. The full results generated from the updated methodology for methane and other greenhouse gases (SC-CO_2, SC-CH4, and SC-N2O) for emissions years 2020 through 2080 are provided in EPA 2023f. [1540]

Table 5-1 summarizes the resulting averaged certainty-equivalent SC-GHG estimates under each near-term discount rate that are used to estimate the climate benefits of the GHG emission reductions expected from the final rule. These estimates are reported in 2022 dollars but are

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[1537] National Academies 2017. "Valuing Climate Damages: Updating Estimation of the Social Cost of Carbon Dioxide." Washington, D.C.: National Academies of Sciences, Engineering, and Medicine, The National Academies Press. https://doi.org/10.17226/24651.

[1538] National Academies 2017. "Valuing Climate Damages: Updating Estimation of the Social Cost of Carbon Dioxide." Washington, D.C.: National Academies of Sciences, Engineering, and Medicine, The National Academies Press. https://doi.org/10.17226/24651.

[1539] EPA 2023f. "Supplementary Material for the Regulatory Impact Analysis for the Final Rulemaking: Standards of Performance for New, Reconstructed, and Modified Sources and Emissions Guidelines for Existing Sources: Oil and Natural Gas Sector Climate Review." EPA Report on the Social Cost of Greenhouse Gases: Estimates Incorporating Recent Scientific Advances, Washington, DC. doi:Docket ID No. EPA-HQ-OAR-2021-0317.

[1540] EPA 2023f. "Supplementary Material for the Regulatory Impact Analysis for the Final Rulemaking: Standards of Performance for New, Reconstructed, and Modified Sources and Emissions Guidelines for Existing Sources: Oil and Natural Gas Sector Climate Review." EPA Report on the Social Cost of Greenhouse Gases: Estimates Incorporating Recent Scientific Advances, Washington, DC. doi:Docket ID No. EPA-HQ-OAR-2021-0317.

otherwise identical to those presented in EPA 2023f.[1541] The SC-GHGs increases over time within the models — i.e., the societal harm from one metric ton emitted in 2030 is higher than the harm caused by one metric ton emitted in 2027 — because future emissions produce larger incremental damages as physical and economic systems become more stressed in response to greater climatic change, and because GDP is growing over time and many damage categories are modeled as proportional to GDP.

[1541] EPA 2023f. "Supplementary Material for the Regulatory Impact Analysis for the Final Rulemaking: Standards of Performance for New, Reconstructed, and Modified Sources and Emissions Guidelines for Existing Sources: Oil and Natural Gas Sector Climate Review." EPA Report on the Social Cost of Greenhouse Gases: Estimates Incorporating Recent Scientific Advances, Washington, DC. doi:Docket ID No. EPA-HQ-OAR-2021-0317.

Table 5-1 Annual Rounded SC-CO_2, SC-CH_4, and SC-N_2O Values, 2027-2055.

	SC-GHG and Near-term Ramsey Discount Rate								
	SC-CO_2 (2022 dollars per metric ton of CO_2)			**SC-CH_4 (2022 dollars per metric ton of CH_4)**			**SC-N_2O (2022 dollars per metric ton of N_2O)**		
Emission Year	**Near-term rate 2.5%**	**2.0%**	**1.5%**	**Near-term rate 2.5%**	**2.0%**	**1.5%**	**Near-term rate 2.5%**	**2.0%**	**1.5%**
2027	150	250	410	1900	2400	3200	47000	70000	110000
2028	160	250	420	2000	2500	3300	48000	72000	110000
2029	160	250	430	2000	2600	3400	49000	73000	110000
2030	160	260	430	2100	2600	3500	50000	74000	120000
2031	160	260	440	2200	2700	3600	51000	76000	120000
2032	170	270	440	2300	2800	3700	52000	77000	120000
2033	170	270	450	2400	2900	3800	53000	79000	120000
2034	170	270	450	2500	3000	4000	54000	80000	120000
2035	180	280	460	2500	3100	4100	55000	81000	120000
2036	180	280	460	2600	3200	4200	57000	83000	130000
2037	180	290	470	2700	3300	4300	58000	84000	130000
2038	190	290	470	2800	3400	4400	59000	86000	130000
2039	190	290	480	2900	3500	4500	60000	87000	130000
2040	190	300	480	3000	3600	4600	61000	88000	130000
2041	200	300	490	3100	3700	4800	62000	90000	140000
2042	200	310	490	3200	3800	4900	63000	91000	140000
2043	200	310	500	3300	3900	5000	65000	93000	140000
2044	210	320	500	3400	4100	5100	66000	95000	140000
2045	210	320	510	3500	4200	5200	67000	96000	140000
2046	210	330	520	3500	4300	5400	69000	98000	150000
2047	220	330	520	3600	4400	5500	70000	99000	150000
2048	220	340	530	3700	4500	5600	70000	100000	150000
2049	230	340	530	3800	4600	5700	72000	100000	150000
2050	230	340	540	3900	4700	5800	73000	100000	150000
2051	230	350	550	4000	4800	6000	75000	100000	150000
2052	240	350	550	4100	4900	6100	76000	110000	160000
2053	240	360	560	4200	5000	6200	77000	110000	160000
2054	240	360	560	4300	5100	6300	78000	110000	160000
2055	250	360	570	4400	5200	6400	79000	110000	160000

Source: (EPA 2023f)

Note: These SC-GHG values are identical to those reported in the technical report (EPA 2023f) adjusted for inflation to 2022 dollars using the annual GDP Implicit Price Deflator values in the U.S. Bureau of Economic Analysis' (BEA) NIPA Table 1.1.9 (Bureau of Economic Analysis (BEA) 2021). The values are stated in $/metric ton GHG and vary depending on the year of GHG emissions. This table displays the values rounded to two significant figures. The annual unrounded values used in the calculations in this RIA are available in Appendix A.5 of (EPA 2023f) and at: www.epa.gov/environmental-economics/scghg.

The methodological updates described above represent a major step forward in bringing SC-GHG estimation closer to the frontier of climate science and economics and address many of the National Academies near-term recommendations.[1542] Nevertheless, the resulting SC-GHG estimates presented in Table 9-1, still have several limitations, as would be expected for any

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[1542] National Academies 2017. "Valuing Climate Damages: Updating Estimation of the Social Cost of Carbon Dioxide." Washington, D.C.: National Academies of Sciences, Engineering, and Medicine, The National Academies Press. https://doi.org/10.17226/24651.

modeling exercise that covers such a broad scope of scientific and economic issues across a complex global landscape. There are still many categories of climate impacts and associated damages that are only partially or not reflected yet in these estimates and sources of uncertainty that have not been fully characterized due to data and modeling limitations. For example, the modeling omits most of the consequences of changes in precipitation, damages from extreme weather events, the potential for nongradual damages from passing critical thresholds (e.g., tipping elements) in natural or socioeconomic systems, and non-climate mediated effects of GHG emissions. More specifically for methane, the SC-CH_4 estimates do not account for the direct health and welfare impacts associated with tropospheric ozone produced by methane. As discussed further in (EPA 2023f)[1543], recent studies have found the global ozone-related respiratory mortality benefits of CH_4 emissions reductions, which are not included in the SC-CH_4 values presented in Table 7-1, to be, in 2022 dollars, approximately $2,700 per metric ton of methane emissions in 2030 (McDuffie, et al. 2023).[1544] In addition, the SC-CH_4 estimates do not reflect that methane emissions lead to a reduction in atmospheric oxidants, like hydroxyl radicals, nor do they account for impacts associated with CO_2 produced from methane oxidizing in the atmosphere. Importantly, the updated SC-GHG methodology does not yet reflect interactions and feedback effects within, and across, Earth and human systems. For example, it does not explicitly reflect potential interactions among damage categories, such as those stemming from the interdependencies of energy, water, and land use. These, and other, interactions and feedbacks were highlighted by the National Academies as an important area of future research for longer-term enhancements in the SC-GHG estimation framework.

5.3 Reserved

5.4 Health Effects Associated with Exposure to Non-GHG Pollutants

Heavy-duty vehicles emit non-GHG pollutants that contribute to ambient concentrations of ozone, PM, NO_2, SO_2, CO, and air toxics. As described in RIA Chapter 4, the increased use of zero-emission technology in the heavy-duty sector would reduce emissions of non-GHG pollutants from heavy-duty vehicles. A discussion of the health effects associated with exposure to these pollutants is presented in this section of the RIA. The following discussion of health impacts is mainly focused on describing the effects of air pollution on the population in general.

Additionally, because children have increased vulnerability and susceptibility for adverse health effects related to air pollution exposures, EPA's findings regarding adverse effects for children related to exposure to pollutants that are impacted by this rule are noted in this section. The increased vulnerability and susceptibility of children to air pollution exposures may arise because infants and children generally breathe more relative to their size than adults, and consequently they may be exposed to relatively higher amounts of air pollution.[1545] Children also

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[1543] EPA 2023f. "Supplementary Material for the Regulatory Impact Analysis for the Final Rulemaking: Standards of Performance for New, Reconstructed, and Modified Sources and Emissions Guidelines for Existing Sources: Oil and Natural Gas Sector Climate Review." EPA Report on the Social Cost of Greenhouse Gases: Estimates Incorporating Recent Scientific Advances, Washington, DC. doi:Docket ID No. EPA-HQ-OAR-2021-0317.

[1544] McDuffie, EE, MC Sarofim, W Raich, M Jackson, H Roman, K Seltzer, BH Henderson, et al. 2023. "The social cost of ozone-related mortality impacts from methane emissions." Earth's Future 11(9). doi:https://doi.org/10.1029/2023EF003853.

[1545] EPA (2009) Metabolically-derived ventilation rates: A revised approach based upon oxygen consumption rates. Washington, DC: Office of Research and Development. EPA/600/R–06/129F. *http://cfpub.epa.gov/ncea/cfm/recordisplay.cfm?deid=202543*.

tend to breathe through their mouths more than adults, and their nasal passages are less effective at removing pollutants which leads to greater lung deposition of some pollutants such as PM.[1546,1547] Furthermore, air pollutants may pose health risks specific to children because children's bodies are still developing. [1548] For example, during periods of rapid growth such as fetal development, infancy and puberty, their developing systems and organs may be more easily harmed.[1549,1550] EPA produces the report titled "America's Children and the Environment," which presents national trends on air pollution and other contaminants and environmental health of children.[1551]

5.4.1 Ozone

5.4.1.1 Background on Ozone

Ground-level ozone pollution forms in areas with high concentrations of ambient NO_X and VOCs when solar radiation is high. Major U.S. sources of NO_X are highway and nonroad motor vehicles and engines, power plants, and other industrial sources; natural sources, such as soil, vegetation, and lightning, are smaller sources. Vegetation is the dominant source of VOCs in the United States. Volatile consumer and commercial products, such as propellants and solvents, highway and nonroad vehicles, engines, fires, and industrial sources also contribute to the atmospheric burden of VOCs at ground-level.

The processes underlying ozone formation, transport, and accumulation are complex. Ground-level ozone is produced and destroyed by an interwoven network of free radical reactions involving the hydroxyl radical (OH), NO, NO_2, and complex reaction intermediates derived from VOCs. Many of these reactions are sensitive to temperature and available sunlight. High ozone events most often occur when ambient temperatures and sunlight intensities remain high for several days under stagnant conditions. Ozone and its precursors can also be transported hundreds of miles downwind, which can lead to elevated ozone levels in areas with otherwise low VOC or NO_X emissions. As an air mass moves and is exposed to changing ambient concentrations of NO_X and VOCs, the ozone photochemical regime (relative sensitivity of ozone formation to NO_X and VOC emissions) can change.

When ambient VOC concentrations are high, comparatively small amounts of NO_X catalyze rapid ozone formation. Without available NO_X, ground-level ozone production is severely limited, and VOC reductions would have little impact on ozone concentrations. Photochemistry

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[1546] U.S. EPA Integrated Science Assessment for Particulate Matter (Final Report, 2019). U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-19/188, 2019. Chapter 4 "Overall Conclusions" p. 4-1.

[1547] Foos, B.; Marty, M.; Schwartz, J.; Bennet, W.; Moya, J.; Jarabek, A.M.; Salmon, A.G. (2008) Focusing on children's inhalation dosimetry and health effects for risk assessment: An introduction. J Toxicol Environ Health 71A: 149–165.

[1548] Children's environmental health includes conception, infancy, early childhood and through adolescence until 21 years of age as described in the EPA Memorandum: Issuance of EPA's 2021 Policy on Children's Health. October 5, 2021. Available at https://www.epa.gov/system/files/documents/2021-10/2021-policy-on-childrens-health.pdf.

[1549] EPA (2006) A Framework for Assessing Health Risks of Environmental Exposures to Children. EPA, Washington, DC, EPA/600/R-05/093F, 2006.

[1550] U.S. Environmental Protection Agency. (2005). Supplemental guidance for assessing susceptibility from early-life exposure to carcinogens. Washington, DC: Risk Assessment Forum. EPA/630/R–03/003F. https://www3.epa.gov/airtoxics/childrens_supplement_final.pdf.

[1551] U.S. EPA. America's Children and the Environment. Available at: https://www.epa.gov/americaschildrenenvironment under these conditions is said to be "NO_X-limited." When NO_X levels are sufficiently high, faster NO_2 oxidation consumes more radicals, dampening ozone production. Under these "VOC-limited" conditions (also referred to as "NO_X-saturated" conditions), VOC reductions are effective in reducing ozone, and NO_X can react directly with ozone resulting in suppressed ozone concentrations near NO_X emission sources. Under these NO_X-saturated conditions, NO_X reductions can increase local ozone under certain circumstances, but overall ozone production (considering downwind formation) decreases and even in VOC-limited areas, NO_X reductions are not expected to increase ozone levels if the NO_X reductions are sufficiently large - large enough for photochemistry to become NO_X-limited.

5.4.1.2 Health Effects Associated with Exposure to Ozone

This section provides a summary of the health effects associated with exposure to ambient concentrations of ozone.[1552] The information in this section is based on the information and conclusions in the April 2020 Integrated Science Assessment for Ozone (Ozone ISA).[1553] The Ozone ISA concludes that human exposures to ambient concentrations of ozone are associated with a number of adverse health effects and characterizes the weight of evidence for these health effects.[1554] The discussion below highlights the Ozone ISA's conclusions pertaining to health effects associated with both short-term and long-term periods of exposure to ozone.

For short-term exposure to ozone, the Ozone ISA concludes that respiratory effects, including lung function decrements, pulmonary inflammation, exacerbation of asthma, respiratory-related hospital admissions, and mortality, are causally associated with ozone exposure. It also concludes that metabolic effects, including metabolic syndrome (i.e., changes in insulin or glucose levels, cholesterol levels, obesity and blood pressure) and complications due to diabetes are likely to be causally associated with short-term exposure to ozone, and that evidence is suggestive of a causal relationship between cardiovascular effects, central nervous system effects and total mortality and short-term exposure to ozone.

For long-term exposure to ozone, the Ozone ISA concludes that respiratory effects, including new onset asthma, pulmonary inflammation and injury, are likely to be causally related with ozone exposure. The Ozone ISA characterizes the evidence as suggestive of a causal relationship for associations between long-term ozone exposure and cardiovascular effects, metabolic effects, reproductive and developmental effects, central nervous system effects and total mortality. The evidence is inadequate to infer a causal relationship between chronic ozone exposure and increased risk of cancer.

Finally, interindividual variation in human responses to ozone exposure can result in some groups being at increased risk for detrimental effects in response to exposure. In addition, some

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[1552] Human exposure to ozone varies over time due to changes in ambient ozone concentration and because people move between locations which have notable different ozone concentrations. Also, the amount of ozone delivered to the lung is not only influenced by the ambient concentrations but also by the breathing route and rate.

[1553] U.S. EPA. Integrated Science Assessment (ISA) for Ozone and Related Photochemical Oxidants (Final Report). U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-20/012, 2020.

[1554] The ISA evaluates evidence and draws conclusions on the causal relationship between relevant pollutant exposures and health effects, assigning one of five "weight of evidence" determinations: causal relationship, likely to be a causal relationship, suggestive of a causal relationship, inadequate to infer a causal relationship, and not likely to be a causal relationship. For more information on these levels of evidence, please refer to Table II in the Preamble of the ISA.

groups are at increased risk of exposure due to their activities, such as outdoor workers and children. The Ozone ISA identified several groups that are at increased risk for ozone-related health effects. These groups are people with asthma, children and older adults, individuals with reduced intake of certain nutrients (i.e., Vitamins C and E), outdoor workers, and individuals having certain genetic variants related to oxidative metabolism or inflammation. Ozone exposure during childhood can have lasting effects through adulthood. Such effects include altered function of the respiratory and immune systems. Children absorb higher doses (normalized to lung surface area) of ambient ozone, compared to adults, due to their increased time spent outdoors, higher ventilation rates relative to body size, and a tendency to breathe a greater fraction of air through the mouth.[1555] Children also have a higher asthma prevalence compared to adults. Recent epidemiologic studies provide generally consistent evidence that long-term ozone exposure is associated with the development of asthma in children. Studies comparing age groups reported higher magnitude associations for short-term ozone exposure and respiratory hospital admissions and emergency room visits among children than for adults. Panel studies also provide support for experimental studies with consistent associations between short-term ozone exposure and lung function and pulmonary inflammation in healthy children. Additional children's vulnerability and susceptibility factors are listed above in Chapter 5.4.

5.4.2 Particulate Matter

5.4.2.1 Background on Particulate Matter

Particulate matter (PM) is a complex mixture of solid particles and liquid droplets distributed among numerous atmospheric gases which interact with solid and liquid phases. Particles in the atmosphere range in size from less than 0.01 to more than 10 micrometers (µm) in diameter.[1556] Atmospheric particles can be grouped into several classes according to their aerodynamic diameter and physical sizes. Generally, the three broad classes of particles include ultrafine particles (UFPs, generally considered as particles with a diameter less than or equal to 0.1 µm [typically based on physical size, thermal diffusivity or electrical mobility]), "fine" particles ($PM_{2.5}$; particles with a nominal mean aerodynamic diameter less than or equal to 2.5 µm), and "thoracic" particles (PM_{10}; particles with a nominal mean aerodynamic diameter less than or equal to 10 µm). Particles that fall within the size range between $PM_{2.5}$ and PM_{10}, are referred to as "thoracic coarse particles" ($PM_{10-2.5}$, particles with a nominal mean aerodynamic diameter

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[1555] Children are more susceptible than adults to many air pollutants because of differences in physiology, higher per body weight breathing rates and consumption, rapid development of the brain and bodily systems, and behaviors that increase chances for exposure. Even before birth, the developing fetus may be exposed to air pollutants through the mother that affect development and permanently harm the individual.

Infants and children breathe at much higher rates per body weight than adults, with infants under one year of age having a breathing rate up to five times that of adults. In addition, children breathe through their mouths more than adults and their nasal passages are less effective at removing pollutants, which leads to a higher deposition fraction in their lungs.

[1556] U.S. EPA. Policy Assessment (PA) for the Review of the National Ambient Air Quality Standards for Particulate Matter (Final Report, 2020). U.S. Environmental Protection Agency, Washington, DC, EPA/452/R-20/002, 2020.

greater than 2.5 µm and less than or equal to 10 µm). EPA currently has standards that regulate $PM_{2.5}$ and PM_{10}.[1557]

Most particles are found in the lower troposphere, where they can have residence times ranging from a few hours to weeks. Particles are removed from the atmosphere by wet deposition, such as when they are carried by rain or snow, or by dry deposition, when particles settle out of suspension due to gravity. Atmospheric lifetimes are generally longest for $PM_{2.5}$, which often remains in the atmosphere for days to weeks before being removed by wet or dry deposition.[1558] In contrast, atmospheric lifetimes for UFP and $PM_{10–2.5}$ are shorter. Within hours, UFP can undergo coagulation and condensation that lead to formation of larger particles in the accumulation mode or can be removed from the atmosphere by evaporation, deposition, or reactions with other atmospheric components. $PM_{10–2.5}$ are also generally removed from the atmosphere within hours, through wet or dry deposition.[1559]

Particulate matter consists of both primary and secondary particles. Primary particles are emitted directly from sources, such as combustion-related activities (e.g., industrial activities, motor vehicle operation, biomass burning), while secondary particles are formed through atmospheric chemical reactions of gaseous precursors (e.g., sulfur oxides (SO_X), nitrogen oxides (NO_X) and volatile organic compounds (VOCs)).

5.4.2.2 Health Effects Associated with Exposure to Particulate Matter

Scientific evidence spanning animal toxicological, controlled human exposure, and epidemiologic studies shows that exposure to ambient PM is associated with a broad range of health effects. These health effects are discussed in detail in the Integrated Science Assessment for Particulate Matter, which was finalized in December 2019 (2019 PM ISA), with a more targeted evaluation of studies published since the literature cutoff date of the 2019 PM ISA in the Supplement to the Integrated Science Assessment for PM (Supplement).[1560,1561] The PM ISA characterizes the causal nature of relationships between PM exposure and broad health categories (e.g., cardiovascular effects, respiratory effects, etc.) using a weight-of-evidence approach.[1562]

[1557] Regulatory definitions of PM size fractions, and information on reference and equivalent methods for measuring PM in ambient air, are provided in 40 CFR Parts 50, 53, and 58. With regard to national ambient air quality standards (NAAQS) which provide protection against health and welfare effects, the 24-hour PM_{10} standard provides protection against effects associated with short-term exposure to thoracic coarse particles (i.e., $PM_{10-2.5}$).

[1558] U.S. EPA. Integrated Science Assessment (ISA) for Particulate Matter (Final Report, 2019). U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-19/188, 2019. Table 2-1.

[1559] U.S. EPA. Integrated Science Assessment (ISA) for Particulate Matter (Final Report, 2019). U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-19/188, 2019. Table 2-1.

[1560] U.S. EPA. Integrated Science Assessment (ISA) for Particulate Matter (Final Report, 2019). U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-19/188, 2019.

[1561] U.S. EPA. Supplement to the 2019 Integrated Science Assessment for Particulate Matter (Final Report, 2022). U.S. Environmental Protection Agency, Washington, DC, EPA/635/R-22/028, 2022.

[1562] The causal framework draws upon the assessment and integration of evidence from across scientific disciplines, spanning atmospheric chemistry, exposure, dosimetry and health effects studies (i.e., epidemiologic, controlled human exposure, and animal toxicological studies), and assess the related uncertainties and limitations that ultimately influence our understanding of the evidence. This framework employs a five-level hierarchy that classifies the overall weight-of-evidence with respect to the causal nature of relationships between criteria pollutant

Within this characterization, the PM ISA summarizes the health effects evidence for short-term (i.e., hours up to one month) and long-term (i.e., one month to years) exposures to $PM_{2.5}$, $PM_{10-2.5}$, and ultrafine particles and concludes that exposures to ambient $PM_{2.5}$ are associated with a number of adverse health effects. The discussion below highlights the PM ISA's conclusions and summarizes additional information from the Supplement where appropriate, pertaining to the health effects evidence for both short- and long-term PM exposures. Further discussion of PM-related health effects can also be found in the 2022 Policy Assessment for the review of the PM NAAQS.[1563]

EPA has concluded that recent evidence in combination with evidence evaluated in the 2009 PM ISA supports a "causal relationship" between both long- and short-term exposures to $PM_{2.5}$ and premature mortality and cardiovascular effects and a "likely to be causal relationship" between long- and short-term $PM_{2.5}$ exposures and respiratory effects.[1564] Additionally, recent experimental and epidemiologic studies provide evidence supporting a "likely to be causal relationship" between long-term $PM_{2.5}$ exposure and nervous system effects and between long-term $PM_{2.5}$ exposure and cancer. Because of remaining uncertainties and limitations in the evidence base, EPA determined the evidence is "suggestive of, but not sufficient to infer, a causal relationship" for long-term $PM_{2.5}$ exposure and reproductive and developmental effects (i.e., male/female reproduction and fertility; pregnancy and birth outcomes), long- and short-term exposures and metabolic effects, and short-term exposure and nervous system effects.

As discussed extensively in the 2019 PM ISA and the Supplement, recent studies continue to support a "causal relationship" between short- and long-term $PM_{2.5}$ exposures and mortality.[1565,1566] For short-term $PM_{2.5}$ exposure, multi-city studies,, in combination with single- and multi-city studies evaluated in the 2009 PM ISA, provide evidence of consistent, positive associations across studies conducted in different geographic locations, populations with different demographic characteristics, and studies using different exposure assignment techniques. Additionally, the consistent and coherent evidence across scientific disciplines for cardiovascular morbidity, including exacerbations of chronic obstructive pulmonary disease (COPD) and asthma, provide biological plausibility for cause-specific mortality and ultimately total mortality. Recent epidemiologic studies evaluated in the Supplement, including studies that employed alternative methods for confounder control, provide additional support to the evidence base that contributed to the 2019 PM ISA conclusion for short-term $PM_{2.5}$ exposure and mortality.

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exposures and health and welfare effects using the following categorizations: causal relationship; likely to be causal relationship; suggestive of, but not sufficient to infer, a causal relationship; inadequate to infer the presence or absence of a causal relationship; and not likely to be a causal relationship (U.S. EPA. (2019). Integrated Science Assessment for Particulate Matter (Final Report). U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-19/188, Section P. 3.2.3).

[1563] U.S. EPA. Policy Assessment (PA) for the Reconsideration of the National Ambient Air Quality Standards for Particulate Matter (Final Report, 2022). U.S. Environmental Protection Agency, Washington, DC, EPA/452/R-22-004, 2022

[1564] U.S. EPA. (2009). Integrated Science Assessment for Particulate Matter (Final Report). U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-08/139F.

1565 U.S. EPA. Integrated Science Assessment (ISA) for Particulate Matter (Final Report, 2019). U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-19/188, 2019.

[1566] U.S. EPA. Supplement to the 2019 Integrated Science Assessment for Particulate Matter (Final Report, 2022). U.S. Environmental Protection Agency, Washington, DC, EPA/635/R-22/028, 2022.

The 2019 PM ISA concluded a "causal relationship" between long-term $PM_{2.5}$ exposure and mortality. In addition to reanalyses and extensions of the American Cancer Society (ACS) and Harvard Six Cities (HSC) cohorts, multiple new cohort studies conducted in the U.S. and Canada, consisting of people employed in a specific job (e.g., teacher, nurse) and that apply different exposure assignment techniques, provide evidence of positive associations between long-term $PM_{2.5}$ exposure and mortality. Biological plausibility for mortality due to long-term $PM_{2.5}$ exposure is provided by the coherence of effects across scientific disciplines for cardiovascular morbidity, particularly for coronary heart disease, stroke and atherosclerosis, and for respiratory morbidity, particularly for the development of COPD. Additionally, recent studies provide evidence indicating that as long-term $PM_{2.5}$ concentrations decrease there is an increase in life expectancy. Recent cohort studies evaluated in the Supplement, as well as epidemiologic studies that conducted accountability analyses or employed alternative methods for confounder controls, support and extend the evidence base that contributed to the 2019 PM ISA conclusion for long-term $PM_{2.5}$ exposure and mortality.

A large body of studies examining both short- and long-term $PM_{2.5}$ exposure and cardiovascular effects builds on the evidence base evaluated in the 2009 PM ISA. The strongest evidence for cardiovascular effects in response to short-term $PM_{2.5}$ exposures is for ischemic heart disease and heart failure. The evidence for short-term $PM_{2.5}$ exposure and cardiovascular effects is coherent across scientific disciplines and supports a continuum of effects ranging from subtle changes in indicators of cardiovascular health to serious clinical events, such as increased emergency department visits and hospital admissions due to cardiovascular disease and cardiovascular mortality. For long-term $PM_{2.5}$ exposure, there is strong and consistent epidemiologic evidence of a relationship with cardiovascular mortality. This evidence is supported by epidemiologic and animal toxicological studies demonstrating a range of cardiovascular effects including coronary heart disease, stroke, impaired heart function, and subclinical markers (e.g., coronary artery calcification, atherosclerotic plaque progression), which collectively provide coherence and biological plausibility. Recent epidemiologic studies evaluated in the Supplement, as well as studies that conducted accountability analyses or employed alternative methods for confounder control, support and extend the evidence base that contributed to the 2019 PM ISA conclusion for both short- and long-term $PM_{2.5}$ exposure and cardiovascular effects.

Studies evaluated in the 2019 PM ISA continue to provide evidence of a "likely to be causal relationship" between both short- and long-term $PM_{2.5}$ exposure and respiratory effects. Epidemiologic studies provide consistent evidence of a relationship between short-term $PM_{2.5}$ exposure and asthma exacerbation in children and COPD exacerbation in adults as indicated by increases in emergency department visits and hospital admissions, which is supported by animal toxicological studies indicating worsening allergic airways disease and subclinical effects related to COPD. Epidemiologic studies also provide evidence of a relationship between short-term $PM_{2.5}$ exposure and respiratory mortality. However, there is inconsistent evidence for respiratory effects, specifically lung function declines and pulmonary inflammation, in controlled human exposure studies. With respect to long term $PM_{2.5}$ exposure, epidemiologic studies conducted in the U.S. and abroad provide evidence of a relationship with respiratory effects, including consistent changes in lung function and lung function growth rate, increased asthma incidence, asthma prevalence, and wheeze in children; acceleration of lung function decline in adults; and respiratory mortality. The epidemiologic evidence is supported by animal toxicological studies, which provide coherence and biological plausibility for a range of effects including impaired lung development, decrements in lung function growth, and asthma development.

Since the 2009 PM ISA, a growing body of scientific evidence examined the relationship between long-term $PM_{2.5}$ exposure and nervous system effects, resulting for the first time in a causality determination for this health effects category of a “likely to be causal relationship.” The strongest evidence for effects on the nervous system comes from epidemiologic studies that consistently report cognitive decrements and reductions in brain volume in adults. The effects observed in epidemiologic studies in adults are supported by animal toxicological studies demonstrating effects on the brain of adult animals including inflammation, morphologic changes, and neurodegeneration of specific regions of the brain. There is more limited evidence for neurodevelopmental effects in children with some studies reporting positive associations with autism spectrum disorder and others providing limited evidence of an association with cognitive function. While there is some evidence from animal toxicological studies indicating effects on the brain (i.e., inflammatory and morphological changes) to support a biologically plausible pathway for neurodevelopmental effects, epidemiologic studies are limited due to their lack of control for potential confounding by co-pollutants, the small number of studies conducted, and uncertainty regarding critical exposure windows.

Building off the decades of research demonstrating mutagenicity, DNA damage, and other endpoints related to genotoxicity due to whole PM exposures, recent experimental and epidemiologic studies focusing specifically on $PM_{2.5}$ provide evidence of a relationship between long-term $PM_{2.5}$ exposure and cancer. Epidemiologic studies examining long-term $PM_{2.5}$ exposure and lung cancer incidence and mortality provide evidence of generally positive associations in cohort studies spanning different populations, locations, and exposure assignment techniques. Additionally, there is evidence of positive associations with lung cancer incidence and mortality in analyses limited to never smokers. The epidemiologic evidence is supported by both experimental and epidemiologic evidence of genotoxicity, epigenetic effects, carcinogenic potential, and that $PM_{2.5}$ exhibits several characteristics of carcinogens, which collectively provides biological plausibility for cancer development and resulted in the conclusion of a “likely to be causal relationship.”

For the additional health effects categories evaluated for $PM_{2.5}$ in the 2019 PM ISA, experimental and epidemiologic studies provide limited and/or inconsistent evidence of a relationship with $PM_{2.5}$ exposure. As a result, the 2019 PM ISA concluded that the evidence is “suggestive of, but not sufficient to infer a causal relationship” for short-term $PM_{2.5}$ exposure and metabolic effects and nervous system effects and for long-term $PM_{2.5}$ exposures and metabolic effects as well as reproductive and developmental effects.

In addition to evaluating the health effects attributed to short- and long-term exposure to $PM_{2.5}$, the 2019 PM ISA also conducted an extensive evaluation as to whether specific components or sources of $PM_{2.5}$ are more strongly related with specific health effects than $PM_{2.5}$ mass. An evaluation of those studies resulted in the 2019 PM ISA concluding that “many $PM_{2.5}$ components and sources are associated with many health effects, and the evidence does not indicate that any one source or component is consistently more strongly related to health effects than $PM_{2.5}$ mass."[1567]

For both $PM_{10-2.5}$ and UFPs, for all health effects categories evaluated, the 2019 PM ISA concluded that the evidence was "suggestive of, but not sufficient to infer, a causal relationship" or "inadequate to determine the presence or absence of a causal relationship." For $PM_{10-2.5}$, although a Federal Reference Method (FRM) was instituted in 2011 to measure $PM_{10-2.5}$ concentrations nationally, the causality determinations reflect that the same uncertainty identified in the 2009 PM ISA with respect to the method used to estimate $PM_{10-2.5}$ concentrations in epidemiologic studies persists. Specifically, across epidemiologic studies, different approaches are used to estimate $PM_{10-2.5}$ concentrations (e.g., direct measurement of $PM_{10-2.5}$, difference between PM_{10} and $PM_{2.5}$ concentrations), and it remains unclear how well correlated $PM_{10-2.5}$ concentrations are both spatially and temporally across the different methods used.

For UFPs, which have often been defined as particles less than 0.1 µm, the uncertainty in the evidence for the health effect categories evaluated across experimental and epidemiologic studies reflects the inconsistency in the exposure metric used (i.e., particle number concentration, surface area concentration, mass concentration) as well as the size fractions examined. In epidemiologic studies the size fraction examined can vary depending on the monitor used and exposure metric, with some studies examining number count over the entire particle size range, while experimental studies that use a particle concentrator often examine particles up to 0.3 µm. Additionally, due to the lack of a monitoring network, there is limited information on the spatial and temporal variability of UFPs within the United States, as well as population exposures to UFPs, which adds uncertainty to epidemiologic study results.

The 2019 PM ISA cites extensive evidence indicating that "both the general population as well as specific populations and lifestages are at risk for $PM_{2.5}$-related health effects."[1568] For example, in support of its "causal" and "likely to be causal" determinations, the ISA cites substantial evidence for (1) PM-related mortality and cardiovascular effects in older adults; (2) PM-related cardiovascular effects in people with pre-existing cardiovascular disease; (3) PM-related respiratory effects in people with pre-existing respiratory disease, particularly asthma exacerbations in children; and (4) PM-related impairments in lung function growth and asthma development in children. The ISA additionally notes that stratified analyses (i.e., analyses that directly compare PM-related health effects across groups) provide strong evidence for racial and ethnic differences in $PM_{2.5}$ exposures and in the risk of $PM_{2.5}$-related health effects, specifically within Hispanic and non-Hispanic Black populations with some evidence of increased risk for populations of low socioeconomic status. Recent studies evaluated in the Supplement support the conclusion of the 2019 PM ISA with respect to disparities in both $PM_{2.5}$ exposure and health risk by race and ethnicity and provide additional support for disparities for populations of lower socioeconomic status.[1569] Additionally, evidence spanning epidemiologic studies that conducted stratified analyses, experimental studies focusing on animal models of disease or individuals with pre-existing disease, dosimetry studies, as well as studies focusing on differential exposure

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[1567] U.S. EPA. Integrated Science Assessment (ISA) for Particulate Matter (Final Report, 2019). U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-19/188, 2019.

[1568] U.S. EPA. Integrated Science Assessment (ISA) for Particulate Matter (Final Report, 2019). U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-19/188, 2019.

[1569] U.S. EPA. Supplement to the 2019 Integrated Science Assessment for Particulate Matter (Final Report, 2022). U.S. Environmental Protection Agency, Washington, DC, EPA/635/R-22/028, 2022.

suggest that populations with pre-existing cardiovascular or respiratory disease, populations that are overweight or obese, populations that have particular genetic variants, and current/former smokers could be at increased risk for adverse $PM_{2.5}$-related health effects. The 2022 Policy Assessment for the review of the PM NAAQS also highlights that factors that may contribute to increased risk of $PM_{2.5}$-related health effects include lifestage (children and older adults), pre-existing diseases (cardiovascular disease and respiratory disease), race/ethnicity, and socioeconomic status.[1570]

5.4.3 Nitrogen Oxides

5.4.3.1 Background on Nitrogen Oxides

Oxides of nitrogen (NO_X) refers to nitric oxide (NO) and nitrogen dioxide (NO_2). Most NO_2 is formed in the air through the oxidation of nitric oxide (NO) that is emitted when fuel is burned at a high temperature. NO_X is a major contributor to secondary $PM_{2.5}$ formation, and NO_X along with VOCs are the two major precursors of ozone.

5.4.3.2 Health Effects Associated with Exposure to Nitrogen Oxides

The most recent review of the health effects of oxides of nitrogen completed by EPA can be found in the 2016 Integrated Science Assessment for Oxides of Nitrogen - Health Criteria (Oxides of Nitrogen ISA).[1571] The primary source of NO_2 is motor vehicle emissions, and ambient NO_2 concentrations tend to be highly correlated with other traffic-related pollutants. Thus, a key issue in characterizing the causality of NO_2-health effect relationships consists of evaluating the extent to which studies supported an effect of NO_2 that is independent of other traffic-related pollutants. EPA concluded that the findings for asthma exacerbation integrated from epidemiologic and controlled human exposure studies provided evidence that is sufficient to infer a causal relationship between respiratory effects and short-term NO_2 exposure. The strongest evidence supporting an independent effect of NO_2 exposure comes from controlled human exposure studies demonstrating increased airway responsiveness in individuals with asthma following ambient-relevant NO_2 exposures. The coherence of this evidence with epidemiologic findings for asthma hospital admissions and emergency department visits as well as lung function decrements and increased pulmonary inflammation in children with asthma describe a plausible pathway by which NO_2 exposure can cause an asthma exacerbation. The 2016 ISA for Oxides of Nitrogen also concluded that there is likely to be a causal relationship between long-term NO_2 exposure and respiratory effects. This conclusion is based on new epidemiologic evidence for associations of NO_2 with asthma development in children combined with biological plausibility from experimental studies.

In evaluating a broader range of health effects, the 2016 ISA for Oxides of Nitrogen concluded that evidence is “suggestive of, but not sufficient to infer, a causal relationship” between short-term NO_2 exposure and cardiovascular effects and mortality and between long-term NO_2 exposure and cardiovascular effects and diabetes, birth outcomes, and cancer. In addition, the scientific evidence is inadequate (insufficient consistency of epidemiologic and

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[1570] U.S. EPA. Policy Assessment (PA) for the Reconsideration of the National Ambient Air Quality Standards for Particulate Matter (Final Report, 2022). U.S. Environmental Protection Agency, Washington, DC, EPA-452/R-22-004, 2022, p. 3-53.

[1571] U.S. EPA. Integrated Science Assessment for Oxides of Nitrogen – Health Criteria (2016 Final Report). U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-15/068, 2016.

toxicological evidence) to infer a causal relationship for long-term NO_2 exposure with fertility, reproduction, and pregnancy, as well as with postnatal development. A key uncertainty in understanding the relationship between these non-respiratory health effects and short- or long-term exposure to NO_2 is co-pollutant confounding, particularly by other roadway pollutants. The available evidence for non-respiratory health effects does not adequately address whether NO_2 has an independent effect or whether it primarily represents effects related to other or a mixture of traffic-related pollutants.

The 2016 ISA for Oxides of Nitrogen concluded that people with asthma, children, and older adults are at increased risk for NO_2-related health effects. In these groups and lifestages, NO_2 is consistently related to larger effects on outcomes related to asthma exacerbation, for which there is confidence in the relationship with NO_2 exposure.

5.4.4 Carbon Monoxide

5.4.4.1 Background on Carbon Monoxide

Carbon monoxide (CO) is a colorless, odorless gas formed by incomplete combustion of carbon-containing fuels and by photochemical reactions in the atmosphere. Nationally, particularly in urban areas, the majority of CO emissions to ambient air come from mobile sources.[1572]

5.4.4.2 Health Effects Associated with Carbon Monoxide

Information on the health effects of carbon monoxide (CO) can be found in the January 2010 Integrated Science Assessment for Carbon Monoxide (CO ISA).[1573] The CO ISA presents conclusions regarding the presence of causal relationships between CO exposure and categories of adverse health effects.[1574] This section provides a summary of the health effects associated with exposure to ambient concentrations of CO, along with the CO ISA conclusions.[1575]

Controlled human exposure studies of subjects with coronary artery disease show a decrease in the time to onset of exercise-induced angina (chest pain) and electrocardiogram changes following CO exposure. In addition, epidemiologic studies presented in the CO ISA observed associations between short-term CO exposure and cardiovascular morbidity, particularly increased emergency room visits and hospital admissions for coronary heart disease (including ischemic heart disease, myocardial infarction, and angina). Some epidemiologic evidence is also available for increased hospital admissions and emergency room visits for congestive heart failure and cardiovascular disease as a whole. The CO ISA concludes that a causal relationship is

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[1572] U.S. EPA, (2010). Integrated Science Assessment for Carbon Monoxide (Final Report). U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-09/019F, 2010.

[1573] U.S. EPA, (2010). Integrated Science Assessment for Carbon Monoxide (Final Report). U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-09/019F, 2010. http://cfpub.epa.gov/ncea/cfm/recordisplay.cfm?deid=218686.

[1574] The ISA evaluates the health evidence associated with different health effects, assigning one of five “weight of evidence” determinations: causal relationship, likely to be a causal relationship, suggestive of a causal relationship, inadequate to infer a causal relationship, and not likely to be a causal relationship. For definitions of these levels of evidence, please refer to Section 1.6 of the ISA.

[1575] Personal exposure includes contributions from many sources, and in many different environments. Total personal exposure to CO includes both ambient and non-ambient components; and both components may contribute to adverse health effects.

likely to exist between short-term exposures to CO and cardiovascular morbidity. It also concludes that available data are inadequate to conclude that a causal relationship exists between long-term exposures to CO and cardiovascular morbidity.

Animal studies show various neurological effects with in-utero CO exposure. Controlled human exposure studies report central nervous system and behavioral effects following low-level CO exposures, although the findings have not been consistent across all studies. The CO ISA concludes that the evidence is suggestive of a causal relationship with both short- and long-term exposure to CO and central nervous system effects.

A number of studies cited in the CO ISA have evaluated the role of CO exposure in birth outcomes such as preterm birth or cardiac birth defects. There is limited epidemiologic evidence of a CO-induced effect on preterm births and birth defects, with weak evidence for a decrease in birth weight. Animal toxicological studies have found perinatal CO exposure to affect birth weight, as well as other developmental outcomes. The CO ISA concludes that the evidence is suggestive of a causal relationship between long-term exposures to CO and developmental effects and birth outcomes.

Epidemiologic studies provide evidence of associations between short-term CO concentrations and respiratory morbidity such as changes in pulmonary function, respiratory symptoms, and hospital admissions. A limited number of epidemiologic studies considered co-pollutants such as ozone, SO_2, and PM in two-pollutant models and found that CO risk estimates were generally robust, although this limited evidence makes it difficult to disentangle effects attributed to CO itself from those of the larger complex air pollution mixture. Controlled human exposure studies have not extensively evaluated the effect of CO on respiratory morbidity. Animal studies at levels of 50-100 ppm CO show preliminary evidence of altered pulmonary vascular remodeling and oxidative injury. The CO ISA concludes that the evidence is suggestive of a causal relationship between short-term CO exposure and respiratory morbidity, and inadequate to conclude that a causal relationship exists between long-term exposure and respiratory morbidity.

Finally, the CO ISA concludes that the epidemiologic evidence is suggestive of a causal relationship between short-term concentrations of CO and mortality. Epidemiologic evidence suggests an association exists between short-term exposure to CO and mortality, but limited evidence is available to evaluate cause-specific mortality outcomes associated with CO exposure. In addition, the attenuation of CO risk estimates which was often observed in co-pollutant models contributes to the uncertainty as to whether CO is acting alone or as an indicator for other combustion-related pollutants. The CO ISA also concludes that there is not likely to be a causal relationship between relevant long-term exposures to CO and mortality.

5.4.5 Sulfur Oxides

5.4.5.1 Background on Sulfur Oxides

Sulfur dioxide (SO_2), a member of the sulfur oxide (SO_X) family of gases, is formed from burning fuels containing sulfur (e.g., coal or oil), extracting gasoline from oil, or extracting metals from ore. SO_2 and its gas phase oxidation products can dissolve in water droplets and further oxidize to form sulfuric acid which reacts with ammonia to form sulfates, which are important components of ambient PM.

5.4.5.2 Health Effects Associated with Exposure to Sulfur Oxides

This section provides an overview of the health effects associated with SO_2. Additional information on the health effects of SO_2 can be found in the 2017 Integrated Science Assessment for Sulfur Oxides – Health Criteria (SO_X ISA).[1576] Following an extensive evaluation of health evidence from animal toxicological, controlled human exposure, and epidemiologic studies, the EPA has concluded that there is a causal relationship between respiratory health effects and short-term exposure to SO_2. The immediate effect of SO_2 on the respiratory system in humans is bronchoconstriction. People with asthma are more sensitive to the effects of SO_2, likely resulting from preexisting inflammation associated with this disease. In addition to those with asthma (both children and adults), there is suggestive evidence that all children and older adults may be at increased risk of SO_2-related health effects. In free-breathing laboratory studies involving controlled human exposures to SO_2, respiratory effects have consistently been observed following 5-10 min exposures at SO_2 concentrations $\geq$ 400 ppb in people with asthma engaged in moderate to heavy levels of exercise, with respiratory effects occurring at concentrations as low as 200 ppb in some individuals with asthma. A clear concentration-response relationship has been demonstrated in these studies following exposures to SO_2 at concentrations between 200 and 1000 ppb, both in terms of increasing severity of respiratory symptoms and decrements in lung function, as well as the percentage of individuals with asthma adversely affected. Epidemiologic studies have reported positive associations between short-term ambient SO_2 concentrations and hospital admissions and emergency department visits for asthma and for all respiratory causes, particularly among children and older adults ($\geq$ 65 years). The studies provide supportive evidence for the causal relationship.

For long-term SO_2 exposure and respiratory effects, the EPA has concluded that the evidence is suggestive of a causal relationship. This conclusion is based on new epidemiologic evidence for positive associations between long-term SO_2 exposure and increases in asthma incidence among children, together with animal toxicological evidence that provides a pathophysiologic basis for the development of asthma. However, uncertainty remains regarding the influence of other pollutants on the observed associations with SO_2 because these epidemiologic studies have not examined the potential for co-pollutant confounding.

Consistent associations between short-term exposure to SO_2 and mortality have been observed in epidemiologic studies, with larger effect estimates reported for respiratory mortality than for cardiovascular mortality. While this finding is consistent with the demonstrated effects of SO_2 on respiratory morbidity, uncertainty remains with respect to the interpretation of these observed mortality associations due to potential confounding by various copollutants. Therefore, the EPA has concluded that the overall evidence is suggestive of a causal relationship between short-term exposure to SO_2 and mortality.

5.4.6 Diesel Exhaust

5.4.6.1 Background on Diesel Exhaust

Diesel exhaust is a complex mixture composed of particulate matter, carbon dioxide, oxygen, nitrogen, water vapor, carbon monoxide, nitrogen compounds, sulfur compounds and numerous

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[1576] U.S. EPA. Integrated Science Assessment (ISA) for Sulfur Oxides – Health Criteria (Final Report, Dec 2017). U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-17/451, 2017.

low-molecular-weight hydrocarbons. A number of these gaseous hydrocarbon components are individually known to be toxic, including aldehydes, benzene and 1,3-butadiene. The diesel particulate matter present in diesel exhaust consists mostly of fine particles (less than 2.5 µm), of which a significant fraction is ultrafine particles (less than 0.1 µm). These particles have a large surface area which makes them an excellent medium for adsorbing organics, and their small size makes them highly respirable. Many of the organic compounds present in the gases and on the particles, such as polycyclic organic matter, are individually known to have mutagenic and carcinogenic properties.

Diesel exhaust varies significantly in chemical composition and particle sizes between different engine types (heavy-duty, light-duty), engine operating conditions (idle, acceleration, deceleration), and fuel formulations (high/low sulfur fuel). Also, there are emissions differences between on-road and nonroad engines because the nonroad engines are generally of older technology. After being emitted in the engine exhaust, diesel exhaust undergoes dilution as well as chemical and physical changes in the atmosphere. The lifetimes of the components present in diesel exhaust range from seconds to months.

5.4.6.2 Health Effects Associated with Exposure to Diesel Exhaust

In EPA's 2002 Diesel Health Assessment Document (Diesel HAD), exposure to diesel exhaust was classified as likely to be carcinogenic to humans by inhalation from environmental exposures, in accordance with the revised draft 1996/1999 EPA cancer guidelines.[1577,1578] A number of other agencies (National Institute for Occupational Safety and Health, the International Agency for Research on Cancer, the World Health Organization, California EPA, and the U.S. Department of Health and Human Services) made similar hazard classifications prior to 2002. EPA also concluded in the 2002 Diesel HAD that it was not possible to calculate a cancer unit risk for diesel exhaust due to limitations in the exposure data for the occupational groups or the absence of a dose-response relationship.

In the absence of a cancer unit risk, the Diesel HAD sought to provide additional insight into the significance of the diesel exhaust cancer hazard by estimating possible ranges of risk that might be present in the population. An exploratory analysis was used to characterize a range of possible lung cancer risk. The outcome was that environmental risks of cancer from long-term diesel exhaust exposures could plausibly range from as low as 10^{-5} to as high as 10^{-3}. Because of uncertainties, the analysis acknowledged that the risks could be lower than 10^{-5}, and a zero risk from diesel exhaust exposure could not be ruled out.

Noncancer health effects of acute and chronic exposure to diesel exhaust emissions are also of concern to EPA. EPA derived a diesel exhaust reference concentration (RfC) from consideration of four well-conducted chronic rat inhalation studies showing adverse pulmonary effects. The RfC is 5 $\mu g/m^3$ for diesel exhaust measured as diesel particulate matter. This RfC does not consider allergenic effects such as those associated with asthma or immunologic or the potential for cardiac effects. There was emerging evidence in 2002, discussed in the Diesel HAD, that

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[1577] U.S. EPA. (1999). Guidelines for Carcinogen Risk Assessment. Review Draft. NCEA-F-0644, July. Washington, DC: U.S. EPA. Retrieved on March 19, 2009 from http://cfpub.epa.gov/ncea/cfm/recordisplay.cfm?deid=54932.

[1578] U.S. EPA (2002). Health Assessment Document for Diesel Engine Exhaust. EPA/600/8-90/057F Office of research and Development, Washington DC. Retrieved on March 17, 2009 from http://cfpub.epa.gov/ncea/cfm/recordisplay.cfm?deid=29060. pp. 1-1 1-2.

exposure to diesel exhaust can exacerbate these effects, but the exposure-response data were lacking at that time to derive an RfC based on these then-emerging considerations. The Diesel HAD states, “With [diesel particulate matter] being a ubiquitous component of ambient PM, there is an uncertainty about the adequacy of the existing [diesel exhaust] noncancer database to identify all of the pertinent [diesel exhaust]-caused noncancer health hazards.” The Diesel HAD also notes “that acute exposure to [diesel exhaust] has been associated with irritation of the eye, nose, and throat, respiratory symptoms (cough and phlegm), and neurophysiological symptoms such as headache, lightheadedness, nausea, vomiting, and numbness or tingling of the extremities.” The Diesel HAD notes that the cancer and noncancer hazard conclusions applied to the general use of diesel engines then on the market and as cleaner engines replace a substantial number of existing ones, the applicability of the conclusions would need to be reevaluated.

It is important to note that the Diesel HAD also briefly summarizes health effects associated with ambient PM and discusses EPA’s then-annual $PM_{2.5}$ NAAQS of 15 µg/m^3. In 2012, EPA revised the level of the annual $PM_{2.5}$ NAAQS to 12 µg/m^3 and in 2024 EPA revised the level of the annual $PM_{2.5}$ NAAQS to 9.0 µg/m^3.[1579] There is a large and extensive body of human data showing a wide spectrum of adverse health effects associated with exposure to ambient PM, of which diesel exhaust is an important component. The $PM_{2.5}$ NAAQS provides protection from the health effects attributed to exposure to $PM_{2.5}$. The contribution of diesel PM to total ambient PM varies in different regions of the country and also within a region from one area to another. The contribution can be high in near-roadway environments, for example, or in other locations where diesel engine use is concentrated.

Since 2002, several new studies have been published which continue to report increased lung cancer risk associated with occupational exposure to diesel exhaust from older engines. Of particular note since 2011 are three new epidemiology studies which have examined lung cancer in occupational populations, including truck drivers, underground nonmetal miners and other diesel motor-related occupations. These studies reported increased risk of lung cancer related to exposure to diesel exhaust, with evidence of positive exposure-response relationships to varying degrees.[1580,1581,1582] These newer studies (along with others that have appeared in the scientific literature) add to the evidence EPA evaluated in the 2002 Diesel HAD and further reinforce the concern that diesel exhaust exposure likely poses a lung cancer hazard. The findings from these newer studies do not necessarily apply to newer technology diesel engines (i.e., heavy-duty highway engines from 2007 and later model years) since the newer engines have large reductions in the emission constituents compared to older technology diesel engines.

In light of the growing body of scientific literature evaluating the health effects of exposure to diesel exhaust, in June 2012 the World Health Organization’s International Agency for Research

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[1579] https://www.epa.gov/pm-pollution/national-ambient-air-quality-standards-naaqs-pm

[1580] Garshick, Eric, Francine Laden, Jaime E. Hart, Mary E. Davis, Ellen A. Eisen, and Thomas J. Smith. 2012. Lung cancer and elemental carbon exposure in trucking industry workers. Environmental Health Perspectives 120(9): 1301-1306.

[1581] Silverman, D. T., Samanic, C. M., Lubin, J. H., Blair, A. E., Stewart, P. A., Vermeulen, R., & Attfield, M. D. (2012). The diesel exhaust in miners study: a nested case–control study of lung cancer and diesel exhaust. Journal of the National Cancer Institute.

[1582] Olsson, Ann C., et al. "Exposure to diesel motor exhaust and lung cancer risk in a pooled analysis from case-control studies in Europe and Canada." American journal of respiratory and critical care medicine 183.7 (2011): 941-948.

on Cancer (IARC), a recognized international authority on the carcinogenic potential of chemicals and other agents, evaluated the full range of cancer-related health effects data for diesel engine exhaust. IARC concluded that diesel exhaust should be regarded as "carcinogenic to humans."[1583] This designation was an update from its 1988 evaluation that considered the evidence to be indicative of a "probable human carcinogen."

5.4.7 Air Toxics

Heavy-duty engine emissions contribute to ambient levels of air toxics that are known or suspected human or animal carcinogens or that have noncancer health effects. These compounds include, but are not limited to, acetaldehyde, benzene, 1,3-butadiene, formaldehyde, and naphthalene. These compounds were all identified as national cancer risk drivers or contributors in the 2019 Air Toxics Screening Assessment (AirToxScreen).[1584,1585]

The most recent available data indicate that millions of Americans live in areas where air toxics pose potential health concerns.[1586,1587] The levels of air toxics to which people are exposed vary depending on where people live and work and the kinds of activities in which they engage, as discussed in detail in EPA's 2007 Mobile Source Air Toxics Rule.[1588] According to EPA's 2017 National Emissions Inventory (NEI), mobile sources were responsible for 39 percent of outdoor anthropogenic toxic emissions. Further, mobile sources were the largest contributor to national average risk of cancer and immunological and respiratory health effects from directly emitted pollutants, according to EPA's Air Toxics Screening Assessment (AirToxScreen) for 2019.[1589,1590] Mobile sources are also significant contributors to precursor emissions which react to form air toxics.[1591] Formaldehyde is the largest contributor to cancer risk of all 72 pollutants quantitatively assessed in the 2019 AirToxScreen. Mobile sources were responsible for 26 percent of primary anthropogenic emissions of this pollutant in the 2017 NEI and are significant contributors to formaldehyde precursor emissions. Benzene is also a large contributor to cancer

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[1583] IARC [International Agency for Research on Cancer]. (2013). Diesel and gasoline engine exhausts and some nitroarenes. IARC Monographs Volume 105. [Online at http://monographs.iarc.fr/ENG/Monographs/vol105/index.php]

[1584] U.S. EPA (2022) Technical Support Document EPA's Air Toxics Screening Assessment. 2018 AirToxScreen TSD. *https://www.epa.gov/system/files/documents/2023-02/AirToxScreen_2018%20TSD.pdf.*

[1585] U.S. EPA (2023) 2019 AirToxScreen Risk Drivers. *https://www.epa.gov/AirToxScreen/airtoxscreen-risk-drivers*.

[1586] Air toxics are pollutants known to cause or suspected of causing cancer or other serious health effects. Air toxics are also known as toxic air pollutants or hazardous air pollutants. *https://www.epa.gov/AirToxScreen/airtoxscreen-glossary-terms#air-toxics.*

[1587] U.S. EPA (2022) Technical Support Document EPA Air Toxics Screening Assessment. 2018 AirToxScreen TSD. *https://www.epa.gov/system/files/documents/2023-02/AirToxScreen_2018%20TSD.pdf.*

[1588] U.S. Environmental Protection Agency (2007). Control of Hazardous Air Pollutants from Mobile Sources; Final Rule. 72 FR 8434, February 26, 2007.

[1589] U.S. EPA. (2022) 2019 AirToxScreen: Assessment Results. *https://www.epa.gov/AirToxScreen/2019-airtoxscreen-assessment-results.*

[1590] AirToxScreen also includes estimates of risk attributable to background concentrations, which includes contributions from long-range transport, persistent air toxics, and natural sources; as well as secondary concentrations, where toxics are formed via secondary formation. Mobile sources substantially contribute to long-range transport and secondarily formed air toxics.

[1591] Rich Cook, Sharon Phillips, Madeleine Strum, Alison Eyth & James Thurman (2020): Contribution of mobile sources to secondary formation of carbonyl compounds, Journal of the Air & Waste Management Association, DOI: 10.1080/10962247.2020.1813839.

risk, and mobile sources account for about 60 percent of average exposure to ambient concentrations.

5.4.7.1 Acetaldehyde

Acetaldehyde is classified in EPA's IRIS database as a probable human carcinogen, based on nasal tumors in rats, and is considered toxic by the inhalation, oral, and intravenous routes.[1592] The inhalation unit risk estimate (URE) in IRIS for acetaldehyde is 2.2×10^{-6} per $\mu g/m^3$.[1593] Acetaldehyde is reasonably anticipated to be a human carcinogen by the NTP in the 14th Report on Carcinogens and is classified as possibly carcinogenic to humans (Group 2B) by the IARC.[1594,1595]

The primary noncancer effects of exposure to acetaldehyde vapors include irritation of the eyes, skin, and respiratory tract.[1596] In short-term (4 week) rat studies, degeneration of olfactory epithelium was observed at various concentration levels of acetaldehyde exposure.[1597] Data from these studies were used by EPA to develop an inhalation reference concentration of 9 $\mu g/m^3$. Some asthmatics have been shown to be a sensitive subpopulation to decrements in functional expiratory volume (FEV1 test) and bronchoconstriction upon acetaldehyde inhalation.[1598] Children, especially those with diagnosed asthma, may be more likely to show impaired pulmonary function and symptoms of asthma than are adults following exposure to acetaldehyde.[1599]

5.4.7.2 Benzene

EPA's Integrated Risk Information System (IRIS) database lists benzene as a known human carcinogen (causing leukemia) by all routes of exposure and concludes that exposure is associated with additional health effects, including genetic changes in both humans and animals

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[1592] U.S. EPA (1991). Integrated Risk Information System File of Acetaldehyde. Research and Development, National Center for Environmental Assessment, Washington, DC. This material is available electronically at https://cfpub.epa.gov/ncea/iris2/chemicalLanding.cfm?substance_nmbr=290.

[1593] U.S. EPA (1991). Integrated Risk Information System File of Acetaldehyde. This material is available electronically at https://cfpub.epa.gov/ncea/iris2/chemicalLanding.cfm?substance_nmbr=290.

[1594] NTP (National Toxicology Program). 2016. Report on Carcinogens, Fourteenth Edition.; Research Triangle Park, NC: U.S. Department of Health and Human Services, Public Health Service. https://ntp.niehs.nih.gov/go/roc14.

[1595] International Agency for Research on Cancer (IARC). (1999). Re-evaluation of some organic chemicals, hydrazine, and hydrogen peroxide. IARC Monographs on the Evaluation of Carcinogenic Risk of Chemical to Humans, Vol 71. Lyon, France.

[1596] U.S. EPA (1991). Integrated Risk Information System File of Acetaldehyde. This material is available electronically at https://cfpub.epa.gov/ncea/iris2/chemicalLanding.cfm?substance_nmbr=290.

[1597] Appleman, L.M., R.A. Woutersen, and V.J. Feron. (1982). Inhalation toxicity of acetaldehyde in rats. I. Acute and subacute studies. Toxicology. 23: 293-297.

[1598] Myou, S.; Fujimura, M.; Nishi K.; Ohka, T.; and Matsuda, T. (1993). Aerosolized acetaldehyde induces histamine-mediated bronchoconstriction in asthmatics. Am. Rev. Respir.Dis.148(4 Pt 1): 940-943.

[1599] California OEHHA, 2014. TSD for Noncancer RELs: Appendix D. Individual, Acute, 8-Hour, and Chronic Reference Exposure Level Summaries. December 2008 (updated July 2014). https://oehha.ca.gov/media/downloads/crnr/appendixd1final.pdf and increased proliferation of bone marrow cells in mice.[1600,1601,1602] EPA states in its IRIS database that data indicate a causal relationship between benzene exposure and acute lymphocytic leukemia and suggest a relationship between benzene exposure and chronic non-lymphocytic leukemia and chronic lymphocytic leukemia. EPA's IRIS documentation for benzene also lists a range of 2.2 x 10^{-6} to 7.8 x 10^{-6} per µg/m^3 as the unit risk estimate (URE) for benzene.[1603,1604] The International Agency for Research on Cancer (IARC) has determined that benzene is a human carcinogen, and the U.S. Department of Health and Human Services (DHHS) has characterized benzene as a known human carcinogen.[1605,1606]

A number of adverse noncancer health effects, including blood disorders such as preleukemia and aplastic anemia, have also been associated with long-term exposure to benzene.[1607,1608] The most sensitive noncancer effect observed in humans, based on current data, is the depression of the absolute lymphocyte count in blood.[1609],[1610] EPA's inhalation reference concentration (RfC) for benzene is 30 µg/m^3. The RfC is based on suppressed absolute lymphocyte counts seen in humans under occupational exposure conditions. In addition, studies sponsored by the Health Effects Institute (HEI) provide evidence that biochemical responses occur at lower levels of

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[1600] U.S. EPA. (2000). Integrated Risk Information System File for Benzene. This material is available electronically at: https://cfpub.epa.gov/ncea/iris2/chemicalLanding.cfm?substance_nmbr=276.

[1601] International Agency for Research on Cancer. (1982). IARC monographs on the evaluation of carcinogenic risk of chemicals to humans, Volume 29, Some industrial chemicals and dyestuffs, International Agency for Research on Cancer, World Health Organization, Lyon, France 1982.

[1602] Irons, R.D.; Stillman, W.S.; Colagiovanni, D.B.; Henry, V.A. (1992). Synergistic action of the benzene metabolite hydroquinone on myelopoietic stimulating activity of granulocyte/macrophage colony-stimulating factor in vitro, Proc. Natl. Acad. Sci. 89:3691-3695.

[1603] A unit risk estimate is defined as the increase in the lifetime risk of an individual who is exposed for a lifetime to 1 µg/m^3 benzene in air.

[1604] U.S. EPA. (2000). Integrated Risk Information System File for Benzene. This material is available electronically at: https://cfpub.epa.gov/ncea/iris2/chemicalLanding.cfm?substance_nmbr=276.

[1605] International Agency for Research on Cancer (IARC, 2018. Monographs on the evaluation of carcinogenic risks to humans, volume 120. World Health Organization – Lyon, France. http://publications.iarc.fr/Book-And-Report-Series/Iarc-Monographs-On-The-Identification-Of-Carcinogenic-Hazards-To-Humans/Benzene-2018.

[1606] NTP (National Toxicology Program). 2016. Report on Carcinogens, Fourteenth Edition.; Research Triangle Park, NC: U.S. Department of Health and Human Services, Public Health Service. https://ntp.niehs.nih.gov/go/roc14

[1607] Aksoy, M. (1989). Hematotoxicity and carcinogenicity of benzene. Environ. Health Perspect. 82: 193-197. EPA-HQ-OAR-2011-0135.

[1608] Goldstein, B.D. (1988). Benzene toxicity. Occupational medicine. State of the Art Reviews. 3: 541-554.

[1609] Rothman, N., G.L. Li, M. Dosemeci, W.E. Bechtold, G.E. Marti, Y.Z. Wang, M. Linet, L.Q. Xi, W. Lu, M.T. Smith, N. Titenko-Holland, L.P. Zhang, W. Blot, S.N. Yin, and R.B. Hayes. (1996). Hematotoxicity among Chinese workers heavily exposed to benzene. Am. J. Ind. Med. 29: 236-246.

[1610] U.S. EPA (2002). Toxicological Review of Benzene (Noncancer Effects). Environmental Protection Agency, Integrated Risk Information System (IRIS), Research and Development, National Center for Environmental Assessment, Washington DC. This material is available electronically at https://cfpub.epa.gov/ncea/iris/iris_documents/documents/toxreviews/0276tr.pdf.

benzene exposure than previously known.[1611,1612,1613,1614] EPA's IRIS program has not yet evaluated these new data. EPA does not currently have an acute reference concentration for benzene. The Agency for Toxic Substances and Disease Registry (ATSDR) Minimal Risk Level (MRL) for acute inhalation exposure to benzene is 29 $\mu g/m^3$ for 1-14 days exposure.[1615,1616]

There is limited information from two studies regarding an increased risk of adverse effects to children whose parents have been occupationally exposed to benzene.[1617,1618] Data from animal studies have shown benzene exposures result in damage to the hematopoietic (blood cell formation) system during development.[1619,1620,1621] Also, key changes related to the development of childhood leukemia occur in the developing fetus.[1622] Several studies have reported that genetic changes related to eventual leukemia development occur before birth. For example, there is one study of genetic changes in twins who developed T cell leukemia at nine years of age.[1623]

5.4.7.1 1,3-Butadiene

EPA has characterized 1,3-butadiene as carcinogenic to humans by inhalation.[1624,1625] The IARC has determined that 1,3-butadiene is a human carcinogen, and the U.S. DHHS has

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[1611] Qu, O.; Shore, R.; Li, G.; Jin, X.; Chen, C.L.; Cohen, B.; Melikian, A.; Eastmond, D.; Rappaport, S.; Li, H.; Rupa, D.; Suramaya, R.; Songnian, W.; Huifant, Y.; Meng, M.; Winnik, M.; Kwok, E.; Li, Y.; Mu, R.; Xu, B.; Zhang, X.; Li, K. (2003). HEI Report 115, Validation & Evaluation of Biomarkers in Workers Exposed to Benzene in China.

[1612] Qu, Q., R. Shore, G. Li, X. Jin, L.C. Chen, B. Cohen, et al. (2002). Hematological changes among Chinese workers with a broad range of benzene exposures. Am. J. Industr. Med. 42: 275-285.

[1613] Lan, Qing, Zhang, L., Li, G., Vermeulen, R., et al. (2004). Hematotoxically in Workers Exposed to Low Levels of Benzene. Science 306: 1774-1776.

[1614] Turtletaub, K.W. and Mani, C. (2003). Benzene metabolism in rodents at doses relevant to human exposure from Urban Air. Research Reports Health Effect Inst. Report No.113.

[1615] U.S. Agency for Toxic Substances and Disease Registry (ATSDR). (2007). Toxicological profile for benzene. Atlanta, GA: U.S. Department of Health and Human Services, Public Health Service. http://www.atsdr.cdc.gov/ToxProfiles/tp3.pdf.

[1616] A minimal risk level (MRL) is defined as an estimate of the daily human exposure to a hazardous substance that is likely to be without appreciable risk of adverse noncancer health effects over a specified duration of exposure.

[1617] Corti, M; Snyder, CA. (1996) Influences of gender, development, pregnancy and ethanol consumption on the hematotoxicity of inhaled 10 ppm benzene. Arch Toxicol 70:209-217.

[1618] McKinney P.A.; Alexander, F.E.; Cartwright, R.A.; et al. (1991) Parental occupations of children with leukemia in west Cumbria, north Humberside, and Gateshead, Br Med J 302:681-686.

[1619] Keller, KA; Snyder, CA. (1986) Mice exposed in utero to low concentrations of benzene exhibit enduring changes in their colony forming hematopoietic cells. Toxicology 42:171-181.

[1620] Keller, KA; Snyder, CA. (1988) Mice exposed in utero to 20 ppm benzene exhibit altered numbers of recognizable hematopoietic cells up to seven weeks after exposure. Fundam Appl Toxicol 10:224-232.

[1621] Corti, M; Snyder, CA. (1996) Influences of gender, development, pregnancy and ethanol consumption on the hematotoxicity of inhaled 10 ppm benzene. Arch Toxicol 70:209-217.

[1622] U.S. EPA. (2002). Toxicological Review of Benzene (Noncancer Effects). National Center for Environmental Assessment, Washington, DC. Report No. EPA/635/R-02/001F. http://www.epa.gov/iris/toxreviews/0276-tr.pdf.

[1623] Ford, AM; Pombo-de-Oliveira, MS; McCarthy, KP; MacLean, JM; Carrico, KC; Vincent, RF; Greaves, M. (1997) Monoclonal origin of concordant T-cell malignancy in identical twins. Blood 89:281-285.

[1624] U.S. EPA. (2002). Health Assessment of 1,3-Butadiene. Office of Research and Development, National Center for Environmental Assessment, Washington Office, Washington, DC. Report No. EPA600-P-98-001F. This document is available electronically at https://cfpub.epa.gov/ncea/iris_drafts/recordisplay.cfm?deid=54499.

[1625] U.S. EPA. (2002) "Full IRIS Summary for 1,3-butadiene (CASRN 106-99-0)" Environmental Protection Agency, Integrated Risk Information System (IRIS), Research and Development, National Center for Environmental Assessment, Washington, DC https://cfpub.epa.gov/ncea/iris2/chemicalLanding.cfm?substance_nmbr=139.

characterized 1,3-butadiene as a known human carcinogen.[1626,1627,1628, 1629] There are numerous studies consistently demonstrating that 1,3-butadiene is metabolized into genotoxic metabolites by experimental animals and humans. The specific mechanisms of 1,3-butadiene-induced carcinogenesis are unknown; however, the scientific evidence strongly suggests that the carcinogenic effects are mediated by genotoxic metabolites. Animal data suggest that females may be more sensitive than males for cancer effects associated with 1,3-butadiene exposure; there are insufficient data in humans from which to draw conclusions about sensitive subpopulations. The URE for 1,3-butadiene is 3×10^{-5} per µg/m^3.[1630] 1,3-butadiene also causes a variety of reproductive and developmental effects in mice; no human data on these effects are available. The most sensitive effect was ovarian atrophy observed in a lifetime bioassay of female mice.[1631] Based on this critical effect and the benchmark concentration methodology, an RfC for chronic health effects was calculated at 0.9 ppb (approximately 2 µg/m^3).

5.4.7.2 Formaldehyde

In 1991, EPA concluded that formaldehyde is a Class B1 probable human carcinogen based on limited evidence in humans and sufficient evidence in animals.[1632] An inhalation URE for cancer and a reference dose for oral noncancer effects were developed by EPA and posted on the IRIS database. Since that time, the NTP and IARC have concluded that formaldehyde is a known human carcinogen.[1633,1634,1635]

The conclusions by IARC and NTP reflect the results of epidemiologic research published since 1991 in combination with previous and more recent animal, human and mechanistic evidence. Research conducted by the National Cancer Institute reported an increased risk of nasopharyngeal cancer and specific lymphohematopoietic malignancies among workers exposed

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[1626] International Agency for Research on Cancer (IARC). (1999). Monographs on the evaluation of carcinogenic risk of chemicals to humans, Volume 71, Re-evaluation of some organic chemicals, hydrazine and hydrogen peroxide , World Health Organization, Lyon, France.

[1627] International Agency for Research on Cancer (IARC). (2008). Monographs on the evaluation of carcinogenic risk of chemicals to humans, 1,3-Butadiene, Ethylene Oxide and Vinyl Halides (Vinyl Fluoride, Vinyl Chloride and Vinyl Bromide) Volume 97, World Health Organization, Lyon, France.

[1628] NTP (National Toxicology Program). 2016. Report on Carcinogens, Fourteenth Edition.; Research Triangle Park, NC: U.S. Department of Health and Human Services, Public Health Service. https://ntp.niehs.nih.gov/go/roc14.

[1629] International Agency for Research on Cancer (IARC). (2012). Monographs on the evaluation of carcinogenic risk of chemicals to humans, Volume 100F chemical agents and related occupations, World Health Organization, Lyon, France.

[1630] U.S. EPA. (2002). “Full IRIS Summary for 1,3-butadiene (CASRN 106-99-0)” Environmental Protection Agency, Integrated Risk Information System (IRIS), Research and Development, National Center for Environmental Assessment, Washington, DC https://cfpub.epa.gov/ncea/iris2/chemicalLanding.cfm?substance_nmbr=139.

[1631] Bevan, C.; Stadler, J.C.; Elliot, G.S.; et al. (1996). Subchronic toxicity of 4-vinylcyclohexene in rats and mice by inhalation. Fundam. Appl. Toxicol. 32:1-10.

[1632] EPA. Integrated Risk Information System. Formaldehyde (CASRN 50-00-0) *https://cfpub.epa.gov/ncea/iris2/chemicalLanding.cfm?substance_nmbr=419.*

[1633] NTP (National Toxicology Program). 2016. Report on Carcinogens, Fourteenth Edition.; Research Triangle Park, NC: U.S. Department of Health and Human Services, Public Health Service. https://ntp.niehs.nih.gov/go/roc14.

[1634] IARC Monographs on the Evaluation of Carcinogenic Risks to Humans Volume 88 (2006): Formaldehyde, 2-Butoxyethanol and 1-tert-Butoxypropan-2-ol.

[1635] IARC Monographs on the Evaluation of Carcinogenic Risks to Humans Volume 100F (2012): Formaldehyde.

to formaldehyde.[1636,1637,1638] A National Institute of Occupational Safety and Health study of garment workers also reported increased risk of death due to leukemia among workers exposed to formaldehyde.[1639] Extended follow-up of a cohort of British chemical workers did not report evidence of an increase in nasopharyngeal or lymphohematopoietic cancers, but a continuing statistically significant excess in lung cancers was reported.[1640] Finally, a study of embalmers reported formaldehyde exposures to be associated with an increased risk of myeloid leukemia but not brain cancer.[1641]

Health effects of formaldehyde in addition to cancer were reviewed by the Agency for Toxics Substances and Disease Registry in 1999, supplemented in 2010, and by the World Health Organization.[1642,1643,1644] These organizations reviewed the scientific literature concerning health effects linked to formaldehyde exposure to evaluate hazards and dose response relationships and defined exposure concentrations for minimal risk levels (MRLs). The health endpoints reviewed included sensory irritation of eyes and respiratory tract, reduced pulmonary function, nasal histopathology, and immune system effects. In addition, research on reproductive and developmental effects and neurological effects was discussed along with several studies that suggest that formaldehyde may increase the risk of asthma – particularly in the young.

In June 2010, EPA released a draft Toxicological Review of Formaldehyde – Inhalation Assessment through the IRIS program for peer review by the National Research Council (NRC) and public comment.[1645] That draft assessment reviewed more recent research from animal and human studies on cancer and other health effects. The NRC released their review report in April 2011.[1646] EPA addressed the NRC (2011) recommendations and applied systematic review methods to the evaluation of the available noncancer and cancer health effects evidence and

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[1636] Hauptmann, M.; Lubin, J. H.; Stewart, P. A.; Hayes, R. B.; Blair, A. 2003. Mortality from lymphohematopoetic malignancies among workers in formaldehyde industries. Journal of the National Cancer Institute 95: 1615-1623.

[1637] Hauptmann, M.; Lubin, J. H.; Stewart, P. A.; Hayes, R. B.; Blair, A. 2004. Mortality from solid cancers among workers in formaldehyde industries. American Journal of Epidemiology 159: 1117-1130.

[1638] Beane Freeman, L. E.; Blair, A.; Lubin, J. H.; Stewart, P. A.; Hayes, R. B.; Hoover, R. N.; Hauptmann, M. 2009. Mortality from lymphohematopoietic malignancies among workers in formaldehyde industries: The National Cancer Institute cohort. J. National Cancer Inst. 101: 751-761.

[1639] Pinkerton, L. E. 2004. Mortality among a cohort of garment workers exposed to formaldehyde: an update. Occup. Environ. Med. 61: 193-200.

[1640] Coggon, D, EC Harris, J Poole, KT Palmer. 2003. Extended follow-up of a cohort of British chemical workers exposed to formaldehyde. J National Cancer Inst. 95:1608-1615.

[1641] Hauptmann, M,; Stewart P. A.; Lubin J. H.; Beane Freeman, L. E.; Hornung, R. W.; Herrick, R. F.; Hoover, R. N.; Fraumeni, J. F.; Hayes, R. B. 2009. Mortality from lymphohematopoietic malignancies and brain cancer among embalmers exposed to formaldehyde. Journal of the National Cancer Institute 101:1696-1708.

[1642] ATSDR. 1999. Toxicological Profile for Formaldehyde, U.S. Department of Health and Human Services (HHS), July 1999.

[1643] ATSDR. 2010. Addendum to the Toxicological Profile for Formaldehyde. U.S. Department of Health and Human Services (HHS), October 2010.

[1644] IPCS. 2002. Concise International Chemical Assessment Document 40. Formaldehyde. World Health Organization.

[1645] EPA (U.S. Environmental Protection Agency). 2010. Toxicological Review of Formaldehyde (CAS No. 50-00-0) – Inhalation Assessment: In Support of Summary Information on the Integrated Risk Information System (IRIS). External Review Draft. EPA/635/R-10/002A. U.S. Environmental Protection Agency, Washington DC [online]. Available: *http://cfpub.epa.gov/ncea/iris_drafts/recordisplay.cfm?deid=223614*.

[1646] NRC (National Research Council). 2011. Review of the Environmental Protection Agency's Draft IRIS Assessment of Formaldehyde. Washington DC: National Academies Press. *http://books.nap.edu/openbook.php?record_id=13142*.

released a new draft IRIS Toxicological Review of Formaldehyde – Inhalation in April 2022.[1647] In this draft, updates to the 1991 IRIS finding include a stronger determination of the carcinogenicity of formaldehyde inhalation to humans, as well as characterization of its noncancer effects to propose an overall reference concentration for inhalation exposure. The National Academies of Sciences, Engineering, and Medicine released their review of EPA's 2022 Draft Formaldehyde Assessment in August 2023, concluding that EPA's "findings on formaldehyde hazard and quantitative risk are supported by the evidence identified." [1648] EPA is currently revising the draft IRIS assessment in response to comments received.[1649]

5.4.7.3 Naphthalene

Naphthalene is found in small quantities in gasoline and diesel fuels. Naphthalene emissions have been measured in larger quantities in both gasoline and diesel exhaust compared with evaporative emissions from mobile sources, indicating it is primarily a product of combustion.

Acute (short-term) exposure of humans to naphthalene by inhalation, ingestion, or dermal contact is associated with hemolytic anemia and damage to the liver and the nervous system.[1650] Chronic (long term) exposure of workers and rodents to naphthalene has been reported to cause cataracts and retinal damage.[1651] Children, especially neonates, appear to be more susceptible to acute naphthalene poisoning based on the number of reports of lethal cases in children and infants (hypothesized to be due to immature naphthalene detoxification pathways).[1652] EPA released an external review draft of a reassessment of the inhalation carcinogenicity of naphthalene based on a number of recent animal carcinogenicity studies.[1653] The draft reassessment completed external peer review.[1654] Based on external peer review comments received, EPA is developing a revised draft assessment that considers inhalation and oral routes of exposure, as well as cancer and noncancer effects.[1655] The external review draft does not

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[1647] U.S. EPA. 2022. IRIS Toxicological Review of Formaldehyde-Inhalation (External Review Draft, 2022). U.S. Environmental Protection Agency, Washington, DC, EPA/635/R-22/039.

[1648] National Academies of Sciences, Engineering, and Medicine. 2023. Review of EPA's 2022 Draft Formaldehyde Assessment. Washington, DC: The National Academies Press. https://doi.org/10.17226/27153

[1649] For more information, see *https://cfpub.epa.gov/ncea/iris_drafts/recordisplay.cfm?deid=248150#*.

[1650] U. S. EPA. 1998. Toxicological Review of Naphthalene (Reassessment of the Inhalation Cancer Risk), Environmental Protection Agency, Integrated Risk Information System, Research and Development, National Center for Environmental Assessment, Washington, DC. This material is available electronically at https://cfpub.epa.gov/ncea/iris_drafts/recordisplay.cfm?deid=56434.

[1651] U. S. EPA. 1998. Toxicological Review of Naphthalene (Reassessment of the Inhalation Cancer Risk), Environmental Protection Agency, Integrated Risk Information System, Research and Development, National Center for Environmental Assessment, Washington, DC. This material is available electronically at https://cfpub.epa.gov/ncea/iris_drafts/recordisplay.cfm?deid=56434.

[1652] U. S. EPA. (1998). Toxicological Review of Naphthalene (Reassessment of the Inhalation Cancer Risk), Environmental Protection Agency, Integrated Risk Information System, Research and Development, National Center for Environmental Assessment, Washington, DC. This material is available electronically at https://cfpub.epa.gov/ncea/iris_drafts/recordisplay.cfm?deid=56434.

[1653] U. S. EPA. (1998). Toxicological Review of Naphthalene (Reassessment of the Inhalation Cancer Risk), Environmental Protection Agency, Integrated Risk Information System, Research and Development, National Center for Environmental Assessment, Washington, DC. This material is available electronically at https://cfpub.epa.gov/ncea/iris_drafts/recordisplay.cfm?deid=56434.

[1654] Oak Ridge Institute for Science and Education. (2004). External Peer Review for the IRIS Reassessment of the Inhalation Carcinogenicity of Naphthalene. August 2004. http://cfpub.epa.gov/ncea/cfm/recordisplay.cfm?deid=84403.

[1655] U.S. EPA. (2021) See: https://cfpub.epa.gov/ncea/iris_drafts/recordisplay.cfm?deid=340791.

represent official agency opinion and was released solely for the purposes of external peer review and public comment. The NTP listed naphthalene as "reasonably anticipated to be a human carcinogen" in 2004 on the basis of bioassays reporting clear evidence of carcinogenicity in rats and some evidence of carcinogenicity in mice.[1656] California EPA has released a new risk assessment for naphthalene, and the IARC has reevaluated naphthalene and re-classified it as Group 2B: possibly carcinogenic to humans.[1657]

Naphthalene also causes a number of non-cancer effects in animals following chronic and less-than-chronic exposure, including abnormal cell changes and growth in respiratory and nasal tissues.[1658] The current EPA IRIS assessment includes noncancer data on hyperplasia and metaplasia in nasal tissue that form the basis of the inhalation RfC of 3 μg/m3.[1659] The ATSDR MRL for acute and intermediate duration oral exposure to naphthalene is 0.6 mg/kg/day based on maternal toxicity in a developmental toxicology study in rats.[1660] ATSDR also derived an ad hoc reference value of 6×10^{-2} mg/m^3 for acute (≤24-hour) inhalation exposure to naphthalene in a Letter Health Consultation dated March 24, 2014 to address a potential exposure concern in Illinois.[1661] The ATSDR acute inhalation reference value was based on a qualitative identification of an exposure level interpreted not to cause pulmonary lesions in mice. More recently, EPA developed acute RfCs for 1-, 8-, and 24-hour exposure scenarios; the ≤24-hour reference value is 2×10^{-2} mg/m^3.[1662] EPA's acute RfCs are based on a systematic review of the literature, benchmark dose modeling of naphthalene-induced nasal lesions in rats, and application of a PBPK (physiologically based pharmacokinetic) model.

5.4.8 Exposure and Health Effects Associated with Traffic

Locations near major roadways generally have elevated concentrations of many air pollutants emitted from motor vehicles. Hundreds of studies have been published in peer-reviewed journals, concluding that concentrations of CO, CO_2, NO, NO_2, benzene, aldehydes, particulate matter, black carbon, and many other compounds are elevated in ambient air within approximately 300-600 meters (about 1,000-2,000 feet) of major roadways. The highest concentrations of most pollutants emitted directly by motor vehicles are found within 50 meters (about 165 feet) of the edge of a roadway's traffic lanes.

[1656] NTP (National Toxicology Program). 2016. Report on Carcinogens, Fourteenth Edition.; Research Triangle Park, NC: U.S. Department of Health and Human Services, Public Health Service. https://ntp.niehs.nih.gov/go/roc14.

[1657] International Agency for Research on Cancer (IARC). (2002). Monographs on the Evaluation of the Carcinogenic Risk of Chemicals for Humans. Vol. 82. Lyon, France.

[1658] U. S. EPA. (1998). Toxicological Review of Naphthalene, Environmental Protection Agency, Integrated Risk Information System, Research and Development, National Center for Environmental Assessment, Washington, DC. This material is available electronically at https://cfpub.epa.gov/ncea/iris_drafts/recordisplay.cfm?deid=56434.

[1659] U.S. EPA. (1998). Toxicological Review of Naphthalene. Environmental Protection Agency, Integrated Risk Information System (IRIS), Research and Development, National Center for Environmental Assessment, Washington, DC https://cfpub.epa.gov/ncea/iris_drafts/recordisplay.cfm?deid=56434.

[1660] ATSDR. Toxicological Profile for Naphthalene, 1-Methylnaphthalene, and 2-Methylnaphthalene (2005). https://www.atsdr.cdc.gov/ToxProfiles/tp67-p.pdf

[1661] ATSDR. Letter Health Consultation, Radiac Abrasives, Inc., Chicago, Illinois (2014). https://www.atsdr.cdc.gov/HAC/pha/RadiacAbrasives/Radiac%20Abrasives,%20Inc.%20_%20LHC%20(Final)%20_%2003-24-2014%20(2)_508.pdf

[1662] U. S. EPA. Derivation of an acute reference concentration for inhalation exposure to naphthalene. Report No. EPA/600/R-21/292. https://cfpub.epa.gov/ncea/risk/recordisplay.cfm?deid=355035.

A large-scale review of air quality measurements in the vicinity of major roadways between 1978 and 2008 concluded that the pollutants with the steepest concentration gradients in vicinities of roadways were CO, ultrafine particles, metals, elemental carbon (EC), NO, NO_X, and several VOCs.[1663] These pollutants showed a large reduction in concentrations within 100 meters downwind of the roadway. Pollutants that showed more gradual reductions with distance from roadways included benzene, NO_2, $PM_{2.5}$, and PM_{10}. In reviewing the literature, Karner et al. (2010) reported that results varied based on the method of statistical analysis used to determine the gradient in pollutant concentration. More recent studies of traffic-related air pollutants continue to report sharp gradients around roadways, particularly within several hundred meters. [1664,1665,1666,1667,1668,1669,1670,1671] There is evidence that EPA's regulations for vehicles have lowered the near-road concentrations and gradients.[1672] Starting in 2010, EPA required through the NAAQS process that air quality monitors be placed near high-traffic roadways for determining concentrations of CO, NO_2, and $PM_{2.5}$. The monitoring data for NO_2 and CO

[1663] Karner, A.A.; Eisinger, D.S.; Niemeier, D.A. (2010). Near-roadway air quality: synthesizing the findings from real-world data. Environ Sci Technol 44: 5334-5344.

[1664] McDonald, B.C.; McBride, Z.C.; Martin, E.W.; Harley, R.A. (2014) High-resolution mapping of motor vehicle carbon dioxide emissions. J. Geophys. Res.Atmos.,119, 5283–5298, doi:10.1002/2013JD021219.

[1665] Kimbrough, S.; Baldauf, R.W.; Hagler, G.S.W.; Shores, R.C.; Mitchell, W.; Whitaker, D.A.; Croghan, C.W.; Vallero, D.A. (2013) Long-term continuous measurement of near-road air pollution in Las Vegas: seasonal variability in traffic emissions impact on air quality. Air Qual Atmos Health 6: 295-305. DOI 10.1007/s11869-012-0171-x.

[1666] Kimbrough, S.; Palma, T.; Baldauf, R.W. (2014) Analysis of mobile source air toxics (MSATs)—Near-road VOC and carbonyl concentrations. Journal of the Air &Waste Management Association, 64:3, 349-359, DOI: 10.1080/10962247.2013.863814.

[1667] Kimbrough, S.; Owen, R.C.; Snyder, M.; Richmond-Bryant, J. (2017) NO to NO_2 Conversion Rate Analysis and Implications for Dispersion Model Chemistry Methods using Las Vegas, Nevada Near-Road Field Measurements. Atmos Environ 165: 23-24.

[1668] Apte, J.S.; Messier, K.P.; Gani, S.; Brauer, M.; Kirchstetter, T.W.; Lunden, M.M.; Marshall, J.D.; Portier, C.J.; Vermeulen, R.C.H.; Hamburg, S.P. (2017) High-Resolution Air Pollution Mapping with Google Street View Cars: Exploiting Big Data. Environ Sci Technol 51: 6999-7008. *https://doi.org/10.1021/acs.est.7b00891*.

[1669] Gu, P.; Li, H.Z.; Ye, Q.; et al. (2018) Intercity variability of particulate matter is driven by carbonaceous sources and correlated with land-use variables. Environ Sci Technol 52: 52: 11545-11554. [Online at *http://dx.doi.org/10.1021/acs.est.8b03833]*.

[1670] Hilker, N.; Wang, J.W.; Jong, C-H.; Healy, R.M.; Sofowote, U.; Debosz, J.; Su, Y.; Noble, M.; Munoz, A.; Doerkson, G.; White, L.; Audette, C.; Herod, D.; Brook, J.R.; Evans, G.J. (2019) Traffic-related air pollution near roadways: discerning local impacts from background. Atmos. Meas. Tech., 12, 5247–5261. *https://doi.org/10.5194/amt-12-5247-2019*.

[1671] Dabek-Zlotorzynska, E., V. Celo, L. Ding, D. Herod, C-H. Jeong, G. Evans, and N. Hilker. 2019. "Characteristics and sources of PM2.5 and reactive gases near roadways in two metropolitan areas in Canada." *Atmos Environ* 218: 116980.

[1672] Sarnat, J.A.; Russell, A.; Liang, D.; Moutinho, J.L; Golan, R.; Weber, R.; Gao, D.; Sarnat, S.; Chang, H.H.; Greenwald, R.; Yu, T. (2018) Developing Multipollutant Exposure Indicators of Traffic Pollution: The Dorm Room Inhalation to Vehicle Emissions (DRIVE) Study. Health Effects Institute Research Report Number 196. [Online at: *https://www.healtheffects.org/publication/developing-multipollutant-exposure-indicators-traffic-pollution-dorm-room-inhalation*].

indicate that in urban areas, monitors near roadways often report the highest concentrations.[1673,1674]

For pollutants with relatively high background concentrations relative to near-road concentrations, detecting concentration gradients can be difficult. For example, many carbonyls have high background concentrations because of photochemical breakdown of precursors from many different organic compounds. However, several studies have measured carbonyls in multiple weather conditions and found higher concentrations of many carbonyls downwind of roadways.[1675,1676] These findings suggest a substantial roadway source of these carbonyls.

In the past 30 years, many studies have been published with results reporting that populations who live, work, or go to school near high-traffic roadways experience higher rates of numerous adverse health effects, compared to populations far away from major roads.[1677] In addition, numerous studies have found adverse health effects associated with spending time in traffic, such as commuting or walking along high-traffic roadways, including studies among children.[1678,1679,1680,1681]

Numerous reviews of this body of health literature have been published. In a 2022 final report, an expert panel of the Health Effects Institute (HEI) employed a systematic review focusing on selected health endpoints related to exposure to traffic-related air pollution.[1682] The HEI panel concluded that there was a high level of confidence in evidence between long-term exposure to traffic-related air pollution and health effects in adults, including all-cause,

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[1673] Gantt, B; Owen, R.C.; Watkins, N. (2021) Characterizing nitrogen oxides and fine particulate matter near major highways in the United States using the National Near-road Monitoring Network. Environ Sci Technol 55: 2831-2838. [Online at *https://doi.org/10.1021/acs.est.0c05851*].

[1674] Lal, R.M.; Ramaswani, A.; Russell, A.G. (2020) Assessment of the near-road (monitoring) network including comparison with nearby monitors within U.S. cities. Environ Res Letters 15: 114026. [Online at *https://doi.org/10.1088/1748-9326/ab8156*]

[1675] Liu, W.; Zhang, J.; Kwon, J.l; et l. (2006). Concentrations and source characteristics of airborne carbonyl compounds measured outside urban residences. J Air Waste Manage Assoc 56: 1196-1204.

[1676] Cahill, T.M.; Charles, M.J.; Seaman, V.Y. (2010). Development and application of a sensitive method to determine concentrations of acrolein and other carbonyls in ambient air. Health Effects Institute Research Report 149. Available at *https://www.healtheffects.org/system/files/Cahill149.pdf*.

[1677] In the widely used PubMed database of health publications, between January 1, 1990 and December 31, 2021, 1,979 publications contained the keywords “traffic, pollution, epidemiology,” with approximately half the studies published after 2015.

[1678] Laden, F.; Hart, J.E.; Smith, T.J.; Davis, M.E.; Garshick, E. (2007) Cause-specific mortality in the unionized U.S. trucking industry. Environmental Health Perspect 115:1192-1196.

[1679] Peters, A.; von Klot, S.; Heier, M.; Trentinaglia, I.; Hörmann, A.; Wichmann, H.E.; Löwel, H. (2004) Exposure to traffic and the onset of myocardial infarction. New England J Med 351: 1721-1730.

[1680] Zanobetti, A.; Stone, P.H.; Spelzer, F.E.; Schwartz, J.D.; Coull, B.A.; Suh, H.H.; Nearling, B.D.; Mittleman, M.A.; Verrier, R.L.; Gold, D.R. (2009) T-wave alternans, air pollution and traffic in high-risk subjects. Am J Cardiol 104: 665-670.

[1681] Adar, S.; Adamkiewicz, G.; Gold, D.R.; Schwartz, J.; Coull, B.A.; Suh, H. (2007) Ambient and microenvironmental particles and exhaled nitric oxide before and after a group bus trip. Environ Health Perspect 115: 507-512.

[1682] HEI Panel on the Health Effects of Long-Term Exposure to Traffic-Related Air Pollution (2022) Systematic review and meta-analysis of selected health effects of long-term exposure to traffic-related air pollution. Health Effects Institute Special Report 23. [Online at *https://www.healtheffects.org/publication/systematic-review-and-meta-analysis-selected-health-effects-long-term-exposure-traffic*] This more recent review focused on health outcomes related to birth effects, respiratory effects, cardiometabolic effects, and mortality.

circulatory, and ischemic heart disease mortality.[1683] The panel also found that there is a moderate-to-high level of confidence in evidence of associations with asthma onset and acute respiratory infections in children and lung cancer and asthma onset in adults. The panel concluded that there was a moderate level of evidence of associations with small for gestational age births, but low-to-moderate confidence for other birth outcomes (term birth weight and preterm birth). This report follows on an earlier expert review published by HEI in 2010, where it found strongest evidence for asthma-related traffic impacts. Other literature reviews have been published with conclusions generally similar to the HEI panels'. [1684,1685,1686,1687] Additionally, in 2014, researchers from the U.S. Centers for Disease Control and Prevention (CDC) published a systematic review and meta-analysis of studies evaluating the risk of childhood leukemia associated with traffic exposure and reported positive associations between postnatal proximity to traffic and leukemia risks, but no such association for prenatal exposures.[1688] The U.S. Department of Health and Human Services' National Toxicology Program published a monograph including a systematic review of traffic-related air pollution and its impacts on hypertensive disorders of pregnancy. The National Toxicology Program concluded that exposure to traffic-related air pollution is "presumed to be a hazard to pregnant women" for developing hypertensive disorders of pregnancy.[1689]

For several other health outcomes there are publications to suggest the possibility of an association with traffic-related air pollution, but insufficient evidence to draw definitive conclusions. Among these outcomes are neurological and cognitive impacts (e.g., autism and

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[1683] Boogaard, H.; Patton, A.P.; Atkinson, R.W.; Brook, J.R.; Chang, H.H.; Crouse, D.L.; Fussell, J.C.; Hoek, G.; Hoffmann, B.; Kappeler, R.; Kutlar Joss, M.; Ondras, M.; Sagiv, S.K.; Samoli, E.; Shaikh, R.; Smargiassi, A.; Szpiro, A.A.; Van Vliet, E.D.S.; Vienneau, D.; Weuve, J.; Lurmann, F.W.; Forastiere, F. (2022) Long-term exposure to traffic-related air pollution and selected health outcomes: A systematic review and meta-analysis. Environ Internatl 164: 107262. [Online at https://doi.org/10.1016/j.envint.2022.107262]

[1684] Boothe, V.L.; Shendell, D.G. (2008). Potential health effects associated with residential proximity to freeways and primary roads: review of scientific literature, 1999-2006. J Environ Health 70: 33-41.

[1685] Salam, M.T.; Islam, T.; Gilliland, F.D. (2008). Recent evidence for adverse effects of residential proximity to traffic sources on asthma. Curr Opin Pulm Med 14: 3-8.

[1686] Sun, X.; Zhang, S.; Ma, X. (2014) No association between traffic density and risk of childhood leukemia: a meta-analysis. Asia Pac J Cancer Prev 15: 5229-5232.

[1687] Raaschou-Nielsen, O.; Reynolds, P. (2006). Air pollution and childhood cancer: a review of the epidemiological literature. Int J Cancer 118: 2920-9.

[1688] Boothe, VL.; Boehmer, T.K.; Wendel, A.M.; Yip, F.Y. (2014) Residential traffic exposure and childhood leukemia: a systematic review and meta-analysis. Am J Prev Med 46: 413-422.

[1689] National Toxicology Program (2019) NTP Monograph on the Systematic Review of Traffic-related Air Pollution and Hypertensive Disorders of Pregnancy. NTP Monograph 7. *https://ntp.niehs.nih.gov/ntp/ohat/trap/mgraph/trap_final_508.pdf.*

reduced cognitive function, academic performance, and executive function) and reproductive outcomes (e.g., preterm birth, low birth weight).[1690,1691,1692,1693,1694,1695]

Numerous studies have also investigated potential mechanisms by which traffic-related air pollution affects health, particularly for cardiopulmonary outcomes. For example, some research indicates that near-roadway exposures may increase systemic inflammation, affecting organ systems, including blood vessels and lungs.[1696,1697,1698,1699] Additionally, long-term exposures in near-road environments have been associated with inflammation-associated conditions, such as atherosclerosis and asthma.[1700,1701,1702]

As described in Chapter 5.6.3, people who live or attend school near major roadways are more likely to be people of color and/or have a low SES. Additionally, people with low SES often live in neighborhoods with multiple stressors and health risk factors, including reduced health insurance coverage rates, higher smoking and drug use rates, limited access to fresh food, visible neighborhood violence, and elevated rates of obesity and some diseases such as asthma, diabetes, and ischemic heart disease. Although questions remain, several studies find stronger associations between air pollution and health in locations with such chronic neighborhood stress,

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[1690] Volk, H.E.; Hertz-Picciotto, I.; Delwiche, L.; et al. (2011). Residential proximity to freeways and autism in the CHARGE study. Environ Health Perspect 119: 873-877.

[1691] Franco-Suglia, S.; Gryparis, A.; Wright, R.O.; et al. (2007). Association of black carbon with cognition among children in a prospective birth cohort study. Am J Epidemiol. doi: 10.1093/aje/kwm308. [Online at *http://dx.doi.org*].

[1692] Power, M.C.; Weisskopf, M.G.; Alexeef, S.E.; et al. (2011). Traffic-related air pollution and cognitive function in a cohort of older men. Environ Health Perspect 2011: 682-687.

[1693] Wu, J.; Wilhelm, M.; Chung, J.; Ritz, B. (2011). Comparing exposure assessment methods for traffic-related air pollution in an adverse pregnancy outcome study. Environ Res 111: 685-692. https://doi.org/10.1016/j.envres.2011.03.008

[1694] Stenson, C.; Wheeler, A.J.; Carver, A.; et al. (2021) The impact of traffic-related air pollution on child and adolescent academic performance: a systematic review. Environ Intl 155: 106696 [Online at *https://doi.org/10.1016/j.envint.2021.106696].*

[1695] Gartland, N.; Aljofi, H.E.; Dienes, K.; et al. (2022) The effects of traffic air pollution in and around schools on executive function and academic performance in children: a rapid review. Int J Environ Res Public Health 19: 749. https://doi.org/10.3390/ijerph19020749

[1696] Riediker, M. (2007). Cardiovascular effects of fine particulate matter components in highway patrol officers. Inhal Toxicol 19: 99-105. doi: 10.1080/08958370701495238

[1697] Alexeef, S.E.; Coull, B.A.; Gryparis, A.; et al. (2011). Medium-term exposure to traffic-related air pollution and markers of inflammation and endothelial function. Environ Health Perspect 119: 481-486. doi:10.1289/ehp.1002560.

[1698] Eckel. S.P.; Berhane, K.; Salam, M.T.; et al. (2011). Residential Traffic-related pollution exposure and exhaled nitric oxide in the Children's Health Study. Environ Health Perspect. doi:10.1289/ehp.1103516.

[1699] Zhang, J.; McCreanor, J.E.; Cullinan, P.; et al. (2009). Health effects of real-world exposure diesel exhaust in persons with asthma. Res Rep Health Effects Inst 138. [Online at *http://www.healtheffects.org*].

[1700] Adar, S.D.; Klein, R.; Klein, E.K.; et al. (2010). Air pollution and the microvasculature: a cross-sectional assessment of in vivo retinal images in the population-based Multi-Ethnic Study of Atherosclerosis. PLoS Med 7(11): E1000372. doi:10.1371/journal.pmed.1000372. Available at *http://dx.doi.org*.

[1701] Kan, H.; Heiss, G.; Rose, K.M.; et al. (2008). Prospective analysis of traffic exposure as a risk factor for incident coronary heart disease: The Atherosclerosis Risk in Communities (ARIC) study. Environ Health Perspect 116: 1463-1468. doi:10.1289/ehp.11290. Available at *http://dx.doi.org*.

[1702] McConnell, R.; Islam, T.; Shankardass, K.; et al. (2010). Childhood incident asthma and traffic-related air pollution at home and school. Environ Health Perspect 1021-1026.

suggesting that populations in these areas may be more susceptible to the effects of air pollution.[1703,1704,1705,1706,1707,1708,1709,1710]

The risks associated with residence, workplace, or school near major roads are of potentially high public health significance due to the large population in such locations.

The 2013 U.S. Census Bureau's American Housing Survey (AHS) was the last AHS that included whether housing units are within 300 feet of an "airport, railroad, or highway with four or more lanes."[1711] The 2013 AHS reports that 17.3 million housing units, or 13 percent of all housing units in the United States, were in such areas. Assuming that populations and housing units are in the same locations, this corresponds to a population of more than 41 million U.S. residents near high-traffic roadways or other transportation sources.[1712] According to the Central Intelligence Agency's World Factbook, based on data collected between 2012-2022, the United States had 6,586,610 km of roadways, 293,564 km of railways, and 13,513 airports.[1713] As such, highways represent the overwhelming majority of transportation facilities described by this factor in the AHS.

Scientific literature suggests that some sociodemographic factors may increase susceptibility to the effects of traffic-associated air pollution. For example, several studies have found stronger adverse health associations in children experiencing chronic social stress, such as living in

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[1703] Islam, T.; Urban, R.; Gauderman, W.J.; et al. (2011). Parental stress increases the detrimental effect of traffic exposure on children's lung function. Am J Respir Crit Care Med.

[1704] Clougherty, J.E.; Kubzansky, L.D. (2009) A framework for examining social stress and susceptibility to air pollution in respiratory health. Environ Health Perspect 117: 1351-1358. Doi:10.1289/ehp.0900612

[1705] Clougherty, J.E.; Levy, J.I.; Kubzansky, L.D.; Ryan, P.B.; Franco Suglia, S.; Jacobson Canner, M.; Wright, R.J. (2007) Synergistic effects of traffic-related air pollution and exposure to violence on urban asthma etiology. Environ Health Perspect 115: 1140-1146. doi:10.1289/ehp.9863.

[1706] Finkelstein, M.M.; Jerrett, M.; DeLuca, P.; Finkelstein, N.; Verma, D.K.; Chapman, K.; Sears, M.R. (2003) Relation between income, air pollution and mortality: a cohort study. Canadian Med Assn J 169: 397-402.

[1707] Shankardass, K.; McConnell, R.; Jerrett, M.; Milam, J.; Richardson, J.; Berhane, K. (2009) Parental stress increases the effect of traffic-related air pollution on childhood asthma incidence. Proc Natl Acad Sci 106: 12406-12411. doi:10.1073/pnas.0812910106.

[1708] Chen, E.; Schrier, H.M.; Strunk, R.C.; et al. (2008). Chronic traffic-related air pollution and stress interact to predict biologic and clinical outcomes in asthma. Environ Health Perspect 116: 970-5.

[1709] Currie, J. and R. Walker (2011) Traffic Congestion and Infant Health: Evidence from E-ZPass. American Economic Journal: Applied Economics, 3 (1): 65-90. https://doi.org/10.1257/app.3.1.65

[1710] Knittel, C.R.; Miller, D.L.; Sanders N.J. (2016) Caution, Drivers! Children Present: Traffic, Pollution, and Infant Health. The Review of Economics and Statistics, 98 (2): 350-366. https://doi.org/10.1162/REST_a_00548

[1711] The variable was known as "ETRANS" in the questions about the neighborhood.

[1712] The analysis of population living near major roads based on the Freight Analysis Framework, version 4, described just below, is intended to provide comparable estimates as the AHS analyses for the conterminous United States (i.e., "the lower 48"). As stated below, population estimates for the two methods result in very good agreement – 41 million people living within 300 feet/100 meters using the AHS 2009 dataset, and 41 million people living within a 100 meters of a road in the FAF4 network using the data in that analysis.

[1713] Central Intelligence Agenda. World Factbook: United States. [Online at *https://www.cia.gov/the-world-factbook/countries/united-states/#transportation*] violent neighborhoods or in homes with low incomes or high family stress.[1714,1715,1716,1717] HEI's 2022 critical review of traffic and health studies mentions additional potential mediators or effect modifiers of the relationship between traffic-related air pollution and health, including preexisting morbidities (e.g., obesity, hypertension), the built environment (i.e., green space, walkability), and socioeconomic characteristics, but notes that additional research is needed to better understand such interactions.[1718]

In examining schools near major roadways, we used the Common Core of Data from the U.S. Department of Education, which includes information on all public elementary and secondary schools and school districts nationwide.[1719] To determine school proximities to major roadways, we used a geographic information system to map each school and roadways based on the U.S. Census's TIGER roadway file.[1720,1721] We estimated that about 10 million students attend schools within 200 meters of major roads, about 20 percent of the total number of public school students in the United States.[1722] About 800,000 students attend public schools within 200 meters of primary roads, or about 2 percent of the total.[1723] We found that students of color were overrepresented at schools within 200 meters of primary roadways, and schools within 200 meters of primary roadways had a disproportionately greater population of students eligible for free or reduced-price lunches. Black students represent 22 percent of students at schools located within 200 meters of a primary road, compared to 17 percent of students in all U.S. schools. Hispanic students represent 30 percent of students at schools located within 200 meters of a primary road, compared to 22 percent of students in all U.S. schools.[1724]

EPA also conducted a study to estimate the number of people living near truck freight routes in the United States, which includes many large highways and other routes where light- and

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[1714] Islam, T., R. Urban, W.J. Gauderman, and et al. 2011. "Parental stress increases the detrimental effect of traffic exposure on children's lung function." Am J Respir Crit Care Med.

[1715] Clougherty, J.E., J.I. Levy, L.D. Kubzansky, and et al. 2007. "Synergistic effects of traffic-related air pollution and exposure to violence on urban asthma etiology." Environ Health Perspect 115: 1140-1146.

[1716] Chen, E., H.M. Schrier, R.C. Strunk, and et al. 2008. "Chronic traffic-related air pollution and stress interact to predict biologic and clinical outcomes in asthma." Environ Health Perspect 116: 970-975.

[1717] Long, D., D. Lewis, and C. Langpap. 2021. "Negative traffic externalities and infant health: the role of income heterogeneity and residential sorting." *Environ and Resource Econ* 80: 637-674.

[1718] HEI. 2022. *HEI Panel on the Health Effects of Long-Term Exposure to Traffic-Related Air Pollution (2022) Systematic review and meta-analysis of selected health effects of long-term exposure to traffic-related air pollution*. Health Effects Institute Special Report 23. https://www.healtheffects.org/system/files/hei-special-report-23_1.pdf.

[1719] *http://nces.ed.gov/ccd/*.

[1720] This information is available at: http://nces.ed.gov/ccd/.

[1721] TIGER/Line shapefiles for the year 2010. [Online at https://www.census.gov/geographies/mapping-files/time-series/geo/tiger-line-file.2010.html]

[1722] Here, "major roads" refer to those TIGER classifies as either "Primary" or "Secondary." The Census Bureau describes primary roads as "generally divided limited-access highways within the Federal interstate system or under state management." Secondary roads are "main arteries, usually in the U.S. highway, state highway, or county highway system."

[1723] For this analysis we analyzed a 200-meter distance based on the understanding that roadways generally influence air quality within a few hundred meters from the vicinity of heavily traveled roadways or along corridors with significant trucking traffic. See U.S. EPA, 2014. Near Roadway Air Pollution and Health: Frequently Asked Questions. EPA-420-F-14-044.

[1724] Pedde, M.; Bailey, C. (2011) Identification of Schools within 200 Meters of U.S. Primary and Secondary Roads. Memorandum to docket EPA-HQ-OAR-2011-0135.

medium-duty vehicles operate.[1725] Based on a population analysis using the U.S. Department of Transportation's (USDOT) Freight Analysis Framework 4 (FAF4) and population data from the 2010 decennial census, an estimated 72 million people live within 200 meters of these FAF4 roads, which are used by all types of vehicles. [1726,] The FAF4 analysis includes the population living within 200 meters of major roads, while the AHS uses a 100-meter distance; the larger distance and other methodological differences explain the difference in the two estimates for populations living near major roads.[1727]

The EPA's Exposure Factor Handbook also indicates that, on average, Americans spend more than an hour traveling each day, bringing nearly all residents into a high-exposure microenvironment for part of the day.[1728,1729] While near-roadway studies focus on residents near roads or others spending considerable time near major roads, the duration of commuting results in another important contributor to overall exposure to traffic-related air pollution. Studies of health that address time spent in transit have found evidence of elevated risk of cardiac impacts.[1730,1731,1732] Studies have also found that school bus emissions can increase student exposures to diesel-related air pollutants, and that programs that reduce school bus emissions may improve health and reduce school absenteeism.[1733,1734,1735,1736]

[1725] U.S. EPA (2021). Estimation of Population Size and Demographic Characteristics among People Living Near Truck Routes in the Conterminous United States. Memorandum to docket EPA-HQ-OAR-2019-0055.

[1726] FAF4 is a model from the USDOT's Bureau of Transportation Statistics (BTS) and Federal Highway Administration (FHWA), which provides data associated with freight movement in the U.S. It includes data from the 2012 Commodity Flow Survey (CFS), the Census Bureau on international trade, as well as data associated with construction, agriculture, utilities, warehouses, and other industries. FAF4 estimates the modal choices for moving goods by trucks, trains, boats, and other types of freight modes. It includes traffic assignments, including truck flows on a network of truck routes. *https://ops.fhwa.dot.gov/freight/freight_analysis/faf/*.

[1727] The same analysis estimated the population living within 100 meters of a FAF4 truck route is 41 million.

[1728] EPA. (2011) Exposure Factors Handbook: 2011 Edition. Chapter 16. Online at *https://www.epa.gov/expobox/about-exposure-factors-handbook*.

[1729] It is not yet possible to estimate the long-term impact of growth in telework associated with the COVID-19 pandemic on travel behavior. There were notable changes during the pandemic. For example, according to the 2021 American Time Use Survey, a greater fraction of workers did at least part of their work at home (38%) as compared with the 2019 survey (24%). [Online at *https://www.bls.gov/news.release/atus.nr0.htm*].

[1730] Riediker, M.; Cascio, W.E.; Griggs, T.R.; et al. (2004) Particulate matter exposure in cars is associated with cardiovascular effects in healthy young men. Am J Respir Crit Care Med 169. [Online at *https://doi.org/10.1164/rccm.200310-1463OC*].

[1731] Peters, A.; von Klot, S.; Heier, M.; et al. (2004) Exposure to traffic and the onset of myocardial infarction. New Engl J Med 1721-1730. [*Online at https://doi.org/10.1056/NEJMoa040203.*]

[1732] Adar, S.D.; Gold, D.R.; Coull, B.A.; (2007) Focused exposure to airborne traffic particles and heart rate variability in the elderly. Epidemiology 18: 95-103 [Online at 351: *https://doi.org/10.1097/01.ede.0000249409.81050.46*].

[1733] Sabin, L.; Behrentz, E.; Winer, A.M.; et al. Characterizing the range of children's air pollutant exposure during school bus commutes. J Expo Anal Environ Epidemiol 15: 377-387. [Online at *https://doi.org/10.1038/sj.jea.7500414*].

[1734] Li, C.; N, Q.; Ryan, P.H.; School bus pollution and changes in the air quality at schools: a case study. J Environ Monit 11: 1037-1042. [*https://doi.org/10.1039/b819458k*].

[1735] Austin, W.; Heutel, G.; Kreisman, D. (2019) School bus emissions, student health and academic performance. Econ Edu Rev 70: 108-12.

[1736] Adar, S.D.; D.Souza, J.; Sheppard, L.; et al. (2015) Adopting clean fuels and technologies on school buses. Pollution and health impacts in children. Am J Respir Crit Care Med 191. [Online at *http://doi.org/10.1164/rccm.201410-1924OC*].

5.5 Welfare Effects Associated with Exposure to Non-GHG Pollutants

This section discusses the environmental effects associated with criteria and toxic pollutants affected by this rule.

5.5.1 Visibility

Visibility can be defined as the degree to which the atmosphere is transparent to visible light.[1737] Visibility impairment is caused by light scattering and absorption by suspended particles and gases. It is dominated by contributions from suspended particles except under pristine conditions. Visibility is important because it has direct significance to people's enjoyment of daily activities in all parts of the country. Individuals value good visibility for the well-being it provides them directly, where they live and work and in places where they enjoy recreational opportunities. Visibility is also highly valued in significant natural areas, such as national parks and wilderness areas, and special emphasis is given to protecting visibility in these areas. For more information on visibility see the final 2019 PM ISA.[1738]

EPA is working to address visibility impairment. Reductions in air pollution from implementation of various programs associated with the Clean Air Act Amendments of 1990 provisions have resulted in substantial improvements in visibility and will continue to do so in the future. Nationally, because trends in haze are closely associated with trends in particulate sulfate and nitrate due to the relationship between their concentration and light extinction, visibility trends have improved as emissions of SO_2 and NO_X have decreased over time due to air pollution regulations such as the Acid Rain Program.[1739] However, in the western part of the country, changes in total light extinction were smaller, and the contribution of particulate organic matter to atmospheric light extinction was increasing due to increasing wildfire emissions.[1740]

In the Clean Air Act Amendments of 1977, Congress recognized visibility's value to society by establishing a national goal to protect national parks and wilderness areas from visibility impairment caused by manmade pollution.[1741] In 1999, EPA finalized the regional haze program to protect the visibility in Mandatory Class I Federal areas.[1742] There are 156 national parks, forests and wilderness areas categorized as Mandatory Class I Federal areas.[1743] These areas are defined in CAA section 162 as those national parks exceeding 6,000 acres, wilderness areas and memorial parks exceeding 5,000 acres, and all international parks which were in existence on August 7, 1977.

[1737] National Research Council, (1993). Protecting Visibility in National Parks and Wilderness Areas. National Academy of Sciences Committee on Haze in National Parks and Wilderness Areas. National Academy Press, Washington, DC. This book can be viewed on the National Academy Press Website at *https://www.nap.edu/catalog/2097/protecting-visibility-in-national-parks-and-wilderness-areas*.

[1738] U.S. EPA. Integrated Science Assessment (ISA) for Particulate Matter (Final Report, 2019). U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-19/188, 2019.

[1739] U.S. EPA. Integrated Science Assessment (ISA) for Particulate Matter (Final Report, 2019). U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-19/188, 2019.

[1740] Hand, JL;Prenni, AJ; Copeland, S; Schichtel, BA; Malm, WC. (2020). Thirty years of the Clean Air Act Amendments: Impacts on haze in remote regions of the United States (1990-2018). Atmos Environ 243: 117865.

[1741] See Section 169(a) of the Clean Air Act.

[1742] 64 FR 35714, July 1, 1999.

[1743] 62 FR 38680-38681, July 18, 1997.

EPA has also concluded that $PM_{2.5}$ causes adverse effects on visibility in other areas that are not targeted by the Regional Haze Rule, such as urban areas, depending on $PM_{2.5}$ concentrations and other factors such as dry chemical composition and relative humidity (i.e., an indicator of the water composition of the particles). The secondary (welfare-based) PM NAAQS provide protection against visibility effects. In recent PM NAAQS reviews, EPA evaluated a target level of protection for visibility impairment that is expected to be met through attainment of the existing secondary PM standards.

5.5.2 Ozone Effects on Ecosystems

The welfare effects of ozone include effects on ecosystems, which can be observed across a variety of scales, i.e., subcellular, cellular, leaf, whole plant, population and ecosystem. Ozone effects that begin at small spatial scales, such as the leaf of an individual plant, when they occur at sufficient magnitudes (or to a sufficient degree), can result in effects being propagated to higher and higher levels of biological organization. For example, effects at the individual plant level, such as altered rates of leaf gas exchange, growth and reproduction, can, when widespread, result in broad changes in ecosystems, such as productivity, carbon storage, water cycling, nutrient cycling, and community composition.

Ozone can produce both acute and chronic injury in sensitive plant species depending on the concentration level and the duration of the exposure.[1744] In those sensitive species[1745], effects from repeated exposure to ozone throughout the growing season of the plant can tend to accumulate, so that even relatively low concentrations experienced for a longer duration have the potential to create chronic stress on vegetation.[1746],[1747] Ozone damage to sensitive plant species includes impaired photosynthesis and visible injury to leaves. The impairment of photosynthesis, the process by which the plant makes carbohydrates (its source of energy and food), can lead to reduced crop yields, timber production, and plant productivity and growth. Impaired photosynthesis can also lead to a reduction in root growth and carbohydrate storage below ground, resulting in other, more subtle plant and ecosystems impacts.[1748] These latter impacts include increased susceptibility of plants to insect attack, disease, harsh weather, interspecies competition and overall decreased plant vigor. The adverse effects of ozone on areas with sensitive species could potentially lead to species shifts and loss from the affected ecosystems,[1749] resulting in a loss or reduction in associated ecosystem goods and services.[1750] Additionally, visible ozone injury to leaves can result in a loss of aesthetic value in areas of special scenic significance like national parks and wilderness areas and reduced use of sensitive ornamentals in landscaping.[1751] In addition to ozone effects on vegetation, newer evidence

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1744 73 FR 16486 (March 27, 2008).

[1745] Only a small percentage of all the plant species growing within the U.S. (over 43,000 species have been catalogued in the USDA PLANTS database) have been studied with respect to ozone sensitivity.

[1746] U.S. EPA. Integrated Science Assessment (ISA) for Ozone and Related Photochemical Oxidants (Final Report). U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-20/012, 2020.

[1747] The concentration at which ozone levels overwhelm a plant's ability to detoxify or compensate for oxidant exposure varies. Thus, whether a plant is classified as sensitive or tolerant depends in part on the exposure levels being considered.

[1748] 73 FR 16492 (March 27, 2008).

[1749] Per footnote above, ozone impacts could be occurring in areas where plant species sensitive to ozone have not yet been studied or identified.

[1750] 73 FR 16493-16494 (March 27, 2008).

[1751] 73 FR 16490/ 16497 (March 27, 2008).

suggests that ozone affects interactions between plants and insects by altering chemical signals (e.g., floral scents) that plants use to communicate to other community members, such as attraction of pollinators.

The most recent Ozone Integrated Science Assessment (ISA) presents more detailed information on how ozone affects vegetation and ecosystems.[1752] The Ozone ISA reports causal and likely causal relationships between ozone exposure and a number of welfare effects and characterizes the weight of evidence for different effects associated with ozone.[1753] The Ozone ISA concludes that visible foliar injury effects on vegetation, reduced vegetation growth, reduced plant reproduction, reduced productivity in terrestrial ecosystems, reduced yield and quality of agricultural crops, alteration of below-ground biogeochemical cycles, and altered terrestrial community composition are causally associated with exposure to ozone. It also concludes that increased tree mortality, altered herbivore growth and reproduction, altered plant-insect signaling, reduced carbon sequestration in terrestrial ecosystems, and alteration of terrestrial ecosystem water cycling are likely to be causally associated with exposure to ozone.

5.5.3 Deposition

The most recent Integrated Science Assessment for Oxides of Nitrogen, Oxides of Sulfur, and Particulate Matter - Ecological Criteria documents the ecological effects of the deposition of these criteria air pollutants.[1754] It is clear from the body of evidence that oxides of nitrogen, oxides of sulfur, and particulate matter contribute to total nitrogen (N) and sulfur (S) deposition. In turn, N and S deposition cause either nutrient enrichment or acidification depending on the sensitivity of the landscape or the biological species in question. Both enrichment and acidification are characterized by an alteration of the biogeochemistry and the physiology of organisms, resulting in ecologically harmful declines in biodiversity in terrestrial, freshwater, wetland, and estuarine ecosystems in the U.S. Decreases in biodiversity mean that some species become relatively less abundant and may be locally extirpated. In addition to the potential loss of unique living species, the decline in total biodiversity can be harmful because biodiversity is an important determinant of the stability of ecosystems and their ability to provide socially valuable ecosystem services.

Terrestrial, wetland, freshwater, and estuarine ecosystems in the U.S. are affected by nitrogen enrichment/eutrophication caused by nitrogen deposition. These effects, though improving recently as emissions and deposition decline, have been consistently documented across the U.S. for hundreds of species and have likely been occurring for decades. In terrestrial systems nitrogen loading can lead to loss of nitrogen-sensitive plant and lichen species, decreased biodiversity of grasslands, meadows and other sensitive habitats, and increased potential for invasive species and potentially for wildfire. In aquatic systems nitrogen loading can alter species assemblages and cause eutrophication. The sensitivity of terrestrial and aquatic

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[1752] U.S. EPA. Integrated Science Assessment (ISA) for Ozone and Related Photochemical Oxidants (Final Report). U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-20/012, 2020.

[1753] The Ozone ISA evaluates the evidence associated with different ozone related health and welfare effects, assigning one of five "weight of evidence" determinations: causal relationship, likely to be a causal relationship, suggestive of a causal relationship, inadequate to infer a causal relationship, and not likely to be a causal relationship. For more information on these levels of evidence, please refer to Table II of the ISA.

[1754] U.S. EPA. Integrated Science Assessment (ISA) for Oxides of Nitrogen, Oxides of Sulfur and Particulate Matter Ecological Criteria (Final Report). U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-20/278, 2020.

ecosystems to acidification from nitrogen and sulfur deposition is predominantly governed by the intersection of geology and deposition. Prolonged exposure to excess nitrogen and sulfur deposition in sensitive areas acidifies lakes, rivers, and soils. Increased acidity in surface waters creates inhospitable conditions for biota and affects the abundance and biodiversity of fishes, zooplankton and macroinvertebrates and ecosystem function. Over time, acidifying deposition also removes essential nutrients from forest soils, depleting the capacity of soils to neutralize future acid loadings and negatively affecting forest sustainability. Major effects in forests include a decline in sensitive tree species, such as red spruce (Picea rubens) and sugar maple (Acer saccharum).

Building materials including metals, stones, cements, and paints undergo natural weathering processes from exposure to environmental elements (e.g., wind, moisture, temperature fluctuations, sunlight, etc.). Pollution can worsen and accelerate these effects. Deposition of PM is associated with both physical damage (materials damage effects) and impaired aesthetic qualities (soiling effects). Wet and dry deposition of PM can physically affect materials, adding to the effects of natural weathering processes, by potentially promoting or accelerating the corrosion of metals, by degrading paints and by deteriorating building materials such as stone, concrete and marble.[1755] The effects of PM are exacerbated by the presence of acidic gases and can be additive or synergistic due to the complex mixture of pollutants in the air and surface characteristics of the material. Acidic deposition has been shown to have an effect on materials including zinc/galvanized steel and other metal, carbonate stone (as monuments and building facings), and surface coatings (paints).[1756] The effects on historic buildings and outdoor works of art are of particular concern because of the uniqueness and irreplaceability of many of these objects. In addition to aesthetic and functional effects on metals, stone and glass, altered energy efficiency of photovoltaic panels by PM deposition is also an emerging consideration for impacts of air pollutants on materials.

5.5.4 Welfare Effects of Air Toxics

Emissions from producing, transporting, and combusting fuel contribute to ambient levels of pollutants that contribute to adverse effects on vegetation. Volatile organic compounds (VOCs), some of which are considered air toxics, have long been suspected to play a role in vegetation damage.[1757] In laboratory experiments, a wide range of tolerance to VOCs has been observed.[1758] Decreases in harvested seed pod weight have been reported for the more sensitive plants, and some studies have reported effects on seed germination, flowering, and fruit ripening. Effects of individual VOCs or their role in conjunction with other stressors (e.g., acidification, drought, temperature extremes) have not been well studied. In a recent study of a mixture of VOCs including ethanol and toluene on herbaceous plants, significant effects on seed production, leaf water content, and photosynthetic efficiency were reported for some plant species.[1759]

[1755] U.S. EPA. Integrated Science Assessment (ISA) for Particulate Matter (Final Report, 2019). U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-19/188, 2019.

[1756] Irving, P.M., e.d. 1991. Acid Deposition: State of Science and Technology, Volume III, Terrestrial, Materials, Health, and Visibility Effects, The U.S. National Acid Precipitation Assessment Program, Chapter 24, page 24–76.

[1757] U.S. EPA. (1991). Effects of organic chemicals in the atmosphere on terrestrial plants. EPA/600/3-91/001.

[1758] Cape JN, ID Leith, J Binnie, J Content, M Donkin, M Skewes, DN Price AR Brown, AD Sharpe. (2003). Effects of VOCs on herbaceous plants in an open-top chamber experiment. Environ. Pollut. 124:341-343.

[1759] Cape JN, ID Leith, J Binnie, J Content, M Donkin, M Skewes, DN Price AR Brown, AD Sharpe. (2003). Effects of VOCs on herbaceous plants in an open-top chamber experiment. Environ. Pollut. 124:341-343.

Research suggests an adverse impact of vehicle exhaust on plants, which has in some cases been attributed to aromatic compounds and in other cases to nitrogen oxides.[1760,1761,1762] The impacts of VOCs on plant reproduction may have long-term implications for biodiversity and survival of native species near major roadways. Most of the studies of the impacts of VOCs on vegetation have focused on short-term exposure, and few studies have focused on long-term effects of VOCs on vegetation and the potential for metabolites of these compounds to affect herbivores or insects.

5.6 Environmental Justice

5.6.1 Overview

Communities with environmental justice concerns, which can include a range of communities and populations, face relatively greater cumulative impacts associated with environmental exposures of multiple types, as well as impacts from non-chemical stressors. Numerous studies have found that environmental hazards such as air pollution are more prevalent in areas where people of color and low-income populations represent a higher fraction of the population compared with the general population.[1763,1764,1765,1766] As described in Chapter 5.4.8, there is some literature to suggest that different sociodemographic factors may increase susceptibility to the effects of traffic-associated air pollution. In addition, compared to non-Hispanic Whites, some other racial groups experience greater levels of health problems during some life stages. For example, in 2018-2020, about 12 percent of non-Hispanic Black; 9 percent of non-Hispanic American Indian/Alaska Native; and 7 percent of Hispanic children were estimated to currently have asthma, compared with 6 percent of non-Hispanic White children.[1767] Nationally, on average, non-Hispanic Black and non-Hispanic American Indian or Alaska Native people also have lower than average life expectancy based on 2019 data.[1768]

EPA's 2016 "Technical Guidance for Assessing Environmental Justice in Regulatory Analysis" provides recommendations on conducting the highest quality analysis feasible of environmental justice (EJ) issues associated with a given regulatory decision, though it is not prescriptive, recognizing that data limitations, time and resource constraints, and analytic

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[1760] Viskari E-L. (2000). Epicuticular wax of Norway spruce needles as indicator of traffic pollutant deposition. Water, Air, and Soil Pollut. 121:327-337.

[1761] Ugrekhelidze D, F Korte, G Kvesitadze. (1997). Uptake and transformation of benzene and toluene by plant leaves. Ecotox. Environ. Safety 37:24-29.

[1762] Kammerbauer H, H Selinger, R Rommelt, A Ziegler-Jons, D Knoppik, B Hock. (1987). Toxic components of motor vehicle emissions for the spruce Picea abies. Environ. Pollut. 48:235-243.

[1763] Rowangould, G.M. (2013) A census of the near-roadway population: public health and environmental justice considerations. Trans Res D 25: 59-67. http://dx.doi.org/10.1016/j.trd.2013.08.003.

[1764] Marshall, J.D. (2000) Environmental inequality: Air pollution exposures in California's South Coast Air Basin. Atmos Environ 21: 5499– 5503. https://doi.org/10.1016/ j.atmosenv.2008.02.005.

[1765] Marshall, J.D. (2008) Environmental inequality: air pollution exposures in California's South Coast Air Basin. Atmos Environ 21: 5499-5503. *https://doi.org/10.1016/j.atmosenv.2008.02.005*.

[1766] Mohai, P.; Pellow, D.; Roberts Timmons, J. (2009) Environmental justice. Annual Reviews 34: 405–430. https://doi.org/10.1146/annurev-environ082508-094348.

[1767] Current Asthma Prevalence by Race and Ethnicity (2018–2020).
[Online at https://www.cdc.gov/asthma/most_recent_national_asthma_data.htm.]

[1768] Arias, E. Xu, J. (2022) United States Life Tables, 2019. National Vital Statistics Report, Volume 70, Number 19. [Online at https://www.cdc.gov/nchs/data/nvsr/nvsr70/nvsr70-19.pdf].]

challenges will vary by media and regulatory context.[1769] Where applicable and practicable, the Agency endeavors to conduct such an EJ analysis. There is evidence that communities with EJ concerns are disproportionately and adversely impacted by heavy-duty vehicle emissions.[1770]

In Chapter 5.6.2, we discuss the EJ impacts of this final rule's GHG emission standards from the anticipated reduction of GHGs. We also discuss in Chapter 5.6.3 the potential additional EJ impacts from the non-GHG (criteria pollutant and air toxic) emissions changes we estimate would result from compliance with the CO_2 emission standards, including impacts near roadways and from upstream sources. EPA did not consider potential adverse disproportionate impacts of vehicle emissions in selecting the CO_2 emission standards, but we provide information about adverse impacts of vehicle emissions for the public's understanding of this rulemaking, which addresses the need to protect public health consistent with CAA section 202(a)(1)-(2). When assessing the potential for disproportionate and adverse health or environmental impacts of regulatory actions on populations with potential EJ concerns, EPA strives to answer the following three broad questions, for purposes of the EJ analysis. (1) Is there evidence of potential EJ concerns in the baseline (the state of the world absent the regulatory action)? Assessing the baseline will allow EPA to determine whether pre-existing disparities are associated with the pollutant(s) under consideration (e.g., if the effects of the pollutant(s) are more concentrated in some population groups); (2) Is there evidence of potential EJ concerns for the regulatory option(s) under consideration? Specifically, how are the pollutant(s) and its effects distributed for the regulatory options under consideration?; and (3) Do the regulatory option(s) under consideration exacerbate or mitigate EJ concerns relative to the baseline? It is not always possible to provide quantitative answers to these questions.

EPA received several comments related to the environmental justice impacts of heavy-duty vehicles in general and the impacts of the proposal specifically. We summarize and respond to those comments in Section 18 of the Response to Comments document that accompanies this rulemaking. After consideration of comments, EPA updated our review of the literature, while maintaining our general approach to the environmental justice analysis. We note that analyses in this section are based on data that was the most appropriate recent data at the time we undertook the analyses. We intend to continue analyzing data concerning disproportionate impacts of pollution in the future, using the latest available data.

5.6.2 GHG Impacts on Environmental Justice and Vulnerable or Overburdened Populations

In the 2009 Endangerment Finding, the Administrator considered how climate change threatens the health and welfare of the U.S. population. As part of that consideration, she also considered risks to people of color and low-income individuals and communities, finding that certain parts of the U.S. population may be especially vulnerable based on their characteristics or circumstances. These groups include economically and socially disadvantaged communities; individuals at vulnerable life stages, such as the elderly, the very young, and pregnant or nursing women; those already in poor health or with comorbidities; the disabled; those experiencing

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[1769] "Technical Guidance for Assessing Environmental Justice in Regulatory Analysis." Epa.gov, Environmental Protection Agency, https://www.epa.gov/sites/production/files/2016-06/documents/ejtg_5_6_16_v5.1.pdf. (June 2016).

[1770] Demetillo, M.A.; Harkins, C.; McDonald, B.C.; et al. (2021) Space-based observational constraints on NO_2 air pollution inequality from diesel traffic in major US cities. Geophys Res Lett 48, e2021GL094333.

homelessness, mental illness, or substance abuse; and Indigenous or other populations dependent on one or limited resources for subsistence due to factors including but not limited to geography, access, and mobility.

Scientific assessment reports produced over the past decade by the USGCRP,[1771] [1772] the IPCC,[1773] [1774] [1775] [1776] the National Academies of Science, Engineering, and Medicine,[1777] [1778] and the EPA[1779] add more evidence that the impacts of climate change raise potential EJ concerns. These reports conclude that less-affluent, traditionally marginalized and predominantly non-White communities can be especially vulnerable to climate change impacts because they tend to have limited resources for adaptation, are more dependent on climate-sensitive resources such as local water and food supplies or have less access to social and information resources. Some communities of color, specifically populations defined jointly by ethnic/racial characteristics and geographic location (e.g., African-American, Black, and Hispanic/Latino

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[1771] USGCRP, 2018: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II* [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, 1515 pp. doi:10.7930/NCA4.2018.

[1772] USGCRP, 2016: *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment*. Crimmins, A., J. Balbus, J.L. Gamble, C.B. Beard, J.E. Bell, D. Dodgen, R.J. Eisen, N. Fann, M.D. Hawkins, S.C. Herring, L. Jantarasami, D.M. Mills, S. Saha, M.C. Sarofim, J. Trtanj, and L. Ziska, Eds. U.S. Global Change Research Program, Washington, DC, 312 pp. *https://health2016.globalchange.gov/*.

[1773] Oppenheimer, M., M. Campos, R. Warren, J. Birkmann, G. Luber, B. O'Neill, and K. Takahashi, 2014: *Emergent risks and key vulnerabilities*. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1039–1099.

[1774] Porter, J.R., L. Xie, A.J. Challinor, K. Cochrane, S.M. Howden, M.M. Iqbal, D.B. Lobell, and M.I. Travasso, 2014: *Food security and food production systems. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 485–533.

[1775] Smith, K.R., A. Woodward, D. Campbell-Lendrum, D.D. Chadee, Y. Honda, Q. Liu, J.M. Olwoch, B. Revich, and R. Sauerborn, 2014: Human health: impacts, adaptation, and co-benefits. In: Climate Change 2014: *Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 709–754.

[1776] IPCC, 2018: Global Warming of 1.5 °C. An IPCC Special Report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. In Press.

[1777] National Research Council. 2011. *America's Climate Choices*. Washington, DC: The National Academies Press. *https://doi.org/10.17226/12781*.

[1778] National Academies of Sciences, Engineering, and Medicine. 2017. *Communities in Action: Pathways to Health Equity*. Washington, DC: The National Academies Press. *https://doi.org/10.17226/24624*.

[1779] EPA. 2021. Climate Change and Social Vulnerability in the United States: A Focus on Six Impacts. U.S. Environmental Protection Agency, EPA 430-R-21-003.

communities; Native Americans, particularly those living on tribal lands and Alaska Natives), may be uniquely vulnerable to climate change health impacts in the U.S., as discussed below. In particular, the 2016 scientific assessment on the *Impacts of Climate Change on Human Health*[1780] found with high confidence that vulnerabilities are place- and time-specific, lifestages and ages are linked to immediate and future health impacts, and social determinants of health are linked to greater extent and severity of climate change-related health impacts. The GHG emission reductions from this final rule would contribute to efforts to reduce the probability of severe impacts related to climate change.

5.6.2.1 Effects on Specific Communities and Populations

Per the Fourth National Climate Assessment (NCA4), “Climate change affects human health by altering exposures to heat waves, floods, droughts, and other extreme events; vector-, food- and waterborne infectious diseases; changes in the quality and safety of air, food, and water; and stresses to mental health and well-being.”[1781] Many health conditions such as cardiopulmonary or respiratory illness and other health impacts are associated with and exacerbated by an increase in GHGs and climate change outcomes, which is problematic as these diseases occur at higher rates within vulnerable communities. Importantly, negative public health outcomes include those that are physical in nature, as well as mental, emotional, social, and economic.

The scientific assessment literature, including the aforementioned reports, demonstrates that there are myriad ways in which particular communities and populations may be affected at the individual and community levels. Individuals face differential exposure to criteria pollutants, in part due to the proximities of highways, trains, factories, and other major sources of pollutant-emitting sources to less-affluent residential areas. Outdoor workers, such as construction or utility crews and agricultural laborers, who frequently are comprised of already at-risk groups, are exposed to poor air quality and extreme temperatures without relief. Furthermore, people in communities with EJ concerns face greater housing, clean water, and food insecurity and bear disproportionate and adverse economic impacts and health burdens associated with climate change effects. They have less or limited access to healthcare and affordable, adequate health or homeowner insurance.[1782] Finally, resiliency and adaptation are more difficult for economically vulnerable communities; these communities have less liquidity, individually and collectively, to move or to make the types of infrastructure or policy changes to limit or reduce the hazards they face. They frequently are less able to self-advocate for resources that would otherwise aid in building resilience and hazard reduction and mitigation.

The assessment literature cited in EPA’s 2009 and 2016 Endangerment and Cause or Contribute Findings, as well as *Impacts of Climate Change on Human Health*, also concluded that certain populations and life stages, including children, are most vulnerable to climate-related

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[1780] USGCRP, 2016: *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment*.

[1781] Ebi, K.L., J.M. Balbus, G. Luber, A. Bole, A. Crimmins, G. Glass, S. Saha, M.M. Shimamoto, J. Trtanj, and J.L. White-Newsome, 2018: Human Health. In Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 539–571. doi: 10.7930/NCA4.2018.CH14.

[1782] USGCRP, 2016: *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment*.

health effects.[1783] The assessment literature produced from 2016 to the present strengthens these conclusions by providing more detailed findings regarding related vulnerabilities and the projected impacts youth may experience. These assessments – including the NCA4 and *The Impacts of Climate Change on Human Health in the United States* (2016) – describe how children's unique physiological and developmental factors contribute to making them particularly vulnerable to climate change. Impacts to children are expected from heat waves, air pollution, infectious and waterborne illnesses, and mental health effects resulting from extreme weather events. In addition, children are among those especially susceptible to allergens, as well as health effects associated with heat waves, storms, and floods. Additional health concerns may arise in low-income households, especially those with children, if climate change reduces food availability and increases prices, leading to food insecurity within households. More generally, these reports note that extreme weather and flooding can cause or exacerbate poor health outcomes by affecting mental health because of stress; contributing to or worsening existing conditions, again due to stress or also as a consequence of exposures to water and air pollutants; or by impacting hospital and emergency services operations.[1784] Further, in urban areas in particular, flooding can have significant economic consequences due to effects on infrastructure, pollutant exposures, and drowning dangers. The ability to withstand and recover from flooding is dependent in part on the social vulnerability of the affected population and individuals experiencing an event.[1785] In addition, children are among those especially susceptible to allergens, as well as health effects associated with heat waves, storms, and floods. Additional health concerns may arise in low-income households, especially those with children, if climate change reduces food availability and increases prices, leading to food insecurity within households.

The Impacts of Climate Change on Human Health[1786] also found that some communities of color, low-income groups, people with limited English proficiency, and certain immigrant groups (especially those who are undocumented) are subject to many factors that contribute to vulnerability to the health impacts of climate change. While difficult to isolate from related socioeconomic factors, race appears to be an important factor in vulnerability to climate-related stress, with elevated risks for mortality from high temperatures reported for Black or African American individuals compared to White individuals after controlling for factors such as air conditioning use. Moreover, people of color are disproportionately more exposed to air pollution based on where they live, and disproportionately vulnerable due to higher baseline prevalence of underlying diseases such as asthma. As explained earlier, climate change can exacerbate local air pollution conditions so this increase in air pollution is expected to have disproportionate and adverse effects on these communities. Locations with greater health threats include urban areas

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[1783] 74 FR 66496, December 15, 2009; 81 FR 54422, August 15, 2016.

[1784] Ebi, K.L., J.M. Balbus, G. Luber, A. Bole, A. Crimmins, G. Glass, S. Saha, M.M. Shimamoto, J. Trtanj, and J.L. White-Newsome, 2018: Human Health. In Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 539–571. doi:10.7930/NCA4.2018.CH14.

[1785] National Academies of Sciences, Engineering, and Medicine 2019. Framing the Challenge of Urban Flooding in the United States. Washington, DC: The National Academies Press. *https://doi.org/10.17226/25381*.

[1786] USGCRP, 2016: The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment. Crimmins, A., J. Balbus, J.L. Gamble, C.B. Beard, J.E. Bell, D. Dodgen, R.J. Eisen, N. Fann, M.D. Hawkins, S.C. Herring, L. Jantarasami, D.M. Mills, S. Saha, M.C. Sarofim, J. Trtanj, and L. Ziska, Eds. U.S. Global Change Research Program, Washington, DC, 312 pp. *http://dx.doi.org/10.7930/J0R49NQX*.

(due to, among other factors, the "heat island" effect where built infrastructure and lack of green spaces increases local temperatures), areas where airborne allergens and other air pollutants already occur at higher levels, and communities experienced depleted water supplies or vulnerable energy and transportation infrastructure.

The recent EPA report on climate change and social vulnerability[1787] examined four socially vulnerable groups (individuals who are low income, minority, without high school diplomas, and/or 65 years and older) and their exposure to several different climate impacts (air quality, coastal flooding, extreme temperatures, and inland flooding). This report found that Black and African-American individuals were 40 percent more likely to currently live in areas with the highest projected increases in mortality rates due to climate-driven changes in extreme temperatures, and 34 percent more likely to live in areas with the highest projected increases in childhood asthma diagnoses due to climate-driven changes in particulate air pollution. The report found that Hispanic and Latino individuals are 43 percent more likely to live in areas with the highest projected labor hour losses in weather-exposed industries due to climate-driven warming, and 50 percent more likely to live in coastal areas with the highest projected increases in traffic delays due to increases in high-tide flooding. The report found that American Indian and Alaska Native individuals are 48 percent more likely to live in areas where the highest percentage of land is projected to be inundated due to sea level rise, and 37 percent more likely to live in areas with high projected labor hour losses. Asian individuals were found to be 23 percent more likely to live in coastal areas with projected increases in traffic delays from high-tide flooding. Persons with low income or no high school diploma are about 25 percent more likely to live in areas with high projected losses of labor hours, and 15 percent more likely to live in areas with the highest projected increases in asthma due to climate-driven increases in particulate air pollution, and in areas with high projected inundation due to sea level rise.

In a more recent 2023 report, *Climate Change Impacts on Children's Health and Well-Being in the U.S.,* the EPA considered the degree to which children's health and well-being may be impacted by five climate-related environmental hazards—extreme heat, poor air quality, changes in seasonality, flooding, and different types of infectious diseases [1788]. The report found that children's academic achievement is projected to be reduced by 4–7 percent per child, as a result of moderate and higher levels of warming, impacting future income levels. The report also projects increases in the numbers of annual emergency department visits associated with asthma, and that the number of new asthma diagnoses increases by 4–11 percent due to climate-driven increases in air pollution relative to current levels. In addition, more than 1 million children in coastal regions are projected to be temporarily displaced from their homes annually due to climate-driven flooding, and infectious disease rates are similarly anticipated to rise, with the number of new Lyme disease cases in children living in 22 states in the eastern and midwestern U.S. increasing by approximately 3,000–23,000 per year compared to current levels. Overall, the report confirmed findings of broader climate science assessments that children are uniquely vulnerable to climate-related impacts and that in many situations, children in the U.S. who identify as Black, Indigenous, and People of Color, are limited English-speaking, do not have

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[1787] EPA. 2021. Climate Change and Social Vulnerability in the United States: A Focus on Six Impacts. U.S. Environmental Protection Agency, EPA 430-R-21-003.

[1788] EPA. 2023. Climate Change Impacts on Children's Health and Well-Being in the U.S., EPA EPA 430-R-23-001 health insurance, or live in low-income communities may be disproportionately more exposed to the most severe adverse impacts of climate change.

Tribes and Indigenous communities face disproportionate and adverse risks from the impacts of climate change, particularly those communities impacted by degradation of natural and cultural resources within established reservation boundaries and threats to traditional subsistence lifestyles. Indigenous communities whose health, economic well-being, and cultural traditions depend upon the natural environment will likely be affected by the degradation of ecosystem goods and services associated with climate change. The IPCC indicates that losses of customs and historical knowledge may cause communities to be less resilient or adaptable.[1789] The NCA4 noted that while Tribes and Indigenous Peoples are diverse and will be impacted by the climate changes universal to all Americans, there are several ways in which climate change uniquely threatens Tribes and Indigenous Peoples' livelihoods and economies.[1790] In addition, as noted in the following paragraph, there can be institutional barriers (including policy-based limitations and restrictions) to their management of water, land, and other natural resources that could impede adaptive measures.

For example, Indigenous agriculture in the Southwest is already being adversely affected by changing patterns of flooding, drought, dust storms, and rising temperatures leading to increased soil erosion, irrigation water demand, and decreased crop quality and herd sizes. The Confederated Tribes of the Umatilla Indian Reservation in the Northwest have identified climate risks to salmon, elk, deer, roots, and huckleberry habitat. Housing and sanitary water supply infrastructure are vulnerable to disruption from extreme precipitation events Additionally, NCA4 noted that Tribes and Indigenous Peoples generally experience poor infrastructure, diminished access to quality healthcare, and greater risk of exposure to pollutants. Consequently, Native Americans often have disproportionately higher rates of asthma, cardiovascular disease, Alzheimer's disease, diabetes, and obesity. These health conditions and related effects (disorientation, heightened exposure to $PM_{2.5}$, *etc.*) can all contribute to increased vulnerability to climate-driven extreme heat and air pollution events, which also may be exacerbated by stressful situations, such as extreme weather events, wildfires, and other circumstances.

NCA4 and IPCC's Fifth Assessment Report[1791] also highlighted several impacts specific to Alaskan Indigenous Peoples. Coastal erosion and permafrost thaw will lead to more coastal erosion, rendering winter travel riskier and exacerbating damage to buildings, roads, and other infrastructure—impacts on archaeological sites, structures, and objects that will lead to a loss of cultural heritage for Alaska's Indigenous people. In terms of food security, the NCA4 discussed reductions in suitable ice conditions for hunting, warmer temperatures impairing the use of traditional ice cellars for food storage, and declining shellfish populations due to warming and acidification. While the NCA4 also noted that climate change provided more opportunity to hunt from boats later in the fall season or earlier in the spring, the assessment found that the net impact was an overall decrease in food security. In addition, the U.S. Pacific Islands and the

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[1789] Porter, *et al.*, 2014: Food security and food production systems.

[1790] Jantarasami, L.C., R. Novak, R. Delgado, E. Marino, S. McNeeley, C. Narducci, J. Raymond-Yakoubian, L. Singletary, and K. Powys Whyte, 2018: Tribes and Indigenous Peoples. In Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 572–603. doi:10.7930/NCA4. 2018. CH15.

[1791] Porter, *et al.*, 2014: Food security and food production systems.

Indigenous communities that live there are also uniquely vulnerable to the effects of climate change due to their remote location and geographic isolation. They rely on the land, ocean, and natural resources for their livelihoods, but they face challenges in obtaining energy and food supplies that need to be shipped in at high costs. As a result, they face higher energy costs than the rest of the nation and depend on imported fossil fuels for electricity generation and diesel. These challenges exacerbate the climate impacts that the Pacific Islands are experiencing. NCA4 notes that Tribes and Indigenous Peoples of the Pacific are threatened by rising sea levels, diminishing freshwater availability, and negative effects to ecosystem services that threaten these individuals' health and well-being.

5.6.3 Non-GHG Impacts

In Chapter 4.6., in addition to GHG emissions impacts, we also discuss potential additional emission changes of non-GHGs (i.e., criteria and air toxic pollutants) that we project from compliance with the final GHG emission standards. This Chapter 5.6.3 describes evidence that communities with EJ concerns are disproportionately and adversely impacted by relevant non-GHG emissions. We discuss the potential impact of non-GHG emissions for two specific contexts: near-roadway (5.6.3.1) and upstream sources (5.6.3.2).

5.6.3.1 Near Roadway Analysis

As described in Chapter 5.4.8 of this RIA, concentrations of many air pollutants are elevated near high-traffic roadways. We recently conducted an analysis of the populations within the CONUS living in close proximity to truck freight routes as identified in USDOT's FAF4.[1792] FAF4 is a model from the USDOT's Bureau of Transportation Statistics and Federal Highway Administration, which provides data associated with freight movement in the United States.[1793] Relative to the rest of the population, people living near FAF4 truck routes are more likely to be people of color and have lower incomes than the general population. People living near FAF4 truck routes are also more likely to live in metropolitan areas. Even controlling for region of the country, county characteristics, population density, and household structure, race, ethnicity, and income are significant determinants of whether someone lives near a FAF4 truck route.

We additionally analyzed other national databases that allowed us to evaluate whether homes and schools were located near a major road and whether disparities in exposure may be occurring in these environments. Until 2009, the U.S. Census Bureau's American Housing Survey (AHS) included descriptive statistics of over 70,000 housing units across the nation and asked about transportation infrastructure near respondents' homes every two years.[1794,1795] We also analyzed

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[1792] U.S. EPA (2021). Estimation of Population Size and Demographic Characteristics among People Living Near Truck Routes in the Conterminous United States. Memorandum to the Docket.

[1793] FAF4 includes data from the 2012 Commodity Flow Survey (CFS), the Census Bureau on international trade, as well as data associated with construction, agriculture, utilities, warehouses, and other industries. FAF4 estimates the modal choices for moving goods by trucks, trains, boats, and other types of freight modes. It includes traffic assignments, including truck flows on a network of truck routes. *https://ops.fhwa.dot.gov/freight/freight_analysis/faf/*.

[1794] U.S. Department of Housing and Urban Development, & U.S. Census Bureau. (n.d.). Age of other residential buildings within 300 feet. In American Housing Survey for the United States: 2009 (pp. A-1). Retrieved from *https://www.census.gov/programs-surveys/ahs/data/2009/ahs-2009-summary-tables0/h150-09.html*.

[1795] The 2013 AHS again included the "etrans" question about highways, airports, and railroads within half a block of the housing unit but has not maintained the question since then.

the U.S. Department of Education’s Common Core of Data, which includes enrollment and location information for schools across the United States.[1796]

In analyzing the 2009 AHS, we focused on whether a housing unit was located within 300 feet of a “4-or-more lane highway, railroad, or airport” (this distance was used in the AHS analysis).[1797] We analyzed whether there were differences between households in such locations compared with those in locations farther from these transportation facilities.[1798] We included other variables, such as land use category, region of country, and housing type. We found that homes with a non-White householder were 22-34 percent more likely to be located within 300 feet of these large transportation facilities than homes with White householders. Homes with a Hispanic householder were 17-33 percent more likely to be located within 300 feet of these large transportation facilities than homes with non-Hispanic householders. Households near large transportation facilities were, on average, lower in income and educational attainment and more likely to be a rental property and located in an urban area compared with households more distant from transportation facilities.

In examining schools near major roadways, we used the Common Core of Data from the U.S. Department of Education, which includes information on all public elementary and secondary schools and school districts nationwide.[1799] To determine school proximities to major roadways, we used a geographic information system to map each school and roadways based on the U.S. Census’s TIGER roadway file.[1800] We estimated that about 10 million students attend schools within 200 meters of major roads, about 20 percent of the total number of public school students in the United States.[1801] About 800,000 students attend public schools within 200 meters of primary roads, or about 2 percent of the total. We found that students of color were overrepresented at schools within 200 meters of primary roadways, and schools within 200 meters of primary roadways had a disproportionate population of students eligible for free or reduced-price lunches.[1802] Black students represent 22 percent of students at schools located within 200 meters of a primary road, compared to 17 percent of students in all U.S. schools. Hispanic students represent 30 percent of students at schools located within 200 meters of a primary road, compared to 22 percent of students in all U.S. schools.

We also reviewed existing scholarly literature examining the potential for disproportionate exposure to these pollutants among people of color and people with low socioeconomic status

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[1796] *http://nces.ed.gov/ccd/*.

[1797] This variable primarily represents roadway proximity. According to the Central Intelligence Agency’s World Factbook, in 2010, the United States had 6,506,204 km of roadways, 224,792 km of railways, and 15,079 airports. Highways thus represent the overwhelming majority of transportation facilities described by this factor in the AHS.

[1798] Bailey, C. (2011) Demographic and Social Patterns in Housing Units Near Large Highways and other Transportation Sources. Memorandum to docket.

[1799] *http://nces.ed.gov/ccd/*.

[1800] Pedde, M.; Bailey, C. (2011) Identification of Schools within 200 Meters of U.S. Primary and Secondary Roads. Memorandum to the docket.

[1801] Here, "major roads" refer to those TIGER classifies as either "Primary" or "Secondary." The Census Bureau describes primary roads as "generally divided limited-access highways within the Federal interstate system or under state management." Secondary roads are "main arteries, usually in the U.S. highway, state highway, or county highway system."

[1802] For this analysis we analyzed a 200-meter distance based on the understanding that roadways generally influence air quality within a few hundred meters from the vicinity of heavily traveled roadways or along corridors with significant trucking traffic. See U.S. EPA, 2014. Near Roadway Air Pollution and Health: Frequently Asked Questions. EPA-420-F-14-044.

(SES). Numerous studies evaluating the demographics and socioeconomic status of populations or schools near roadways have found that they include a greater percentage of residents of color, as well as lower SES populations (as indicated by variables such as median household income). Locations in these studies include Los Angeles, CA; Seattle, WA; Wayne County, MI; Orange County, FL; Tampa, FL; the State of California; the State of Texas; and nationally.[1803,1804,1805,1806,1807,1808,1809,1810,1811,1812,1813,1814] Such disparities may be due to multiple

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[1803] Marshall, J.D. (2008) Environmental inequality: air pollution exposures in California's South Coast Air Basin. Atmos Environ 42: 5499-5503. doi:10.1016/j.atmosenv.2008.02.00

[1804] Su, J.G.; Larson, T.; Gould, T.; Cohen, M.; Buzzelli, M. (2010) Transboundary air pollution and environmental justice: Vancouver and Seattle compared. GeoJournal 57: 595-608. doi:10.1007/s10708-009-9269-6

[1805] Chakraborty, J.; Zandbergen, P.A. (2007) Children at risk: measuring racial/ethnic disparities in potential exposure to air pollution at school and home. J Epidemiol Community Health 61: 1074-1079. doi:10.1136/jech.2006.054130.

[1806] Green, R.S.; Smorodinsky, S.; Kim, J.J.; McLaughlin, R.; Ostro, B. (2004) Proximity of California public schools to busy roads. Environ Health Perspect 112: 61-66. doi:10.1289/ehp.6566

[1807] Wu, Y; Batterman, S.A. (2006) Proximity of schools in Detroit, Michigan to automobile and truck traffic. J Exposure Sci & Environ Epidemiol. doi:10.1038/sj.jes.7500484.

[1808] Su, J.G.; Jerrett, M.; de Nazelle, A.; Wolch, J. (2011) Does exposure to air pollution in urban parks have socioeconomic, racial, or ethnic gradients? Environ Res 111: 319-328.

[1809] Jones, M.R.; Diez-Roux, A.; Hajat, A.; et al. (2014) Race/ethnicity, residential segregation, and exposure to ambient air pollution: The Multi-Ethnic Study of Atherosclerosis (MESA). Am J Public Health 104: 2130-2137. [Online at: *https://doi.org/10.2105/AJPH.2014.302135*.].

[1810] Stuart A.L., Zeager M. (2011) An inequality study of ambient nitrogen dioxide and traffic levels near elementary schools in the Tampa area. Journal of Environmental Management. 92(8): 1923-1930. https://doi.org/10.1016/j.jenvman.2011.03.003.

[1811] Stuart A.L., Mudhasakul S., Sriwatanapongse W. (2009) The Social Distribution of Neighborhood-Scale Air Pollution and Monitoring Protection. Journal of the Air & Waste Management Association. 59(5): 591-602. https://doi.org/10.3155/1047-3289.59.5.591

[1812] Willis M.D., Hill E.L., Kile M.L., Carozza S., Hystad P. (2020) Assessing the effectiveness of vehicle emission regulations on improving perinatal health: a population-based accountability study. International Journal of Epidemiology. 49(6): 1781–1791. https://doi.org/10.1093/ije/dyaa137

[1813] Collins, T.W., Grineski, S.E., Nadybal, S. (2019) Social disparities in exposure to noise at public schools in the contiguous United States. Environ. Res. 175, 257–265. https://doi.org/10.1016/j.envres.2019.05.024.

[1814] Kingsley S., Eliot M., Carlson L., Finn J., MacIntosh D.L., Suh H.H., Wellenius G.A. (2014) Proximity of US schools to major roadways: a nationwide assessment. J Expo Sci Environ Epidemiol. 24: 253–259. https://doi.org/10.1038/jes.2014.5

factors, such as historic segregation, redlining, residential mobility, and daily mobility.[1815,1816,1817,1818,1819,1820]

Several publications report nationwide analyses that compare the demographic patterns of people who do or do not live near major roadways.[1821,1822,1823,1824,1825,1826] Three of these studies found that people living near major roadways are more likely to be people of color or of low SES.[1827,1828,1829] They also found that the outcomes of their analyses varied between regions within the United States. However, only one such study looked at whether such conclusions were confounded by living in a location with higher population density and looked at how demographics differ between locations nationwide.[1830] That study generally found that higher density areas have higher proportions of low-income residents and people of color. In other

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[1815] Depro, B.; Timmins, C. (2008) Mobility and environmental equity: do housing choices determine exposure to air pollution? Duke University Working Paper.

[1816] Rothstein, R. The Color of Law: A Forgotten History of How Our Government Segregated America. New York: Liveright, 2018.

[1817] Lane, H.J.; Morello-Frosch, R.; Marshall, J.D.; Apte, J.S. (2022) Historical redlining is associated with present-day air pollution disparities in US Cities. Environ Sci & Technol Letters 9: 345-350. DOI: [Online at: https://doi.org/10.1021/acs.estlett.1c01012].

[1818] Ware, L. (2021) Plessy's legacy: the government's role in the development and perpetuation of segregated neighborhoods. RSF: The Russel Sage Foundation Journal of the Social Sciences, 7:92-109. DOI: DOI: 10.7758/RSF.2021.7.1.06.

[1819] Archer, D.N. (2020) "White Men's Roads through Black Men's Homes": advancing racial equity through highway reconstruction. Vanderbilt Law Rev 73: 1259.

[1820] Park, Y.M.; Kwan, M.-P. (2020) Understanding Racial Disparities in Exposure to Traffic-Related Air Pollution: Considering the Spatiotemporal Dynamics of Population Distribution. Int. J. Environ. Res. Public Health. 17 (3): 908. https://doi.org/10.3390/ijerph17030908

[1821] Rowangould, G.M. (2013) A census of the U.S. near-roadway population: public health and environmental justice considerations. Transportation Research Part D; 59-67.

[1822] Tian, N.; Xue, J.; Barzyk. T.M. (2013) Evaluating socioeconomic and racial differences in traffic-related metrics in the United States using a GIS approach. J Exposure Sci Environ Epidemiol 23: 215-222.

[1823] CDC (2013) Residential proximity to major highways – United States, 2010. Morbidity and Mortality Weekly Report 62(3): 46-50.

[1824] Clark, L.P.; Millet, D.//B., Marshall, J.D. (2017) Changes in transportation-related air pollution exposures by race-ethnicity and socioeconomic status: outdoor nitrogen dioxide in the United States in 2000 and 2010. Environ Health Perspect *https://doi.org/10.1289/EHP959*.

[1825] Mikati, I.; Benson, A.F.; Luben, T.J.; Sacks, J.D.; Richmond-Bryant, J. (2018) Disparities in distribution of particulate matter emission sources by race and poverty status. Am J Pub Health *https://ajph.aphapublications.org/doi/abs/10.2105/AJPH.2017.304297?journalCode=ajph.*

[1826] Alotaibi, R.; Bechle, M.; Marshall, J.D.; Ramani, T.; Zietsman, J.; Nieuwenhuijsen, M.J.; Khreis, H. (2019) Traffic related air pollution and the burden of childhood asthma in the continuous United States in 2000 and 2010. Environ International 127: 858-867. *https://www.sciencedirect.com/science/article/pii/S0160412018325388*.

[1827] Tian, N.; Xue, J.; Barzyk. T.M. (2013) Evaluating socioeconomic and racial differences in traffic-related metrics in the United States using a GIS approach. J Exposure Sci Environ Epidemiol 23: 215-222.

[1828] Rowangould, G.M. (2013) A census of the U.S. near-roadway population: public health and environmental justice considerations. Transportation Research Part D; 59-67.

[1829] CDC (2013) Residential proximity to major highways – United States, 2010. Morbidity and Mortality Weekly Report 62(3): 46-50.

[1830] Rowangould, G.M. (2013) A census of the U.S. near-roadway population: public health and environmental justice considerations. Transportation Research Part D; 59-67.

publications assessing a city, county, or state, the results are similar.[1831,1832,1833] Furthermore, students of lower-income families and students with disabilities are more likely to travel to school by bus or public transit than are other students.[1834,1835,1836]

Two recent studies provide strong evidence that reducing emissions from heavy-duty vehicles is likely to reduce the disparity in exposures to traffic-related air pollutants. Both use NO_2 observations from the recently launched TROPospheric Ozone Monitoring Instrument satellite sensor as a measure of air quality, which provides high-resolution observations that heretofore were unavailable from any satellite.[1837]

One study evaluated NO_2 concentrations during the COVID-19 lockdowns in 2020 and compared them to NO_2 concentrations from the same dates in 2019.[1838] That study found that average NO_2 concentrations were highest in areas with the lowest percentage of White populations, and that the areas with the greatest percentages of non-White or Hispanic populations experienced the greatest declines in NO_2 concentrations during the lockdown. These NO_2 reductions were associated with the density of highways in the local area.

In the second study, NO_2 measured from 2018-2020 was averaged by racial groups and income levels in 52 large U.S. cities.[1839] Using census tract-level NO_2, the study reported average population-weighted NO_2 levels to be 28 percent higher for low-income non-White people compared with high-income White people. The study also used weekday-weekend differences and bottom-up emission estimates to estimate that diesel traffic is the dominant source of NO_2 disparities in the studied cities.

Overall, there is substantial evidence that people who live or attend school near major roadways are more likely to be of a non-White race, Hispanic, and/or have a low SES. As described in Chapter 5.4.8, traffic-related air pollution may have disproportionate and adverse impacts on health across racial and sociodemographic groups. We expect communities near roads will benefit from the reduced vehicle emissions of PM, NOx, SO_2, VOC, CO, and mobile

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[1831] Pratt, G.C.; Vadali, M.L.; Kvale, D.L.; Ellickson, K.M. (2015) Traffic, air pollution, minority, and socio-economic status: addressing inequities in exposure and risk. Int J Environ Res Public Health 12: 5355-5372. *http://dx.doi.org/10.3390/ijerph120505355*.

[1832] Sohrabi, S.; Zietsman, J.; Khreis, H. (2020) Burden of disease assessment of ambient air pollution and premature mortality in urban areas: the role of socioeconomic status and transportation. Int J Env Res Public Health doi:10.3390/ijerph17041166.

[1833] Aizer A., Currie J. (2019) Lead and Juvenile Delinquency: New Evidence from Linked Birth, School, and Juvenile Detention Records. The Review of Economics and Statistics. 101 (4): 575–587. https://doi.org/10.1162/rest_a_00814

[1834] Bureau of Transportation Statistics (2021) The Longer Route to School. [Online at https://www.bts.gov/topics/passenger-travel/back-school-2019]

[1835] Wheeler, K.; Yang, Y.; Xiang, H. (2009) Transportation use patterns of U.S. children and teenagers with disabilities. Disability and Health J 2: 158-164. https://doi.org/10.1016/j.dhjo.2009.03.003

[1836] Park, K.; Esfahani, H.N.; Novack, V.L.; et al. (2022) Impacts of disability on daily travel behaviour: A systematic review. Transport Reviews 43: 178-203. https://doi.org/10.1080/01441647.2022.2060371

[1837] TROPospheric Ozone Monitoring Instrument (TROPOMI) is part of the Copernicus Sentinel-5 Precursor satellite.

[1838] Kerr, G.H.; Goldberg, D.L.; Anenberg, S.C. (2021) COVID-19 pandemic reveals persistent disparities in nitrogen dioxide pollution. PNAS 118. *https://doi.org/10.1073/pnas.2022409118*.

[1839] Demetillo, M.A.; Harkins, C.; McDonald, B.C.; et al. (2021) Space-based observational constraints on NO2 air pollution inequality from diesel traffic in major US cities. Geophys Res Lett 48, e2021GL094333. *https://doi.org/10.1029/2021GL094333*.

source air toxics projected to result from this final rule. Although we were not able to conduct air quality modeling of the estimated emission reductions, we believe it a fair inference that because vehicular emissions disproportionately and adversely affect these communities with environmental justice concerns due to roadway proximity, and because we project this rule will result in significant reductions in vehicular emissions, these communities' exposures to non-GHG air pollutants will be reduced. EPA is considering how to better estimate the near-roadway air quality impacts of its regulatory actions and how those impacts are distributed across populations.

5.6.3.2 Upstream Source Impacts

As described in Chapter 4.5. of the RIA, we expect some non-GHG emissions reductions from sources related to refining petroleum fuels and increases in emissions from EGUs, both of which would lead to changes in exposure for people living in communities near these facilities. The EGU emissions increases become smaller over time because of changes in the projected power generation mix as electricity generation uses less fossil fuels.

Analyses of communities in close proximity to EGUs have found that a higher percentage of communities of color and low-income communities live near these sources when compared to national averages.[1840] EPA compared the percentages of people of color and low-income populations living within three miles of fossil fuel-fired power plants regulated under EPA's Acid Rain Program and/or EPA's Cross-State Air Pollution Rule to the national average and found that there is a greater percentage of people of color and low-income individuals living near these power plants than in the rest of the country on average. According to 2020 census data, on average, the U.S. population is comprised of 40 percent people of color and 30 percent low-income individuals. In contrast, the population living near fossil fuel-fired power plants is comprised of 53 percent people of color and 34 percent low-income individuals.[1841] Historically redlined neighborhoods are more likely to be downwind of fossil fuel power plants and to experience higher levels of exposure to relevant emissions than non-redlined neighborhoods.[1842] Analysis of populations near refineries and oil and gas wells also indicates there may be potential disparities in pollution-related health risk from these sources.[1843,1844,1845,1846] See also Chapter 4 of this RIA, discussing issues pertaining to lifecycle emissions more generally.

[1840] See 80 FR 64662, 64915–64916 (October 23, 2015).

[1841] U.S. EPA (2023) 2021 Power Sector Programs - Progress Report. *https://www3.epa.gov/airmarkets/progress/reports/*

[1842] Cushing L.J., Li S., Steiger B.B., Casey J.A. (2023) Historical red-lining is associated with fossil fuel power plant siting and present-day inequalities in air pollutant emissions. Nature Energy. 8: 52–61. https://doi.org/10.1038/s41560-022-01162-y

[1843] U.S. EPA (2014). Risk and Technology Review—Analysis of Socio-Economic Factors for Populations Living Near Petroleum Refineries. Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina. January.

[1844] Carpenter, A., and M. Wagner. Environmental justice in the oil refinery industry: A panel analysis across United States counties. J. Ecol. Econ. V. 159 (2019).

[1845] Gonzalez, J.X., et al. Historic redlining and the siting of oil and gas wells in the United States. J. Exp. Sci. & Env. Epi. V. 33. (2023). p. 76-83.

[1846] In comparison to the national population, the EPA publication reports higher proportions of the following population groups in block groups with higher cancer risk associated with emissions from refineries: "minority," "African American," "Other and Multiracial," "Hispanic or Latino," "Ages 0-17," "Ages 18-64," "Below the Poverty Level," "Over 25 years old without a HS diploma," and "Linguistic isolations."

Chapter 6 Economic and Other Impacts

This chapter discusses potential impacts of the final rule on HD vehicle sales including potential impacts on vehicles sales, and potential shifts among modes and classes of vehicles, and between domestic and foreign sales, under the modeled potential compliance pathway. It also discusses the acceptance of ZEVs by HD purchasers and the potential for rebound effects on VMT. This chapter then discusses the potential impacts of the rule on employment. Finally, this chapter discusses the impacts of the rule on U.S. oil imports and electricity consumption.

6.1 Impact on Sales, Fleet Turnover, Mode Shift, Class Shift, and Domestic Production

6.1.1 Vehicle Sales and Fleet Turnover

The effects of the CO_2 emission standards under the modeled potential compliance pathway on HD vehicle sales will depend, at least in part, on the extent to which purchasers consider fuel, maintenance, and repair savings associated with the HD GHG Phase 3 program in their purchase decisions. Our analyses for the modeled potential compliance pathway indicate that, while some heavy-duty ZEVs and associated EVSE, as applicable, will be more expensive to purchase than comparable ICE vehicles, ZEVs will be less expensive to operate and maintain than comparable ICE vehicles. The more these savings are considered, the smaller the impact on sales due to an increase in the price of the vehicle. In addition, if the savings considered by a purchaser outweigh the increase in the price of the vehicle and EVSE, which we show is possible with most ZEVs (see RIA Chapter 2.9.4.2), sales of that vehicle may increase.

In addition to effects on total sales of HD vehicles, perceptions about post-regulation vehicles and cost differences between pre- and post-regulation vehicles (both upfront and operational costs) have the potential to lead to an increase in the sale of ICE vehicles before the standards become effective in order to avoid perceived potential cost, quality, or other changes due to the regulation, a phenomenon called “pre-buy.” These are vehicles that are purchased earlier than would have happened in the absence of the standards. Another reason pre-buy might occur is due to purchaser beliefs about the availability of their vehicle type of choice in the post-regulation market. For example, if purchasers think that they might not be able to get the HD ICE vehicle they want after the regulation is promulgated, they may pre-buy a HD ICE vehicle.[1847]

Our assessment, with respect to ZEV technologies included in our potential compliance pathway, is that purchasers’ consideration of the lower operational costs of ZEVs, as well as the federal vehicle and battery tax credits, and EVSE tax credits for those purchasers eligible for them, will mitigate possible pre-buy by reducing the perceived purchase price or lifetime operational costs difference of a new, post-rule ZEV compared to a new pre- or post-rule comparable ICE vehicle. We also expect that the final rule’s more gradual phase-in of more stringent standards compared to the proposal will mitigate possible pre-buy. Additionally, pre-buy, to the extent it might occur, could be mitigated in multiple other ways, including by reducing the higher upfront cost of post-regulation vehicles, or by reducing uncertainty about new technology through purchasers being educated on the new technology, or increasing

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[1847] We note that the HD TRUCS model used in this rulemaking to analyze ZEV technologies matched performance capabilities of ZEVs to an existing ICE vehicle for each use case where the ZEV vehicle technologies are technologically feasible.

exposure to the new technology. For example, education on the benefits of ZEV ownership and operational characteristics (for example, reduced operating costs, decreased exposure to exhaust emissions and engine noise, and smoother acceleration) and on charging and hydrogen refueling infrastructure technology and availability may lead to less uncertainty about each of these technologies. Though our final standards do not mandate the use of a specific technology, they may increase purchaser exposure to ZEVs, as well as incentivize manufacturers and dealers to educate HD vehicle purchasers on ZEVs, including the benefits of ZEVs, accelerating the reduction of purchaser risk aversion (see RIA Chapter 6.2). Local and federal actions investing in ZEV infrastructure and supply chain, including the CHIPS Act, BIL and IRA, will lead to reduced uncertainty surrounding ZEV ownership, likely further mitigating possible pre-buy. For more information on purchaser acceptance of HD ZEVs, see RIA Chapter 6.2. For more information on the charging and hydrogen refueling infrastructure analysis in this rule, see RIA Chapters 1.6, 1.8, and 2.6.

As noted in Preamble ES.D, the estimated fleet-average costs to manufacturers per-vehicle for this rule are less than those estimated for the HD GHG Phase 2 rule, which EPA found to be reasonable, and we do not have data showing a significant level of pre-buy for Phase 2. As also noted in Preamble ES.D, HD ZEV purchasers’ incremental upfront costs (after the tax credits) are recovered through operational savings such that payback occurs between two and four years on average for vocational vehicles, two years for short-haul tractors, and five years on average for long-haul tractors. These operational cost savings, and the associated payback of higher upfront costs, will also mitigate pre-buy to the extent they are considered in the purchase decision. With respect to possible purchaser anxiety over being unable to purchase an ICE vehicle after promulgation of the regulation, we note that these final standards do not mandate the production or purchase of any particular vehicle or use of any particular technology in such vehicles. As described in Preamble Section ES.C, and Preamble Section II, we model a potential compliance pathway to meet the standards with a diverse mix of ICE vehicle and ZEV technologies, as well as additional compliance pathways to meet the standards that do not include increasing utilization of ZEV technologies. In addition, the phasing-in of the standards will allow ample time for purchasers to make decisions about their vehicle of choice and the potential compliance pathway modeled for this rule reflects that the majority of vehicles will remain ICE vehicles, even in MY 2032.

In addition to pre-buy, there is the possibility of “low-buy,” a scenario in which there would be a decrease in HD vehicle sales after the regulation becomes effective. In a low-buy scenario, sales of HD vehicles would decrease in the months after the regulation becomes effective, compared to what would have happened in the absence of the regulation, due to purchasers either pre-buying or delaying a planned purchase. Low-buy may be due directly to pre-buy, where vehicle purchases that would have been made in the months after the effective date of the new emission standards are pulled forward to before the effective date of the new emission standards. Alternatively, low-buy may be due to purchasers delaying the purchase of a new vehicle due to the new emissions standards, for example because of increased costs or uncertainty related to the regulated vehicles. If pre-buy is smaller than low-buy, to the extent they both might occur, this would lead to reduced fleet turnover, at least in the short-term.[1848] The older trucks would remain

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[1848] Fleet turnover refers to the pace at which new vehicles are purchased and older vehicles are retired. A slower fleet turnover means older vehicles are kept on the road longer, and the fleet is older on average. A faster fleet turnover means that the fleet is younger, on average.

in use longer than they would have in the absence of the new emission standards. This would lead to lower emission reductions than we estimate will be achieved as a result of the standards. If pre-buy is larger than low-buy, short-term fleet turnover would increase; fleets would be, on average, comprised of newer model year vehicles. Though these new vehicles are expected to have lower emissions than the vehicles they are replacing, and emission reductions would be expected to be larger than under a scenario where low-buy exceeds pre-buy, emission reductions would still be lower than we estimated will be achieved as a result of the emission standards. Under a situation where low-buy matches pre-buy, we would also expect lower emission reductions than estimated, and emission reductions would likely be somewhere between the two relative pre-buy/low-buy scenarios discussed above. We expect low-buy, to the extent it might occur, to be mitigated under the same circumstances described above for pre-buy. Both pre-buy and low-buy, if they were to occur, are short-term phenomena.

At proposal, we discussed an analysis of previously promulgated EPA HD emission standards that indicates that where pre- or low-buy is seen, the magnitude has been small.[1849] EPA recently contracted with Eastern Research Group, Inc. (ERG) to complete a literature review on research that estimates sales impacts, as well as to conduct original research to estimate sales impacts for previous EPA HD vehicle rules on pre- and low-buy for HD vehicles. This work suggested that pre- and low-buy effects may occur for up to a year before or after a regulation is implemented, if they occur at all.[1850,1851] The resulting analysis examined the effect of four HD regulations, those that became effective in 2004, 2007, 2010 and 2014, on the sales of Class 6, 7 and 8 vehicles over the twelve months before and after each standard.[1852] For the purposes of this discussion, we will call these the 2004 rule, 2007 rule, 2010 rule and 2014 rule. The 2004, 2007 and 2010 rules focused on reducing criteria pollutant emissions. The 2014 rule (the HD GHG Phase 1 rule promulgated in 2014) focused on reducing GHG emissions. The report finds little evidence of sales impacts for Class 6 and 7 vehicles. For Class 8 vehicles, evidence of pre-buy was found before the 2010 rule's implementation and for only one month before the 2014 rule's implementation dates, and evidence of low-buy was found after the 2002, 2007 and 2010 rules'

[1849] For example, Lam, T., and Bausell, C. "Strategic Behaviors Toward Environmental Regulation: A Case of Trucking Industry." Contemporary Economic Policy 25(1): 3-13. 2007, Rittenhouse, K., and Zaragoza-Watkins,M. "Anticipation and Environmental Regulation." Journal of Environmental Economics and Management 89: 255-277. 2018, and an unpublished report by Harrison, D., Jr., and LeBel, M. "Customer Behavior in Response to the 2007 Heavy-Duty Engine Emission Standards: Implications for the 2010 NOX Standard." NERA Economic Consulting. 2008. For EPA's summary on these studies, see the EPA peer review study U.S. Environmental Protection Agency. "Analysis of Heavy-Duty Vehicle Sales Impacts Due to New Regulation." EPA-420-R-21-013. 2021. https://cfpub.epa.gov/si/si_public_pra_view.cfm?dirEntryID=349838&Lab=OTAQ, or the recently published EPA Heavy-Duty 2027 rule at Docket ID EPA-HQ-2019-0555

[1850] U.S. Environmental Protection Agency. "Analysis of Heavy-Duty Vehicle Sales Impacts Due to New Regulation." EPA-420-R-21-013. 2021. https://cfpub.epa.gov/si/si_public_pra_view.cfm?dirEntryID=349838&Lab=OTAQ

[1851] This report will be referred to as the ERG report in the rest of this discussion.

[1852] The 2004 rule, "Final Rule for Control of Emission of Air Pollution From Highway Heavy-Duty Engines", was finalized in 1997. The 2007 and 2010 rules were finalized as phase-ins in the "Final Rule for Control of Emissions of Air Pollution from 2004 and Later Model Year Heavy-Duty Highway Engines and Vehicles; Revision of Light-Duty On-Board Diagnostics Requirements" in 2000. The 2014 GHG rule, "Final Rule for Phase 1 Greenhouse House Emissions Standards and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles," was finalized in 2011. These rules can be found on the EPA website https://www.epa.gov/regulations-emissions-vehicles-and-engines/regulations-emissions-commercial-trucks-and-buses-heavy.

implementation dates. The report findings, however, do suggest that the range of possible results include a lower bound of zero, i.e., no pre-buy or low-buy due to EPA rules.[1853]

However, at proposal we also made it clear that, while it is instructive that the ERG report found little to no pre-buy or low-buy effects due to our HD rules, the approach to estimate a change in the sales of HD vehicles before and after the promulgation of a rule due to the cost of that rule (as was done in the ERG report) should not be used to estimate sales effects from this rule for three main reasons.[1854] First, most of the statistically significant sales effects in the report were estimated using data from criteria pollutant rules (the 2002, 2004 and 2007 rules), which are not appropriate for use in estimating effects from GHG rules. This is due to differences in how costs are incurred and benefits to HD vehicle purchasers are accrued as a result of HD vehicle criteria pollutant regulations versus HD GHG regulations, which may lead to differences in how HD vehicle buyers react to a particular regulation. For example, the 2014 rule reduced GHG emissions, and had lower estimates of associated technology costs relative to the criteria pollutant rules, and compliance with the GHG rule was associated with fuel savings. We also expect operating savings due to this rule, as described in Chapter 3.4.

Second, there was relatively more uncertainty in the net estimated price change from the 2014 GHG rule than in the criteria pollutant rules. The performance-based GHG standards had many different compliance pathways which led to both capital cost increases, as well as reductions in operating costs through fuel savings. As such, the cost of the regulation could vary greatly across firms, and may have led to net cost savings. As this estimated change in cost is what was used to estimate the effect of the rule on pre-buy and low-buy, the likely variation in net costs of the rule are associated with uncertainty about the results of the pre-buy and low-buy sales effects from the 2014 rule.

Third, the approach outlined in the ERG report was estimated only using data from HD ICE vehicles (for example, cost of compliance due to adding HD ICE engine technologies to a HD ICE engine). The modeled potential compliance pathway for this rule includes ZEV technologies, which are associated with additional EVSE infrastructure. The possible impacts of this are not represented in the results of the report.

Though there is uncertainty related to the costs used in the 2014 rule analysis, the results of the ERG report, combined with the literature review completed for the report, indicate that there is little evidence of pre-buy or low-buy associated with GHG rules. This is supported by data from the U.S. Bureau of Economic Analysis, which shows that sales of heavy-weight trucks were fairly consistently increasing from the end of 2009 through the end of 2015.[1855] Altogether, this suggests that there was likely little to no pre- or low-buy due to the 2014 GHG rule.

Though the increased purchase price due to this rule could potentially lead to pre- and/or low-buy, it is unlikely to occur in a significant manner. Specifically, we expect that they will either

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[1853] The ERG report includes statistically significant results of no effect for pre-buy on the 2002 rule, as well as results where no effect cannot be ruled out for pre-buy on the 2007, 2010 and 2014 rules, and for low-buy on the 2002, 2010 and 2014 rules.

[1854] See the Chapter 10 in the RIA for the HD 2027 rule for an example of how we might estimate potential impacts of a HD regulation on vehicle sales, including pre-buy and low-buy, using the approach introduced in the ERG report. 88 FR 14296. January 24, 2023.

[1855] The graph of monthly, seasonally adjusted heavy weight truck sales from the Bureau of Economic Analysis can be found at: https://fred.stlouisfed.org/series/HTRUCKSSAAR.

not occur at all, or if they do, occur in a limited way that will not significantly affect the GHG emissions reductions projected by this rule or that would unduly disrupt the HD vehicle market. This is due, in part, to the operating cost savings we estimate will be achieved in complying with this rule. For the modeled compliance pathway for this rule, that cost savings are expected to wholly offset the increase upfront purchase cots for ZEVs, which leads to payback periods of between two and five years. The historical data described in this section indicate that little to no pre- or low-buy has been seen from previously promulgated EPA HD emission standards. Lastly, it should be noted that many studies estimating how large or expensive purchases are made, including that of HD vehicles, purchase decisions are heavily influenced by macroeconomic factors unrelated to regulations, for example, interest rates, economic activity, and the general state of the economy.[1856] For example, according to the Economic Research Division of the Federal Reserve, retail sales of heavy weight trucks fell dramatically between September of 2019 and May of 2020 (about 46 percent fewer sales), likely in great part due to the COVID-19 pandemic, and then they rebounded through the May of 2021 to be only about 13 percent lower than in September of the previous year.[1857] The historical data described in this section, relatively low projection of the increase in market share for ZEVs in the modeled potential compliance pathway, and the associated continued availability of ICE vehicles, also support little to no pre- or low-buy due to this rule. It should be noted, however, that, unlike the previous HD regulations, infrastructure availability and the perception of the same is likely to impact purchase decisions. This is discussed more in RIA Chapter 6.2.

This rule is expected to lead to a decrease in total HD highway fleet emissions, though this decrease will happen gradually as the HD fleet turns over.[1858] This is because the fraction of the total on-highway HD vehicle fleet that are new compliant vehicles will initially be a small portion of the entire HD market. As more vehicles compliant with this rule are sold, and as older HD vehicles are retired, greater emission reductions will accumulate. The emission reductions attributable to each HD segment that will be affected by this rule will depend on many factors, including the rate of purchase of compliant vehicles in each market segment over time and the proportion of those vehicles that utilize each of the mix of technologies under the compliance pathways manufacturers choose. For example, if ZEV technologies uptake occurs faster than projected under the modeled potential compliance pathway, emission reductions will accumulate faster than estimated. In addition, if pre-buy or low-buy occurs associated with this rule, emission reductions will be smaller than estimated as well. This is because, under pre-buy conditions, fleets would, on average, be comprised of newer model year vehicles. Though these new vehicles are expected to have lower emissions than the vehicles they are replacing, emission reductions could still be lower than we estimate will be achieved as a result of the final emission standards. Under low-buy, we expect older, more polluting, HD vehicles to remain in use longer than they otherwise would in the absence of new regulation. If pre-buy is smaller than low-buy, to the extent both might occur, this would lead to a slower fleet turnover, at least in the short

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[1856] See the literature review found in the ERG report mentioned earlier in this Section, “Analysis of Heavy-Duty Vehicle Sales Impacts Due to New Regulation.” Found at *https://cfpub.epa.gov/si/si_public_pra_view.cfm?dirEntryID=349838&Lab=OTAQ* for more information.

[1857] The graph of monthly, seasonally adjusted heavy weight truck sales from the Bureau of Economic Analysis can be found at: https://fred.stlouisfed.org/series/HTRUCKSSAAR.

[1858] See Preamble Section V and RIA Chapter 4.4 for details on estimated HD emissions effects due to this final rule.

term.[1859] Conversely, if pre-buy is larger than low-buy, short-term fleet turnover would increase and fleets would, on average, be comprised of newer model year vehicles, and though emission reductions would be expected to be larger than under a scenario where low-buy exceeds pre-buy, emission reductions would still be lower than we estimate will be achieved as a result of the final emission standards. Under a situation where low-buy matches pre-buy, we would also expect lower emission reductions than estimated, and emission reductions would likely be somewhere between the two relative pre-buy/low-buy scenarios discussed in this paragraph.

6.1.2 Mode Shift

Mode shift would occur if goods that would normally be shipped by HD vehicles are shipped by another method (e.g., rail, boat, air) due to the emission standards. EPA does not expect this rule to result in a transportation mode shift. Generally, shipping cargo via truck is more expensive per ton-mile than barge or rail, and less expensive than air.[1860,1861] This is due to many factors, not the least of which is labor costs (each truck has at least one driver). Even though trucking is more expensive than rail or marine on a ton-mile basis, it is a very attractive transportation alternative for several reasons: shipping via truck is generally faster and more convenient than rail or marine, trucks can reach more places, and trucks may be less constrained by available infrastructure than barge or rail. In addition, shipping via truck does not require trans-shipments (transferring from one mode to another, for example to deliver cargo to or from the port or rail yard), and it allows partial deliveries at many locations. This speed, infrastructure availability, and delivery flexibility make trucking the transportation solution of choice for many kinds of cargo across most distances. As a result, smaller shipments of higher-valued goods (e.g., consumer goods) tend to be transported by air or truck, while larger shipments of lower-valued goods (e.g., raw materials) tend to go via rail or barge.[1860,1862]

Studies of intermodal freight shifts, such as Comer et al. (2010) or Bushnell and Hughes (2019), focus on changes in cost per ton-mile as a potential source of transportation mode shift.[1860,1862] Comer et al. note, for instance, that fuel consumption "depend[s] on the type of freight being moved, route characteristics, transport speed, and locomotive/truck characteristics."[1860] Bushnell and Hughes estimate that increased fuel prices for truck transportation lead to small substitutions between truck and rail for small or large shipments, and higher shifts for intermediate-sized shipments.[1862] The findings from this study suggest that the variation in the kinds and values of goods shipped by different modes likely result in only a small amount of mode shift in response to a change in operating cost (e.g., fuel prices). However, due to data availability, this study approximates freight rates with fuel costs, assumes shipping distances using different modes are the same, and mostly does not consider transportation

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[1859] Fleet turnover refers to the pace at which new vehicles are purchased and older vehicles are retired. A slower fleet turnover means older vehicles are kept on the road longer, and the fleet is older on average. A faster fleet turnover means that the fleet is younger, on average.

[1860] Comer, B.; Corbett, J. J.; Hawker, J.S.; Korfmacher, K.; Lee , E.E.; Prokop, C.; and Winebrake. J. "Marine Vessels as Substitutes for Heavy-Duty Trucks in Great Lakes Freight Transportation." Journal of the Air & Waste Management Association 60: 884-890. 2010.

[1861] U.S. EPA Office of Transportation and Air Quality. "Economic Impacts of the Category 3 Marine Rule on Great Lakes Shipping." EPA-420-R-12-005. 2012.

[1862] Bushnell, J., and Hughes, J. "Mode Choice, Energy Consumption and Emissions in U.S. Freight Transportation." Working paper. 2019. Available online: https://spot.colorado.edu/~jonathug/Jonathan_E._Hughes/Main_files/Freight_Modes.pdf, accessed 10/21/2019.

availability constraints affecting some modes in some regions. These limitations may distort the effects they estimate.

A mode shift study EPA carried out in 2012 in the context of new sulfur limits for fuel used in large ships operating on the Great Lakes may help address some of these limitations.[1861] The methodology used a combination of geospatial modeling and freight rate analysis to examine the impact of an increase in ship operating costs. While the focus of the study was transportation mode shift away from marine and toward land, it noted that truck transportation is far more expensive than both rail and marine on a ton-mile basis.[1863] It also shows that even a large percentage increase in marine fuel costs did not raise freight rates by a similar percentage, because fuel costs are only part of total operating costs. In the case of truck transportation, operating costs are a much smaller portion of total costs. The results of this study combined with the others cited in this section indicate that changing the cost of truck transportation is unlikely to create mode shift.

Whether shippers switch to a different transportation mode for freight depends not only on the cost per mile of the shipment (i.e., freight rate), but also the value of the shipment, the speed of transport needed for shipment (for example, for non-durable goods), and the availability of supporting infrastructure (e.g., rail lines, highways, waterways). Shifting from HD vehicles to other modes of transportation may occur if the cost of shipping goods by truck increases relative to shipping by other modes in cases where there is another mode of transport available that can meet the required timing. Though we are unable to estimate what affect this rule might have on shipping costs, in part because we are not able to estimate how a change in upfront vehicle costs affects shipping rates, or how much of a change in operational costs is passed through to the shipping rates, we do estimate that, under the potential compliance pathway projected for this rule, average net upfront costs are paid back in five years or less for the vehicle groups affected by this rule, and these vehicles are expected to experience reduced operational costs. In addition, the vehicles that comply with this rule are expected to have positive total costs of ownership over both five- and ten-year time horizons, and thus, we do not expect a significant increase in shipping rates. For these reasons, we do not expect mode shift from HD vehicles to a different mode of transportation is a likely outcome of this regulation.[1864]

6.1.3 Class Shift

Class shift would occur if purchasers shift their purchases from one class of vehicle to another class of vehicle due to impacts of the rule on vehicle attributes, including performance and relative costs, among vehicle types that could practically be switched. Heavy-duty vehicles are typically configured and purchased to perform a function. For example, a concrete mixer truck is purchased to transport concrete, a combination tractor is purchased to move freight with the use of a trailer, and a Class 4 box truck could be purchased to make deliveries. The purchaser makes decisions based on many attributes of the vehicle, including the gross vehicle weight rating, which in part determines the amount of freight or equipment that can be carried. If the Phase 3 standards impact either the performance or cost of a vehicle relative to the other vehicle classes,

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[1863] Figure 1-5 in U.S. EPA Office of Transportation and Air Quality. "Economic Impacts of the Category 3 Marine Rule on Great Lakes Shipping." EPA-420-R-12-005. 2012.

[1864] We note that a study published by Argonne National Laboratory in 2017 indicates that if mode shift were to occur as a result of this rule, it would likely result in further decreasing transportation GHG emissions and upstream energy usage. https://publications.anl.gov/anlpubs/2017/08/137467.pdf.

then purchasers may choose to purchase a different vehicle, resulting in the unintended consequence of increased fuel consumption or GHG emissions in-use.

A purchaser in need of a specific vocational vehicle, such as a bus, box truck or street sweeper, would not be able to shift the purchase to a vehicle with a less stringent emission standard (such as the optional custom chassis standards for emergency vehicles, recreational vehicles, or mixed use (nonroad) type vehicles) and still meet their needs. The purchaser makes decisions based on many attributes of the vehicle, including the gross vehicle weight rating or gross combined weight rating of the vehicle, which in part determines the amount of freight or equipment that can be carried. Due to this, it is not likely feasible for purchasers to switch to other vehicle classes simply due to the emission standards.

As described in Section II.D.3 of the Preamble, we account for differences in vehicle uses and payload capacity in HD TRUCS, incorporating that analysis into our consideration of possible compliance pathways to support the feasibility of the final standards. In the modeled potential compliance pathway, we estimate the new vehicles produced and sold that are compliant with the rule, including ZEVs, are able to perform the same function as vehicles produced without the rule in place. For example, BEV technologies were not included within the potential compliance pathway in situations where the performance needs of a BEV would result in a battery that was too large or heavy due to the impact on payload and potential work accomplished relative to a comparable ICE vehicle.[1865] Also, it should be noted that for this final rule, we projected multiple pathways to compliance, including pathways that did not project an increase in ZEV penetration. Furthermore, although there are possible pathways that include reduced ZEV penetration compared to the modeled potential compliance pathway estimated in the analysis for this rule, there may also be greater ZEV penetration in one or more vehicle classes than we estimate in the modeled potential compliance pathway.

Class shift could occur if one class of vehicle becomes significantly more expensive relative to another class of vehicle due to the technology and operating costs associated with the new emission standards. We expect that class shifting, if it does occur, would be very limited because this rule applies new emission standards to all HD vehicle classes that would practically be switched as described in Preamble Section II. In addition, the purchase cost of HD vehicles typically increases with the class of the vehicle, and the modeled compliance pathway for this rule does not lead to situations where the cost to purchase a heavier class of vehicles becomes lower than the cost to purchase a lighter class (see Preamble Section II.F.2). Also, the average payback period for the technologies in the modeled potential compliance pathway for all of the classes of vehicles are within the first ownership period, and our analysis shows a positive total cost of ownership over a five-year time horizon.

If a limited amount of shifting were to occur, we would expect negligible emission impacts (compared to those emission reductions estimated to occur as a result of the emission standards). For more information see Preamble Section VI.E.1.

6.1.4 Domestic Production

The final standards are not expected to provide incentives for manufacturers to shift between domestic and foreign production. This is because the standards apply to any vehicles sold in the

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[1865] We assess the incremental weight increase or decrease of ZEVs compared to ICE vehicles in RIA Chapter 2.9.1.

U.S. regardless of where they are produced. If foreign manufacturers already have relatively more expertise in satisfying the requirements of the standards, there may be some initial incentive for foreign production. However, offsetting this potential effect, and given increasing global interest in reducing vehicle emissions, specifically through the use of ZEV technologies, as domestic manufacturers produce vehicles with reduced emissions (including ZEVs) the opportunity for domestic manufacturers to sell in other markets might increase. To the extent that the requirements of this rule might lead to application and use of technologies that other countries may seek now or in the future, developing this capacity for domestic producers now may provide some additional ability to serve those markets. In addition, this rule and other federal actions including the IRA and BIL support the U.S. in our efforts to remain competitive on a global scale by encouraging and supporting the expansion of and investment in domestic manufacturing of ZEV technologies, supply chains, charging infrastructure and other industries related to green transportation technology.

As discussed in Preamble Section ES.B, and RIA Chapter 1.3, IRA section 13502, “Advanced Manufacturing Production Credit,” contains a battery tax credit for the production and sale of battery cells and modules (of up to $45 per kilowatt-hour (kWh), and for 10 percent of the cost of producing applicable critical minerals (including those found in batteries and fuel cells, provided that the minerals meet certain specifications)), which is conditioned on such components or minerals being produced in the United States and, thus, is designed to encourage such domestic production. Our cost analysis reflects that in our modeled potential compliance pathway we project an increasing percentage of batteries used in HD BEVs will be eligible for this tax credit beginning in MY 2027 through MY 2032, in addition to consideration of the other tax incentives that apply to vehicle and EVSE purchasers, as described in Sections II and IV of the Preamble and Chapters 2 and 3 of the RIA.

6.2 Purchaser Acceptance

In the modeled potential compliance pathway for the final rule, we project an increase in the adoption of HD BEVs and FCEVs for most of the HD vehicle types for MYs 2027 and beyond (see preamble Section II or the RIA Chapter 2 for details). As explained in RIA Chapter 2.10, although some HD ZEVs have higher upfront purchaser costs for some vehicles than comparable ICE vehicles (including consideration of EVSE, as applicable), our cost analysis shows that this incremental upfront purchaser cost difference would be partially or fully offset by a combination of the federal vehicle purchase tax credits, battery tax credits, and EVSE tax credits for HD ZEVs that are available through MY 2032, and further offset over time through the operational cost savings. Our analysis shows that, in our modeled compliance pathway, the vehicle types for which we project ZEV adoption for MY 2032 have an average payback period of between two and five years, depending on the regulatory group, when compared to a comparable ICE vehicle, even after considering the upfront purchaser and operating costs of the associated EVSE.[1866] The savings are due to our assessment of the expected cost savings in fuel, maintenance, and repair over the life of the HD ZEV when compared to a comparable ICE vehicle. See Sections II and IV of the preamble and Chapters 2 and 3 of this RIA for further discussion of payback.

[1866] Estimates of average per-ZEV payback of purchaser upfront costs shown in RIA Chapter 2.10.6 show LHD vocational vehicles have a payback period of 2 years, MHD vocation vehicles have a payback period of 3 years, HHD vocational vehicles have a payback period of 4 years, day cab tractors have a payback period of 2 years, and sleeper cab tractors have a payback period of 5 years.

Businesses that operate HD vehicles are under competitive pressure to reduce operating costs, which should encourage purchasers to identify and rapidly adopt new vehicle technologies that reduce operating costs. As outlays for labor and fuel generally constitute the two largest shares of HD vehicle operating costs, depending on the price of fuel, distance traveled, type of HD vehicle, and commodity transported (if any), businesses that operate HD vehicles face strong incentives to reduce these costs.[1867,1868] Thus, potential savings in operating costs appear to offer HD vehicle buyers strong incentives to pay higher upfront prices for vehicles that feature technology or equipment that reduces operating costs, such as HD ZEVs as explained above. Economic theory suggests a normally functioning competitive market would lead HD vehicle buyers to want to purchase, and HD vehicle manufacturers to incorporate, technologies that contribute to lower net costs.

Indeed, given EPA's assessment in HD TRUCS for this rule showing significant reductions in operating costs for HD ZEVs compared to comparable ICE vehicles, economic theory suggests that the market should deliver those savings, and increase ZEV adoption, even without EPA's standards. We are currently seeing increasing demand for, and increasing investment in, ZEV technology prior to the adoption of the final standards.[1869] Thus, even with our revised reference case for the final rule, it is possible that adoption of ZEVs, and other technologies, could occur more rapidly than EPA projects in the reference case.[1870]

Though theory suggests the market should adopt technology associated with operating cost savings (like ZEVs), as discussed extensively in the HD Phase 2 rule,[1871] an "energy efficiency gap" or "energy paradox" has existed, where available technologies that would reduce the total cost of ownership for the vehicle (when evaluated over their expected lifetimes using conventional discount rates) have not been widely adopted, or the adoption is relatively slow, despite their potential to repay buyers' initial investments rapidly. Economic research offers several possible explanations for why the prospect of these apparent savings might not lead HD manufacturers and buyers to adopt technologies that are expected to reduce operating costs. Though existing research focuses specifically on adoption of ICE technologies that result in decreased fuel costs, many of the explanations may also hold true for the adoption of ZEV technologies, which we estimate will result in decreased fuel or other operating costs. Explanations include constraints on access to capital for investment, imperfect or asymmetrical information about the new technology (for example, real-world operational cost savings, durability, or performance), uncertainty about supporting infrastructure (for example, ease of charging a BEV), uncertainty about the resale market, and first-mover disadvantages for manufacturers. Below, we discuss how some of these may impact the adoption of HD ZEVs as well as factors that may mitigate them.

Constraints on investment, either for manufacturers of the technology or for potential purchasers of the technology, lead to slower adoption rates. Federal or other incentives to manufacture or purchase energy efficient technology will reduce the impact that constraints on investment have on adoption of that technology. For ZEVs, the availability of existing

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[1867] American Transportation Research Institute, *An Analysis of the Operational Costs of Trucking,* September 2013. Docket ID: EPA–HQ–OAR–2014–0827–0512.

[1868] Transport Canada, Operating Cost of Trucks, 2005. Docket ID: EPA–HQ–OAR–2014–0827–0070.

[1869] See Preamble ES.C.

[1870] EPA's reference case is discussed in RIA Chapter 4.

[1871] See 81 FR at 73859-62.

incentives, including the Federal purchaser (vehicle and EVSE) and battery manufacturing tax credits in the IRA, is expected to lead to lower upfront costs for purchasers of HD ZEVs than would otherwise occur.[1872] More specifically, we expect that adoption rates of HD ZEVs would be impacted by purchasers taking advantage of existing incentives, specifically the IRA vehicle tax credit and EVSE tax credit (as applicable),[1873] to lower the upfront costs for purchasers of HD ZEVs (including depot EVSE). We expect this will result in a higher ZEV adoption rate than would otherwise exist absent such incentives, and so counteracts the energy efficiency gap under the modeled potential compliance pathway for manufacturers.

In addition, as purchasers consider more of the operational cost savings, for example, of a ZEV over a comparable ICE vehicle, in their purchase decision, the smaller the impact the higher upfront costs for purchasers has on that decision, and purchasers are more likely to purchase the vehicle with that technology (in this example, a ZEV). However, one reason purchasers may not consider the full, or even a portion of, operational cost savings of a ZEV over a comparable ICE vehicle, is due to uncertainty, e.g., uncertainty about future fuel and electricity prices.[1874] Adoption may be affected by additional areas of uncertainty as well such as purchasers' impressions of BEV charging and FCEV fueling infrastructure support and availability, perceptions of the comparisons of quality and durability of the different HD powertrains, and resale value of the vehicle. Another factor that may affect adoption of ZEVs is purchasers' uncertainty about the technology, both with respect to ZEVs, as well as with new technology applied to ICE vehicles.[1875]

In a working paper by Bae, et al. (2022),[1876] the authors report the results of interviews conducted in 2018 and 2019 with eighteen HD fleet operators in California on their perspectives on viable alternative fuel options over the next decade and beyond, as well as what motivators or barriers exist to adopting those alternatives. Though electric, hydrogen, compressed natural gas and hybrid options were generally seen as viable in the 2030's, operators reported concerns related to functional unsuitability of electric options, uncompetitive upfront costs of hydrogen, and unpromising support from state government. In addition, for electric and hydrogen options specifically, fleet operators expressed concern that infrastructure might not be ready to support electric or hydrogen adoption, that there is an uncertain return on investment, and that there is a perceived unavailability of vehicles.

We first note that significant changes have already occurred since these interviews were conducted, including an increase in the number of HD ZEV models available in the market, and the important incentives provided in the BIL and the IRA which provide support for development and purchase of heavy-duty ZEVs, including reducing the costs of purchasing ZEVs and reducing the costs of ZEV refueling infrastructure. In addition, as described in RIA Chapter 1.6, there are several existing and planned projects from manufacturers and other entities

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[1872] Note that the incentives exist in the reference case and under our final standards case.

[1873] The IRA battery tax credit is also expected to reduce upfront costs for purchasers, although it is a tax credit for battery manufacturers, not purchasers. We expect vehicle manufacturers to reduce the price of their vehicles in accordance with their ability to take advantage of this battery tax credit in order to remain competitive in the market.

[1874] See Chapter 6.1.1 for further discussion on how uncertainty related to ZEVs may affect vehicles sales.

[1875] As mentioned in Preamble ES.F, some manufacturers are including maintenance in leasing agreements. This could reduce uncertainty related to new technology.

[1876] Bae, Youngeun and Rindt, Craig R. and Mitra, Suman and Ritchie, Stephen G., Fleet Operator Perspectives on Alternative Fuels for Heavy-Duty Vehicles. 2022. Available at SSRN: https://ssrn.com/abstract=4253440 aimed at expanding public charging infrastructure for electric trucks or other commercial vehicles. As HD ZEVs become more affordable and more represented on the roadways, we expect uncertainty related to this technology, including uncertainty related to durability and resale value, to wane. We acknowledge that such uncertainties, as well as other uncertainties including infrastructure, could affect manufacturer compliance strategies and potentially lead to compliance strategy decisions involving fewer ZEV technologies than we project in the potential compliance pathway for these standards (including a compliance pathway that does not utilize ZEV technologies at all), which may reduce the non-GHG emission reductions estimated in this rule.[1877] As discussed in detail in RIA Chapter 2.6 and 2.10.3, EPA has carefully analyzed the infrastructure needs and costs to support the potential compliance pathway's technology packages that support the MY 2027-2032 standards. Additionally, as purchasers learn more about ZEV technologies, and as the penetration of the technologies and supporting infrastructure in the market increases, the exposure to ZEV technologies in the real world will reduce uncertainty related to viability or durability of the vehicles and the availability of supporting infrastructure. As described in RIA 1.5, about 60 makes and models of HD BEVs were available for purchase, with more product lines in some stage of early development, with the market projected to grow to about 180 models of HD BEVs by MY 2024. In addition, companies with large distribution needs, including UPS, FedEx, DHL, Walmart, Anheuser-Busch Co., Amazon and PepsiCo Inc., have expressed significant interest in fleet electrification. For example, Amazon and UPS placed orders for 10,000 BEVs in 2020, with Amazon planning to scale up to 100,000 BEV vans by 2030. In 2022, PepsiCo added their first of 100 planned Tesla Semis to its fleet. Some fleet owners and operators, including Amazon and Walmart, are also considering hydrogen technologies to lower fleet emissions. Though increasing penetration of HD ZEVs is projected to continue to happen regardless of the standards, as explained in our reference case, these standards are expected to help accelerate the process, incentivizing manufacturers to educate purchasers on the benefits of their compliance strategy technologies, like HD ZEVs.

Another reason purchasers may not consider the full, or even a portion of the, operational cost savings of a ZEV over a comparable ICE vehicle is if a principal-agent problem exists, causing split incentives.[1878] A principal-agent problem could exist if truck operators (agents) and truck purchasers who are not also operators (principals) value characteristics of the trucks under purchase consideration differently (split incentives) which could lead to differences in purchase decisions between truck operators and truck purchasers. Characteristics may include physical characteristics (for example noise, vibration or acceleration), cost characteristics (for example operational costs, purchase prices, or cost of EVSE installation), or other characteristics (for example availability of EVSE infrastructure). Such potential split incentives, or market failures, could, for example, impact HD ZEV adoption rates if agents weigh characteristics more associated with ICE vehicles greater than those associated with ZEV vehicles in a manner different than represented in the analysis of the modeled compliance pathway for this rule. The possibility of a principal-agent problem could be mitigated through measures that cause an alignment of interests between the principal and the agent, for example, measures that lead to sharing of the benefits and/or costs that may cause the issue. While this is a theoretical issue, EPA is not aware of any data or analysis persuasively demonstrating if the principal-agent

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[1877] This is assuming that the GHG standards are being met, and assuming there are no pre- or low-buy effects.

[1878] A principal-agent problem happens when there is a conflict in priorities (split incentives) between a "principal," or the owner of an asset, and an "agent," or the person to whom control of the asset has been delegated, such as a manager or HD vehicle operator.

problem significantly affects HD vehicle purchases generally, or specifically with respect to HD ZEV purchases. However, we note that, given the commercial nature of how HD vehicles are used and the need to minimize costs in competitive business environments, we think it is reasonable, absent empirical evidence to the contrary, to conclude that truck purchasers are very unlikely to ignore the significant operational cost savings associated with HD ZEVs.

Though ZEVs are being introduced in the HD market, their adoption is currently low, and their representation in the resale market is almost non-existent.[1879] There is uncertainty surrounding the ability of the original owners to recover their original investment. In addition, the uncertainties mentioned above for new HD ZEV buyers, including those related to payback, durability, and infrastructure, also exist for purchasers of used ZEVs. However, some uncertainties will likely be reduced. For example, the used ZEV market will mature more slowly than the new ZEV market, giving time for future used ZEV owners to learn about the technology and for the supporting infrastructure to mature. As more used ZEVs enter the market, uncertainty related to used ZEVs, and the associated resale market, will shrink.

Potential “first-mover disadvantage” may exist in manufacturing, especially in situations where developing, implementing, or marketing a new technology requires large initial investment. For example, in order for someone to purchase a HD ZEV for their specific needs, the vehicle that meets those needs must exist in the market. The first-mover disadvantage occurs when the “first-mover” pays a higher proportion of the costs of developing, implementing, or marketing a new technology and loses the long-term advantage when other businesses move into that market. However, there could also be “dynamic increasing returns” to adopting new technologies, wherein the value of a new technology may depend on how many other companies have adopted the technology. Additionally, there can be research and development synergies when many companies work on the same technologies at the same time, assuming there's a reason to innovate at the same time.

Standards such as those in this rule can create conditions under which companies invest in major innovations. As discussed in RIA Chapter 1.5, HD manufacturers are already producing some ZEV models and investing in the development and production of additional models, and large companies that rely on HD vehicles have already expressed an interest in purchasing HD ZEV technology. This rule is expected to provide a meaningful signal to manufacturers to produce more technologies with the potential to reduce large amounts of GHG emissions, like HD ZEV models, to invest in educating purchasers on the benefits of such technologies, and to invest in supporting infrastructure. For example, Daimler Trucks North America, Volvo Trucks, Navistar, PACCAR, and Cummins are a few of the HD companies investing in ZEVs, including

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[1879] In Chapter 2.12 of the RIA, we provide a discussion and analysis of HD vehicle total cost of ownership, which includes an estimate of residual values, though we do not distinguish by powertrain technology.

in ZEV infrastructure, and supporting the education of ZEV purchasers.[1880,1881] We also note that under the modeled potential compliance pathway for this rule, we project demand for infrastructure buildout, and therefore utilities may rely on this rule as support for building out such infrastructure.[1882]

To take into consideration of purchaser acceptance of BEVs and FCEVs , we used the tools and information available to evaluate and project ZEV adoption rates in HD TRUCS, in consideration and recognition of the various factors that may affect the adoption of technology in the real world. We acknowledge that the data and research needed to definitively discuss what affects whether HD buyers will adopt BEVs or FCEVs is limited.[1883] Based on our consideration of available information, we expect that, similar to the decisions made by LD vehicle EV buyers, part of the decision on whether to purchase a BEV or FCEV over an ICE vehicle may depend on the relative price of the vehicles, the amount to which purchasers account for fuel, and other operating cost savings in their purchase decision, and on understanding (or perceived understanding) of the charging or refueling infrastructure. In addition, more unique to the HD market, we expect that understanding of the technical suitability of the vehicle to its intended application may impact the decision of whether to purchase an HD ZEV or ICE vehicle. For example, a long-haul Class 8 tractor will have different needs than a local delivery Class 8 tractor.

In our modeled potential compliance pathway that supports the feasibility of the standards, we account for and consider willingness to purchase considerations in several ways (and, correspondingly, impacts on HD ZEV adoption included in the modeled potential compliance pathway). This includes considering uncertainty about vehicle weight, component (e.g., battery) sizing, infrastructure availability, upfront purchaser costs, and payback for purchasers, as well as including limitations in our analysis to phase in the final standards to provide additional time and a slower pace of adjustment in early model years. For example, our HD TRUCS analysis applies oversize factors for batteries to account for temperature effects, potential battery degradation and

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[1880] Daimler Truck North America. “Daimler Trucks North America, Portland General Electric open first-of-its-kind heavy-duty electric truck charging site”. April 21, 2021. Available online: *https://northamerica.daimlertruck.com/PressDetail/daimler-trucks-north-america-portland-general-2021-04-21.*

[1880] Volvo Trucks USA. “Volvo Trucks Simplifies EV Charger Procurement with Vendor Direct Shipping Program”. September 29, 2022. Available online: *https://www.volvotrucks.us/news-and-stories/press-releases/2022/september/volvo-trucks-simplifies-ev-charger-procurement-with-vendor-direct-shipping-program*. Navistar. “Navistar and In-Charge Energy Now Offer Carbon-Neurtral Electric Vehicle Charging”. Available online: *https://news.navistar.com/2021-10-25-Navistar-and-In-Charge-Energy-Now-Offer-Carbon-Neutral-Electric-Vehicle-Charging*. Paccar Parts. “Electric Vehicle Chargers”. Available online: *https://www.paccarparts.com/technology/ev-chargers/*..

[1881] See also RIA Chapters 1.5 and 1.6 for more information on announcements from manufacturers regarding ZEVs and infrastructure.

[1882] See Comments of Edison Electric Institute EPA-HQ-OAR-2022-0985-1509 at 6 (“A HDV Phase 3 rule that supports the continued electrification of the transportation sector and leverages the existing investment in the electric system and the electric sector’s ongoing clean energy transformation will provide both environmental benefits and send appropriate signals to support the continued buildout of infrastructure to support increased electrification.”).

[1883] EPA has recently completed an in-depth, peer reviewed, study of adoption of LD BEVs. See “Literature Review of U.S. Consumer Acceptance of New Personally Owned Light Duty Plug-in Electric Vehicles” at *https://cfpub.epa.gov/si/si_public_record_report.cfm?Lab=OTAQ&dirEntryId=353465* for more information.

more; we sized most batteries for the 90th percentile of estimated VMT;[1884] and we sized EVSE such that vehicles' batteries could be fully recharged during the dwell time available to specific vehicle applications. In addition, in our HD TRUCS analysis we cap the ZEV adoption rate for each vehicle type to be no more than 70 percent for MY 2032 and no more than 20 percent in MY 2027. For more detail on the constraints we considered and included, see Preamble Sections II.D, II.E and II.F. In the HD TRUCS analysis, we developed a method to include consideration of payback in assessing adoption rates of BEVs and FCEVs for the modeled potential compliance pathway after considering methods in the literature.[1885] Our payback curve, and methods considered and explored in the formulation of the method used in this rule, are described in RIA Chapter 2.7. As stated there, given information currently available, and our experience with the HD vehicle industry, payback period is the most relevant metric to the HD vehicle industry.[1886] The payback schedule caps used in our model are lower in MY 2027 compared to MY 2032 to recognize additional time for the ZEV technology and infrastructure to mature. Fleet owners and drivers will have had more exposure to ZEV technology in 2032 compared to 2027, which may work to alleviate concerns related to ZEVs (for example, concerns of reliability) and result in a lower impression of risk of these newer technologies. In addition, infrastructure to support ZEV technologies will have had more time to expand and mature, further supporting increased HD ZEV adoption rates.

In summary, EPA recognizes that businesses that operate HD vehicles are under competitive pressure to reduce operating costs, which should encourage HD vehicle buyers to identify and rapidly adopt cost-effective technologies that reduce operating costs and the total cost of ownership. Outlays for labor and fuel generally constitute the two largest shares of HD vehicle operating costs, depending on the price of fuel, distance traveled, type of HD vehicle, and commodity transported (if any), so businesses that operate HD vehicles face strong incentives to reduce these costs. However, EPA also recognizes that there is uncertainty related to technologies that manufacturers may adopt in their compliance strategies for this final rule, like ZEVs, that may impact the adoption of these technologies even though they reduce operating costs. Markets for both new and used HD vehicles may face these problems, although it is difficult to assess empirically the degree to which they do. We expect these final Phase 3 standards as well as other factors we discussed will help overcome such barriers by incentivizing the development of technologies and supporting infrastructure that reduce operating costs and total cost of ownership, like ZEV technologies, and reduce uncertainties for HD vehicle purchasers on such technologies' benefits and other potential concerns. As noted, the final rule also sends a signal to electric utilities of demand under the modeled potential compliance pathway, and thus provides support justifying buildout of electrification infrastructure.

[1884] We designed a small number of vehicle types in HD TRUCS to refuel (with electricity or hydrogen) en-route, sizing them such that they could reach the 90th percentile VMT with one half hour or less refueling event per day—within a driver's required break period. We modeled the ZEV adoption rate for these vehicle types as 0 percent prior to MY 2030, when we anticipate that sufficient en-route refueling infrastructure will be available to support these types of vehicles.

[1885] Adoption rates estimated in HD TRUCS are one of several factors considered in determining the appropriate level of the standards. These estimated adoption rates in HD TRUCS demonstrate that the adoption rates in our modeled potential compliance pathway are all feasible.

[1886] Our assessment of total cost of ownership, shown in RIA Chapter 2.12, further supports our assessment of payback periods.

6.3 VMT Rebound

The "rebound effect" refers to the increase in demand for an energy service when the cost of the energy service is reduced due to efficiency improvements.[1887,1888,1889] In the context of HD vehicles, this has been interpreted as more intensive vehicle use, resulting in an increase in liquid fuel consumption, in response to increased ICE vehicle fuel efficiency. Although much of this possible vehicle use increase is likely to take the form of an increase in the number of miles vehicles are driven, it can also take the form of increases in the loaded operating weight of a vehicle or altering routes and schedules in response to improved fuel efficiency of the HD ICE vehicle. More intensive use of those HD ICE vehicles consumes fuel and generates emissions, which reduces fuel savings and avoided emissions that would otherwise be expected to result from increasing fuel efficiency of HD ICE vehicles.

Unlike the LD vehicle rebound effect, there is little published literature on the HD vehicle rebound effect, and all of it focuses on increased ICE fuel efficiency. Winebrake et al. (2012) suggest that vocational trucks and tractor trailers have a rebound effect of essentially zero. Leard et al. (2015) estimate that tractor trailers have a rebound effect of 30 percent, while vocational vehicles have a 10 percent rebound rate.[1890] Patwary et al. (2021) estimated that the average rebound effect of the U.S. road freight sector is between about 7 to 9 percent, though their study indicated that rebound has increased over time.[1891] This is slightly smaller than the value found by Leard et al. (2015) for the similar sector of tractors.

In the HD GHG Phase 2 final rule RIA, we estimated a 5 percent rebound effect for vocational trucks and for tractors being applied to ICE vehicles. These estimates were determined using the most recent studies in HD rebound at the time, as well as in response to comments submitted on the proposed HD GHG Phase 2 rule. As mentioned above, all the current research focuses on VMT rebound of HD ICE vehicles. With respect to ZEVs, specifically, we do not have data that operational cost savings of switching from an ICE vehicle to a ZEV will affect the VMT of that vehicle, nor do we have data on how changing fuel prices might affect VMT of ZEVs over time. Given the increasing penetration of ZEVs in the HD fleet, even in the reference case, as well as the wide range of effects discussed in the literature, we do not believe the rebound estimates in literature cited here are appropriate for use in our analysis. In addition, the majority of research on VMT rebound has been performed in the light-duty vehicle context. The factors influencing light-duty and heavy-duty VMT are generally different. For example, light-duty VMT is generally related to personal considerations, including costs and benefits associated with driving, while HD VMT is more a function of profits or impacts on labor. It is

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[1887] Winebrake, J.J., Green, E.H., Comer, B., Corbett, J.J., Froman, S., 2012. Estimating the direct rebound effect for on-road freight transportation. Energy Policy 48, 252-259.

[1888] Greene, D.L., Kahn, J.R., Gibson, R.C., 1999, "Fuel economy rebound effect for U.S. household vehicles," The Energy Journal, 20.

[1889] For a discussion of the wide range of definitions found in the literature, see Appendix D: Discrepancy in Rebound Effect Definitions, in EERA (2014), "Research to Inform Analysis of the Heavy-Duty vehicle Rebound Effect," and Excerpts of Draft Final Report of Phase 1 under EPA contract EP-C-13-025. (Docket ID: EPA-HQ-OAR-2014-0827). See also Greening, L.A., Greene, D.L., Difiglio, C., 2000, "Energy efficiency and consumption — the rebound effect — a survey," Energy Policy, 28, 389-401.

[1890] Leard, B., Linn, J., McConnell, V., and Raich, W. (2015). Fuel Costs, Economic Activity, and the Rebound Effect for Heavy-Duty Trucks. Resources For the Future Discussion Paper, 14-43.

[1891] Patwary, A. L., Yu, T. E., English, B.C., Hughes, D. W., and Cho, S. H. (2021). Estimating the rebound effect of the US road freight transport. Transportation Research Record, 2675(6), 165-174.

also important to note that even if there is an increase in VMT in new vehicles, this may be offset by a decrease in VMT on older vehicles. This may occur if operational cost savings on newer vehicles due to this rule lead operators to shift VMT to these newer, more efficient vehicles.

As in the proposal, we are not estimating any VMT rebound due to this rule (or, put another way, we estimate the effect is zero). If either ICE vehicles or ZEVs instead do exhibit some rebound effect, our approach would include slight overestimates of the emission reductions associated with these standards, as well as slight underestimates of additional traffic congestions and collisions. However, there may also be reductions in the severity of collisions if the rebound effect leads to lighter loads, as these lighter trucks would be less likely to cause an injury or fatality in a collision.[1892] Also, if rebound occurs, there may be some increase in non-GHG emissions and in brake and tire wear, but also an increase in benefits associated with increased vehicle use (for example, increased economic activity associated with the services provided by those vehicles), as well as positive impacts on employment. However, possible rebound may be reduced if owner/operators use those operational cost savings in other ways, for example to reduce their payback period. Also, as noted in the Winebrake at al. (2012) study, possible rebound impacts are likely reduced by adjustments in other operational costs such as labor, and the nature of the freight industry as an input to a larger supply chain system.

6.4 Employment Impacts

This section discusses potential employment impacts of the regulation. If the U.S. economy is at full employment, we expect that even a large-scale environmental regulation is unlikely to have a noticeable impact on aggregate net employment. Instead, labor would primarily be reallocated from one productive use to another, as workers transition away from jobs that are less environmentally protective and towards jobs that are more environmentally protective. Affected sectors may nevertheless experience transitory effects as workers change jobs. Some workers may retrain or relocate in anticipation of new requirements or require time to search for new jobs, while shortages in some sectors or regions could bid up wages to attract workers. These adjustment costs can lead to local labor disruptions. Even if the net change in the national workforce is small, localized reductions in employment may adversely impact individuals and communities just as localized increases may have positive impacts. If the economy is operating at less than full employment, economic theory does not clearly indicate the direction or magnitude of the net impact of environmental regulation on employment; it could cause either a short-run net increase or short-run net decrease as discussed further below.

6.4.1 Background and Literature

Economic theory of labor demand indicates that employers affected by environmental regulation may change their demand for different types of labor in different ways. They may increase their demand for some types, decrease demand for other types, or maintain demand for still other types. The uncertain direction of labor impacts is due to the different ways regulations affect labor demand. A variety of conditions can affect employment impacts of environmental regulation, including baseline labor market conditions, employer and worker characteristics, industry, and region. In general, the employment effects of environmental regulation are difficult to disentangle from other economic changes, including, for example, the impacts of the

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[1892] Nehiba, C., 2020. Taxed to death? Freight truck collision externalities and diesel taxes, Regional Science and Urban Economics, Volume 85.

coronavirus pandemic on labor markets, the general state of the macroeconomy, as well as a myriad of business decisions that affect employment. These changes have variable employment impacts, both over time and across regions and industries. In light of these difficulties, we look to economic theory to provide a constructive framework for approaching these assessments and for better understanding the inherent complexities in such assessments.

In this chapter, we describe three ways employment at the firm level might be affected by changes in a firm's production costs due to environmental regulation: a factor-shift effect, in which post-regulation production technologies may have different labor intensities than their pre-regulation counterparts; a demand effect, caused by higher production costs increasing market prices and decreasing demand; and a cost effect, caused by additional environmental protection costs leading regulated firms to increase their use of inputs, including labor, to produce the same level of output. These effects are outlined in a paper by Morgenstern et al. (2002), which provides the theoretical foundation for EPA's analysis of the impacts of this regulation on labor.[1893] Due to data limitations, EPA is not quantifying the impacts of the final regulation on firm-level employment for affected companies, although we acknowledge these potential impacts. Instead, for our analysis of the potential compliance pathway, we describe possible effects on employment due to utilization of ZEV technologies, and then discuss factor-shift, demand, and cost employment effects for the regulated sector at the industry level.

Additional papers approach employment effects through similar frameworks. Berman and Bui (2001)[1894] model two components that drive changes in firm-level labor demand: output effects and substitution effects.[1895] Deschênes (2018)[1896] describes environmental regulations as requiring additional capital equipment for pollution abatement that does not increase labor productivity. For an overview of the neoclassical theory of production and factor demand, see Chapter 9 of Layard and Walters' Microeconomic Theory.[1897] Ehrenberg and Smith (2000)[1898] describe how, at the industry level, labor demand is more likely to be responsive to regulatory costs if: (1) the elasticity of labor demand is high relative to the elasticity of labor supply, and (2) labor costs are a large share of total production costs.

Arrow, Cropper, et al. (1996)[1899] state that, in the long run, environmental regulation is expected to cause a shift of employment among employers rather than affect the general employment level. Even if they are mitigated by long-run market adjustments to full

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[1893] Morgenstern, R., Pizer, W., & Shih, J.-S. (2002). Jobs Versus the Environment:" An Industry-Level Perspective. Journal of Environmental Econometrics and Management, 43, 412-436.

[1894] Berman, E., & Bui, L. (2001). Environmental Regulation and Labor Demand: Evidence from the South Coast Air Basin. *Journal of Public Economics, 79*(2), 265-295

[1895] Berman and Bui (2001) also discuss a third component, the impact of regulation on factor prices, but conclude that this effect is unlikely to be important for large competitive factor markets, such as labor and capital.

[1896] Deschenes, O. (2018). Balancing the Benefits of Environmental Regulations for Everyone and the Costs to Workers adn Firms. *IZA World of Labor, 22v2*. Retrieved from https://wol.iza.org/uploads/articles/458/pdfs/environmental-regulations-and-labor-markets.pdf

[1897] Layard, R., & Walters, A. (1978). Microeconomic Theory. London: McGraw-Hill.

[1898] Ehrenberg, R., & Smith, R. (2000). Modern Labor Economics: Theory and Public Policy. Addison Wesley Longman, Inc.

[1899] Arrow, R., Cropper, M., Eads, G., Hahn, R., Lave, L., Noll, R., Stavins, R. (1996). Is There a Role for Benefit-Cost Analysis in Environmental, Health, and Safety Regulation? *Science, 272*(5259), 221-222 employment, many regulatory actions have transitional effects in the short run.[1900,1901] These movements of workers in and out of jobs in response to environmental regulation are potentially important distributional impacts of interest to policy makers. Of particular concern are transitional job losses experienced by workers operating in declining industries, exhibiting low migration rates, or living in communities or regions where unemployment rates are high.

Workers affected by changes in labor demand due to regulation may experience a variety of impacts including job gains or involuntary job loss and unemployment. Compliance with environmental regulation can result in increased demand for the inputs or factors (including labor) used in the production of environmental protection. However, the regulated sector generally relies on revenues generated by their other market outputs to cover the costs of supplying increased environmental quality, which can lead to reduced demand for labor and other factors of production used to produce the market output. Workforce adjustments in response to decreases in labor demand can be costly to firms as well as workers, so employers may choose to adjust their workforce over time through natural attrition or reduced hiring, rather than incur costs associated with job separations (see, for instance, Curtis (2018)[1902] and Hafstead and Williams (2018)[1903]).

As suggested in this discussion, the overall employment effects of environmental regulation are difficult to estimate. Estimation is difficult due to the multitude of small changes that occur in different sectors related to the regulated industry, both upstream and downstream, or in sectors producing substitute or complimentary products. In the following sections, we qualitatively discuss potential impacts of the rule on the vehicle manufacturing, battery production, and charging and refueling infrastructure sectors due to the utilization of ZEV technologies under the potential compliance pathway, and due to the factor-shift, demand and cost effects. Then, we briefly discuss potential impacts on additional sectors such as the retail firms selling products transported by HD trucks and the petroleum refining industry.

6.4.2 Potential Employment Impacts of the Final Rule

Manufacturing vehicles that include GHG-reducing technology may lead to employment effects. For example, should manufacturers choose to comply by using ZEV technologies as part of their compliance strategies, the increasing adoption of BEVs and FCEVs in the market is likely to affect both the number and the nature of employment in the HD manufacturing and related sectors, such as providers of battery charging and refueling infrastructure. Over time, as ZEVs become a greater portion of the new HD vehicle fleet, the kinds of jobs in HD manufacturing would be expected to change. For instance, there will be no need for engine and exhaust system assembly for BEVs, while many assembly tasks will instead involve electrical rather than mechanical fitting. Batteries represent a significant portion of the manufacturing content of an electrified vehicle, and some automakers are likely to purchase the cells, if not pre-

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[1900] Smith, V. (2015). Should Benefit-Cost Methods Take Account of High Unemployment? Review of Environmental Economics and Policy, 9(2), 165-178.

[1901] U.S. OMB. (2015). 2015 Report to Congress on the Benefits and Costs of Federal Regulations and Agency Compliance with the Unfunded Mandates Reform Act. Retrieved from https://obamawhitehouse.archives.gov/sites/default/files/omb/inforeg/2015_cb/2015-cost-benefit-repot.pdf/

[1902] Curtis, M. (2018). Who Loses Under Cap-and-Trade Programs? The Labor Market Effects of the NOx Budget Trading Program. The Review of Economics and Statistics, 100(1), 151-166.

[1903] Hafstead, M., & Williams III, R. (2018). Unemployment and Environmental Regulation in General Equilibrium. Journal of Public Economics, 160, 50-65.

assembled modules or packs, from suppliers whose employment will thereby be affected. Employment will be affected in building and maintaining battery charging or fuel cell refueling infrastructure needed to support the ever-increasing number of ZEVs on the road, as well as in the maintenance and operation of distribution infrastructure for fossil fuels. For much of these effects, there is not enough data to quantitatively assess how employment might change as a function of the increased electrification expected to result under the standards.

A recent report from the Seattle Jobs Initiative identified sectors most strongly associated with LD ICE vehicle and BEV production, where electrical equipment and manufacturing and other electrical equipment and component manufacturing were said to be associated with LD BEV production (including batteries), and motor vehicle manufacturing, motor vehicle body and trailer manufacturing, and motor vehicle parts manufacturing were associated with both LD BEV and ICE vehicle production.[1904] These sectors also include HD vehicle manufacturing. The Employment Requirements Matrix (ERM) provided by the U.S. Bureau of Labor Statistics (BLS) provides direct estimates of employees per $1 million in expenditures for a total of 202 aggregated sectors that roughly correspond to the 4-digit NAICS code level, and provides data from 1997 through 2022.[1905] These estimates are averages, covering all the activities in these sectors and may not be representative of the labor effects when expenditures are required for specific activities, or when manufacturing processes change due to compliance activities in such a way that labor intensity changes. For instance, the ratio of workers to production cost for the motor vehicle body and trailer manufacturing sector represents this ratio for all motor vehicle body and trailer manufacturing activities, and not just for production processes related to emission reductions compliance activities. In addition, these estimates do not include changes in sectors that supply these sectors, such as steel or electronics producers. However, examining that data over time suggests general employment trends in light- and heavy-duty manufacturing. Using this historical data, we can see that the workers per $1 million in sales for all six of these sectors has, generally, decreased over time. Over time, the amount of labor needed in the motor vehicle industry has changed: automation and improved production methods have generally led to significant productivity increases. The BLS ERM, for instance, provides estimates that, in 2002, about 0.95 workers in the Motor Vehicle Manufacturing sector was needed per $1 million, (in 2022$), while, for 2022 this figure had decreased to only 0.76 workers per $1 million (2022$). Though two sectors mainly associated with the production of components that go into BEVs and the battery electric portion of PHEV manufacturing, electrical equipment manufacturing and other electrical equipment and component manufacturing, show an increase in recent years.

Figure 6-1 shows the estimates of employment per $1 million of expenditure for each sector for each data source over the past twenty years, adjusted to 2022 dollars using the U.S. Bureau of Economic Analysis Gross Domestic Product Implicit Price Deflator retrieved from the Federal

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[1904] Seattle Jobs Initiative. (2020). Amping Up Electric Vehicle Manufacturing in the PNW: Opportunities for Business, Workforce, and Education. Retrieved from https://www.seattle.gov/Documents/Departments/OSE/ClimateDocs/TE/EV%20Field%20in%20OR%20and%20WA_February20.pdf

[1905] Bureau of Labor Statistics. (2023). Real Domestic Employment Requirements. Retrieved January 2023, from http://www.bls.gov/emp/ep_data_emp_requirements.htm

Reserve Bank of St. Louis. The values are adjusted to remove effects of imports through the use of a ratio of domestic production to domestic sales of 0.81.[1906]

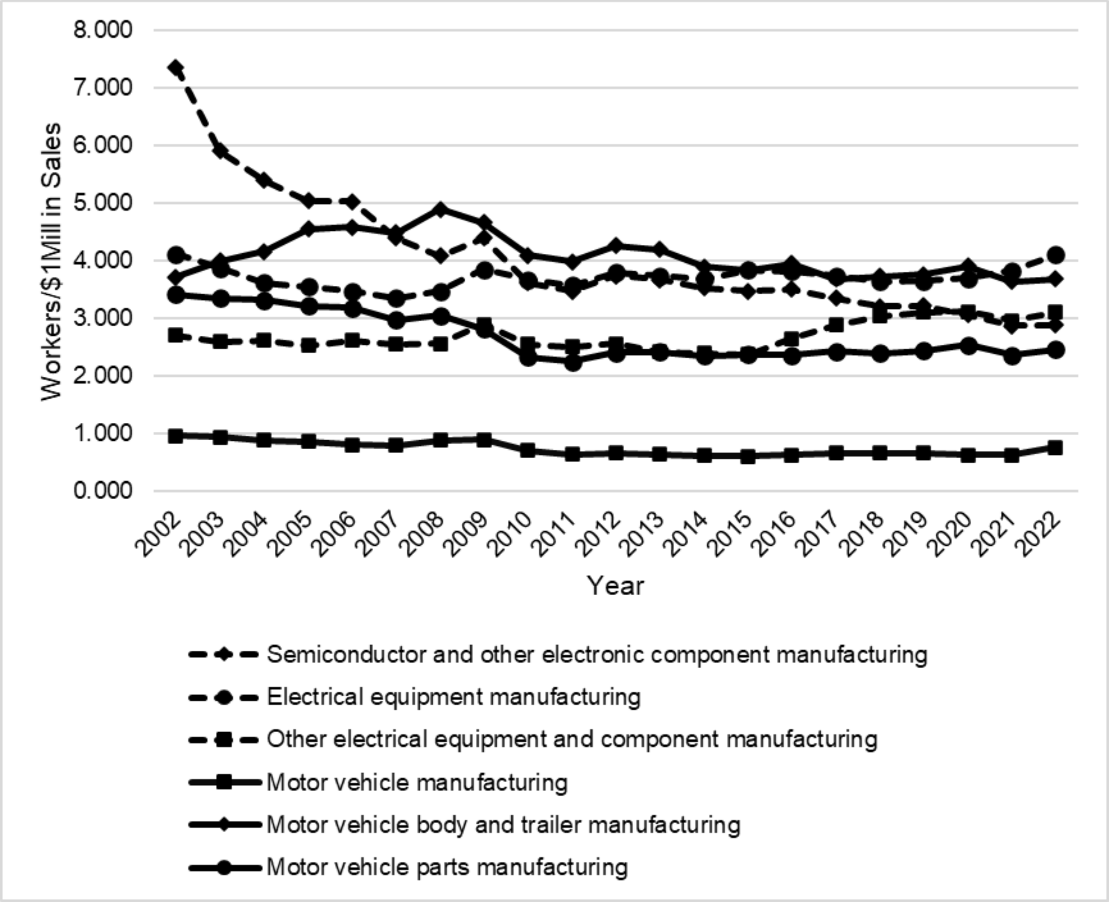

Figure 6-1 Workers per million dollars in sales, adjusted for domestic production.

Though most of the research on employment effects associated with a market shift from ICE vehicles to ZEVs is focused on the light-duty market, many of the same ideas transfer to the HD market as well. Generally, research is not consistent on the expected direction or magnitude of change in employment as new ICE vehicle sales are replaced with new BEV or fuel cell vehicle sales. The BlueGreen Alliance states that although battery electric vehicles have fewer parts than their ICE counterparts, there is potential for job growth in electric vehicle component manufacturing, including batteries, electric motors, regenerative braking systems and semiconductors, and manufacturing those components in the US can lead to an increase in jobs.[1907] They go on to state that if the U.S. does not become a major producer for these components, there is risk of job loss. EDF also reports that the job growth and investment in the EV sector that has been seen over the last eight years is expected to continue, with new factories

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[1906] To estimate the proportion of domestic production affected by the change in sales, we use data from WardsAuto for total car and truck production in the U.S. compared to total car and truck sales in the U.S. Over the period 2012-2022, the proportion averages 84 percent. From 2017-2022, the proportion average is slightly lower, at 81 percent.

[1907] BlueGreen Alliance. (2021). Backgrounder: EVs are Coming. Will They be Made in the USA? Retrieved from https://www.bluegreenalliance.org/wp-content/uploads/2021/04/Backgrounder-EVs-Are-Coming.-Will-They-Be-Made-in-the-USA-vFINAL.pdf or production lines for EVs, batteries, components and chargers supporting more than 125,000 jobs being announced across 26 states.[1908] In updates reported to EPA in comments on the proposed rule, EDF reports that more than 70,000 jobs have been created in U.S. battery and battery component production since 2015.

In anticipation of shifts in the skills necessary for workers in the automobile industry due to a greater share of electric vehicles, the International Union, United Automobile, Aerospace and Agricultural Implement Workers of America (UAW) states that re-training programs will be needed to prepare workers that might be displaced by the shift to the new technology.[1909] Though the UAW commented that a slower increase in the penetration of EVs in the market than what we estimated in our proposal will better support employees in auto manufacturing and the supporting industries, they are also working to support employees as this shift in manufacturing is being made, as evidenced by the recent UAW autoworkers strike, with one goal being to support to employees working on EVs.[1910] Volkswagen states that labor requirements for ICE vehicles are about 70% higher than their electric counterpart, but these changes in employment intensities in the manufacturing of the vehicles can be offset by shifting to the production of new components, for example batteries or battery cells.[1911] Research from the Seattle Jobs initiative indicates that employment in a collection of sectors related to both battery electric and ICE vehicle manufacturing is expected to grow slightly through 2029.[1912] Though most of these statements are specifically referring to light-duty vehicles, they hold true for the HD market as well.

Climate Nexus also indicates that increasing penetrations of electric vehicles will lead to a net increase in jobs, a claim that is partially supported by the rising investment in batteries, vehicle manufacturing and charging stations.[1913] The expected investment mentioned by Climate Nexus is also supported by recent federal investment which will allow for increased investment along the vehicle supply chain, including domestic critical minerals, materials processing, battery manufacturing, charging infrastructure, and vehicle assembly and vehicle component manufacturing, both in the LD and HD markets.[1914] This investment includes the BIL, the

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[1908] EDF. (2023). New climate laws drive boom in electric vehicle jobs. Retrieved November 1, 2023 from https://vitalsigns.edf.org/story/new-climate-laws-drive-boom-electric-vehicle-jobs

[1909] UAW. (2020). Taking the High Road: Strategies for a Fair EV Future. Retrieved from https://uaw.org/wp-content/uploads/2019/07/190416-EV-White-Paper-REVISED-January-2020-Final.pdf

[1910] Olander, O., and Niedzwiadek, N. (2023). What the pending UAW-Big 3 deals mean for workers, Biden and the economy. Politico. Retrieved November 3, 2023 from https://www.politico.com/news/2023/10/30/uaw-big-3-labor-biden-economy-00124368

[1911] Herrmenn, F., Beinhauer, W., Borrmann, D., Hertwig, M., Mack, J., Potinecke, T., . . . Rally, P. (2020). Employment 2030: Effect of Electric Mobility and Digitalisation on the Quality ond Quantity of Employment at Volkswagen. Fraunhofer Institute for Industrial Engineering IAO. Retrieved from https://www.volkswagenag.com/presence/stories/2020/12/frauenhofer-studie/6095_EMDI_VW_Summary_um.pdf

[1912] Seattle Jobs Initiative. (2020). Amping Up Electric Vehicle Manufacturing in the PNW: Opportunities for Business, Workforce, and Education. Retrieved from https://www.seattle.gov/Documents/Departments/OSE/ClimateDocs/TE/EV%20Field%20in%20OR%20and%20WA_February20.pdf

[1913] Climate Nexus. (2022). Job Impacts From the Shift to Electric Cars and Trucks. Retrieved December 2022, from https://climatenexus.org/climate-issues/energy/ev-job-impacts/

[1914] Inflation Reduction Act of 2022, H.R. 5376 (117th Cong., 2nd sess. 2022).

CHIPS Act,[1915] and the IRA, which are expected to create domestic employment opportunities along the full automotive sector supply chain, from components and equipment manufacturing and processing to final assembly, as well as incentivize the development of reliable EV battery supply chains both for BEVs and PHEVs.[1916] The IRA is expected to impact domestic employment through conditions on eligibility for purchase incentives and battery manufacturing incentives. These conditions include contingencies for domestic assembly, domestic critical materials production, and domestic battery manufacturing. As an example, a new joint venture between Daimler Trucks, Cummins, and PACCAR recently announced a new battery factory to be built in the U.S. to manufacture cells and packs initially focusing on heavy-duty and industrial applications was announced in September 2023.[1917] The BlueGreen Alliance and the Political Economy Research Institute estimate that the IRA will create over 9 million jobs over the next decade, with about 400,000 of those jobs being attributed directly to the IRA's battery and fuel cell vehicle provisions.[1918,1919] In addition, the IRA is expected to lead to increased demand in ZEVs through tax credits for purchasers of ZEVs. However, even with increases in employment in component production and new domestic jobs related to ZEVs, these shifts in production of HD vehicles may negatively affect workers currently employed in production of ICE vehicles.

As discussed in RTC Section 19.6, there are many existing and planned projects focused on training new and existing employees in fields related to green jobs, and specifically green jobs associated with electric vehicle production, maintenance and repair, and the associated charging infrastructure. This includes work by the Joint Office of Energy and Transportation (JOET), created by the BIL, which supports efforts related to deploying infrastructure, chargers, and zero emission transit and school buses.[1920] One example of a project from the JOET is the Ride and Drive grant program, which targets investments in EV charging resiliency, community-driven workforce development and EV charging performance and reliability. Another example is the Battery Workforce Initiative established by the Department of Energy (DOE) in coordination with the Department of Labor (DOL), AFL-CIO, and other organizations with the goal of

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[1915] The CHIPS Act is the Creating Helpful Incentives to Produce Semiconductors and Science Act and was signed into law on August 9, 2022. It is designed to strengthen supply chains, domestic manufacturing, and national security. More information can be found at *https://www.whitehouse.gov/briefing-room/statements-releases/2022/08/09/fact-sheet-chips-and-science-act-will-lower-costs-create-jobs-strengthen-supply-chains-and-counter-china/*.

[1916] More information on how these acts are expected to aid employment growth and create opportunities for growth along the supply chain can be found in the January, 2023 White House publication "Building a Clean Energy Economy: A Guidebook to the Inflation Reduction Act's Investments in Clean Energy and Climate Action." found online at https://www.whitehouse.gov/wp-content/uploads/2022/12/Inflation-Reduction-Act-Guidebook.pdf

[1917] Daimler Trucks North America. "Accelera by Cummins, Daimler Truck and PACCAR form a joint venture to advance battery cell production in the United States." September 6, 2023. Available online: *https://media.daimlertruck.com/marsMediaSite/en/instance/ko/Accelera-by-Cummins-Daimler-Truck-and-PACCAR-form-a-joint-venture-to-advance-battery-cell-production-in-the-United-States.xhtml?oid=52385590* (last accessed October 23, 2023).

[1918] Note that these are not all net new employment and reflects where workers may be hired away from other jobs. As the labor market gets tighter and the economy is closer to full employment, there will be a greater number of employees shifting from one job to another.

[1919] Political Economy Research Institute. (2022). *Job Creation Estimates Through Proposed Inflation Reduction Act.* University of Massachusetts Amherst. Retrieved from https://www.bluegreenalliance.org/site/9-million-good-jobs-from-climate-action-the-inflation-reduction-act/

[1920] More information on these programs, and other programs, can be found in the memo "Labor/Employment Initiatives in the Battery/Vehicle Electrification Space" from the Employment and Training Administration (ETA) at DOL to Elizabeth Miller, located in the docket for this rule.

accelerating the development of high-quality training. DOL has also established the Building Pathways to Infrastructure Jobs Grant Program, which support worker-centered sector strategy training programs. DOL also provides grants to help community colleges provide skilled pathways to good jobs in the transportation and clean energy sectors. DOL is also providing technical assistance to the Southeast EV Collaborative, which is made up of collection of state workforce agencies in the southeast region of the U.S. focused on identifying opportunities to work together to provide equitable access to good jobs across the region.

6.4.3 The Factor-Shift Effect

The factor-shift effect refers to employment changes due to changes in labor intensity of production resulting from compliance activities. The final standards do not mandate the use of a specific technology, and EPA anticipates that a compliant fleet under the standards will include a diverse range of technologies including ICE vehicle and ZEV technologies. A factor shift effect of this rule might occur if this regulation affects the labor intensity of production of ICE vehicles. It may also occur if a ZEV replaces an ICE vehicle (holding total sales constant). We do not have data on how the regulation might affect labor intensity of production within ICE vehicle production. ZEVs and ICE vehicles require different inputs and have different costs of powertrain production, though there are many common parts as well. There is little research on the relative labor intensity needs of producing a HD ICE vehicle and producing a comparable HD ZEV. Though there are some news articles and research from the light-duty motor vehicle market, they do not provide a clear indication of the relationship between employment needs for ZEVs and ICE vehicles. Some studies find that LD BEVs are less complex, requiring fewer person-hours to assemble than a comparable ICE vehicle.[1921] Others find that there is not a significant difference in the employment needed to produce LD ICE vehicles when compared to BEVs.

EPA worked with a research group, FEV, to produce a peer-reviewed tear-down study of a BEV (Volkswagen ID.4) to its comparable ICE vehicle counterpart (Volkswagen Tiguan).[1922] Included in this study are estimates of labor intensity needed to produce each vehicle under three different assumptions of vertical integration of manufacturing scenarios ranging from a scenario where most of the assemblies and components are sourced from outside suppliers to a scenario where most of the assemblies and components are assembled in house. Under the low and moderate levels of vertical integration, results indicate that assembly time of the BEV at the plant is reduced compared to assembly time of the ICE vehicle.[1923] Under a scenario of high vertical integration, which includes the BEV battery assembly, results show an increase in time needed to assemble the BEV. When powertrain systems are ignored (battery, drive units, transmission, and engine assembly), the BEV requires more time to assemble under all three vertical integration scenarios. The results indicate that the largest difference in assembly comes from the building of the battery pack assembly. When the battery cells are built in-house, the BEV will require more labor hours to build. Though this research, along with the other studies mentioned above, focus

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[1921] Barrett, Jim and Josh Bivens. “The stakes for workers in how policymakers manage the coming shift to all-electric vehicles”. Economic Policy Institute. September 22, 2021. Available online: https://www.epi.org/publication/ev-policy-workers/.

[1922] See RIA Chapter 2.5.2.2.3 for more information.

[1923] In the FEV report, "assembly time" is the time (in hours) it takes to assemble the vehicle from the component parts.

on LD electrification, it is likely the same principles apply to the manufacturing of electric HD vehicles.

What is not discussed in this research is that battery cells must be built, regardless of where that occurs. As described above, and in Section II.D of the Preamble, battery plants are being planned and built in the U.S., with support from the IRA, BIL and CHIPs. Though we have more information today on differences in the time it takes to build an ICE vehicle and a comparable BEV or PHEV, we do not have enough information to estimate a factor-shift effect of the final rule. We do not know how OEMs will be (and are) manufacturing their vehicles, or what this will look like in several years as the MY 2027 and later standards become effective and the projected share of electric vehicles being produced and sold increases. Nor do we have information on labor needs of other low or zero-emission heavy-duty vehicles compared to internal combustion gas or diesel powertrain vehicles. We can say, generally, that the study described above indicates that if production of electric vehicles and their power supplies take place in the U.S. at the same rates as ICE vehicles, we do not expect employment in vehicle production to fall due to increasing penetration of HD electric vehicles, and it may likely increase. As production in the related sectors of battery production and the construction of charging and refueling stations is ramped up, their labor intensities may increase or decrease relative to the reference case scenario. Given the current lack of data and inconsistency in the existing literature, we are unable to estimate a quantitative factor-shift effect as a function of this rule.

6.4.4 The Demand Effect

The demand effect refers to potential employment changes due to changes in new HD vehicle sales. In general, if HD ICE vehicle sales increase, keeping the share of ZEVs in the new HD vehicle fleet constant, more people would be needed to assemble trucks and the components used to manufacturer them. On the other hand, if HD ZEV sales increase, we expect more people would be needed to assemble ZEVs and their components, including batteries. If ZEVs and ICE vehicles have different labor intensities of production, the relative change in ZEV and ICE sales would impact the demand effect on employment. If, for example, the ZEV sales increased relative to ICE vehicles, the increase in employment would depend on the relative labor intensities. Additionally, short-term effects might be seen if pre- or low-buy were to occur, depending on the magnitude of those effects (as discussed above). If they are of small magnitudes, as expected, turnover of workers might not be affected. At higher magnitudes, if pre-buy occurs, HD vehicle sales may increase temporarily, leading to temporary increases in employment in the related manufacturing sectors. If low-buy occurs, there may be temporary decreases in employment in the related manufacturing sectors. However, as noted above, EPA does not expect significant pre-buy or low-buy resulting from this rule. In addition, as noted in RIA Chapter 6.1, we do not anticipate much mode or class shift in HD market affected by this rule, which also supports a minimal demand effect on employment.

6.4.5 The Cost Effect

The cost effect on employment refers to the impact on labor due to increased costs of adopting technologies needed for vehicles to meet new emission standards, with the condition that other factors (output and factor intensities) are held constant. In the HD ICE vehicle manufacturing sector, if firms invest in lower-emitting HD ICE vehicles, there might be labor used to implement those technologies. For firms producing ZEVs, we do not expect the rule to require additional compliance activities, as such vehicles by definition have zero tailpipe emissions.[1924] In addition, the standards do not mandate the use of a specific technology and EPA anticipates that a compliant fleet under the standards will include a diverse range of technologies including ICE and ZEV technologies. Under the additional compliance pathways projected for this final rule that include only technology adoption in ICE vehicles, we expect there could be some increase in employment related to implementing these ICE technologies. However, the level of employment due to implementing new ICE technology as result of this rule will depend on the relative rate of the adoption of the technology.

6.4.6 Overall Effects

In conclusion, the overall effect of the rule on HD manufacturing employment depends on the relative magnitude of factor-shift, cost, and demand effects. Due to a lack of data, we are not able to estimate quantitative employment effects from this rule on HD manufacturing. The qualitative discussion above suggests that the direction of impacts could potentially be positive or negative. If HD vehicle production shifts from HD ICE to HD ZEV, there may be negative impacts on workers currently employed in ICE production. However, looking more broadly and including consideration of employment impacts on battery manufacturing and battery and refueling infrastructure, Climate Nexus indicates that increasing penetrations of electric vehicles will lead to a net increase in jobs, as described in Chapter 6.4.2. This is also supported by recent federal investment which will allow for increased investment along the vehicle supply chain, including domestic battery manufacturing, charging infrastructure, and vehicle manufacturing. The BIL was signed in November 2021 and provides over $24 billion in investment in electric vehicle chargers, critical minerals, and components needed by domestic manufacturers of EV batteries and for clean transit and school buses.[1925] The CHIPS Act, signed in August 2022, invests in expanding America's manufacturing capacity for the semiconductors used in electric vehicles and chargers. [1926]

We note that employment impacts may be felt outside of the U.S., though this depends on many factors, including firm-level decisions, macroeconomic factors in different locations, geographic-based specializations, and more. We also note that, as discussed in 6.1.4, the final standards are not expected to provide incentives for manufacturers to shift between domestic and foreign production. Furthermore, the IRA provides incentives for producers to expand domestic manufacturing of BEVs and domestic sourcing of components and critical minerals needed to produce them.[1927] The IRA also provides incentives for consumers to purchase both new and used ZEVs. These pieces of legislation are expected to create domestic employment opportunities along the full automotive sector supply chain, from components and equipment manufacturing and processing to final assembly, as well as incentivize the development of

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[1924] We note that there may be indirect impacts, for example through battery durability monitoring or warranty requirements. See Preamble Section III.B for more information on these requirements.

[1925] The Bipartisan Infrastructure Law is officially titled the Infrastructure Investment and Jobs Act. More information can be found at https://www.fhwa.dot.gov/bipartisan-infrastructure-law/

[1926] The CHIPS and Science Act was signed by President Biden in August, 2022 to boost investment in, and manufacturing of, semiconductors in the U.S. The fact sheet can be found at https://www.whitehouse.gov/briefing-room/statements-releases/2022/08/09/fact-sheet-chips-and-science-act-will-lower-costs-create-jobs-strengthen-supply-chains-and-counter-china/

[1927] Inflation Reduction Act of 2022, H.R. 5376 (117th Cong., 2nd sess. 2022).

reliable EV battery supply chains.[1928] Importantly, domestic employment is expected to be positively impacted due to the domestic assembly, production and manufacturing conditions on eligibility for purchase incentives and battery manufacturing incentives in the IRA. Estimates from the BlueGreen Alliance and the Political Economy Research Institute state that the IRA could lead to over 9 million jobs over the next decade, about 400,000 of which are attributed directly to the IRA's battery and fuel cell vehicle provisions.[1929]

6.4.7 Employment in Additional Related Sectors

As the share of ZEVs in the HD market increases under the potential compliance pathway, we also expect effects on employment in the associated BEV charging and hydrogen refueling infrastructure industries, described in RIA Chapters 1.6 and 1.8. This can happen through many avenues, including increased demand for batteries, and therefore increased employment needs, through greater demand for charging and fueling infrastructure to support more ZEVs, leading to more private and public charging facilities being constructed, or through greater use of existing facilities, which can lead to increased maintenance needs for those facilities. For example, as described in RIA Chapter 2.10.3, we estimated the total number of EVSE ports that will be required to support the depot-charged BEVs in the technology packages developed to support the MY 2027–2032 standards. We find about 520,000 EVSE ports will be needed at depots across all six model years. This increased demand in EVSE will increase the employment in this sector. Employment related to constructing and maintaining these facilities is expected to increase. Though we received comments with concerns that there are not enough qualified technicians to support the infrastructure needs estimated as a function of this rule under the potential compliance pathway, we expect this to be a gradual increase, with more technicians being trained over time. If there is a shortage of technicians in this sector, economic theory suggests that as demand for technicians in this sector increases, employment in the industry may become more attractive (either due to higher wages because of the rarity of the skill set, more opportunities due to high demand for the skill set, or both), and the number of workers willing to train, and companies willing to invest in those workers, is expected to increase. Also, as described elsewhere in this chapter, Federal actions, as well as projects through federal agencies and other groups have already been and are expected to continue to support and expand training for employees in this sector. See RIA Chapters 1.3.2 and 1.6.2 (along with RTC Section 6) for a summary of planned and ongoing charging infrastructure investments.

EPA expects possible employment impacts on additional downstream and upstream sectors from the shifts in HD vehicle manufacturing due to this rule. With respect to the potential for downstream effects, this action could provide some positive impacts on the supply of drivers in the heavy-duty trucking industry. As discussed in Preamble Section IV, under the potential compliance pathway the reduction in fuel costs from purchasing a ZEV instead of an ICE vehicle is expected to not only reduce operating costs for ZEV owners and operators, compared to an ICE vehicle, but may also provide additional incentives to purchase a HD ZEV over a HD ICE

[1928] More information on how these Acts are expected to aid employment growth and create opportunities for growth along the supply chain can be found in the January 2023 White House publication "Building a Clean Energy Economy: A Guidebook to the Inflation Reduction Act's Investments in Clean Energy and Climate Action." found online at https://www.whitehouse.gov/wp-content/uploads/2022/12/Inflation-Reduction-Act-Guidebook.pdf

[1929] Political Economy Research Institute. (2022). *Job Creation Estimates Through Proposed Inflation Reduction Act.* University of Massachusetts Amherst. Retrieved from https://www.bluegreenalliance.org/site/9-million-good-jobs-from-climate-action-the-inflation-reduction-act/

vehicle. For example, in comments submitted on the proposal, the Clean Air Task Force, RMI and the Zero Emission Transportation Association stated that electric trucks are desirable to drivers because they are more comfortable, have a smoother ride with minimal vibrations, produce less noise pollution, do not smell, and have a high-tech driving experience. The commenters state that the more desirable electric trucks have the possibility of decreasing truck driver shortages and increasing driver retention.

Another potential downstream impact is on the services provided by HD vehicles. Because of the diversity of the HD vehicle market, we expect entities from a wide range of transportation sectors to purchase vehicles subject to the emission standards. HD vehicles are typically commercial in nature, and typically provide an "intermediate good," meaning that they are used to provide a commercial service (transporting goods, municipal service vehicles, etc.), rather than serving as final consumer goods themselves (as most light-duty vehicles do). As a result, the purchase price of a new HD vehicle likely impacts the price of the service provided by that vehicle. Purchase incentives, as might be available for a new ZEV, may also impact the price of services provided through the impact on the upfront cost of that vehicle. In addition, lifetime operating costs may impact the prices of services provided. If a change in these costs results in higher prices for the services provided by these vehicles compared to the same services provided by a pre-regulation vehicle, it would potentially reduce demand for the services such vehicles provide. In turn, there may be less employment in the sectors providing such services. On the other hand, if a change in these costs results in lower prices for services provided, there may be an increase in employment in the sectors providing such services. We estimate that there are savings over the life of operating a ZEV relative to an ICE vehicle, which may decrease downstream prices. We expect that the actual effects on demand for the services provided by these vehicles and related employment will depend on cost pass-through, as well as responsiveness of demand to changes in transportation cost, should such changes occur.[1930]

This action may also produce upstream employment effects in other sectors, for example, in firms providing liquid fuel. While reduced liquid fuel consumption represents cost savings for purchasers of liquid fuel, it could also represent a loss in value of output for the petroleum refining industry, which could result in reduced employment in that sector. These impacts may also pass up the supply chain to, for example, pipeline construction, operation and maintenance, and domestic oil production. In this final rule, we estimate that the reduction in fuel consumption (see RIA Chapter 6.5) will be met by increasing net exports by half of the amount of reduced domestic demand for refined product, with the other half being met by reductions in U.S. refinery output (see RIA Chapter 4.3 for more information on our assumptions of changes in U.S. refinery output). As discussed in RIA Chapter 4.3, there have been several closures or conversions of refineries in recent years that are attributed to many factors, including lower fuel demand due to COVID-19 or decisions to pivot away from fossil fuels. Though the reduced domestic output may lead to future closures or conversions of individual refineries, we are unable to estimate the future decisions of refineries to keep operating, shut down or convert away from fossil fuels because they depend on the economics of individual refineries, economic conditions of parent companies, long-term strategies for each company, and on the larger macro-economic conditions of both the U.S. and the global refinery market. Therefore, we are unable to estimate the possible effect this rule will have on employment in the petroleum refining sector.

[1930] Cost pass-through refers to the amount of increase in up-front cost incurred by the HD vehicle owner that is then passed on to their customers in the form of higher prices for services provided by the HD vehicle owner.

However, because the petroleum refining industry is material intensive and not labor intensive, and we estimate that only part of the reduction in liquid fuel consumption will be met by reduced refinery production in the U.S., we expect that any employment effect due to reduced petroleum demand will be small.

An additional employment impact could be felt on the industries that service and maintain HD vehicles. Due to less need for maintenance of ZEV vehicles relative to ICE vehicles, demand for such workers could decrease. In addition, commenters stated that, similar to technicians supporting charging infrastructure, there is currently a lack of qualified technicians able to service and maintain HD ZEVs. However, this may be a short-term issue. As the share of HD ZEVs in the market grows, demand for qualified technicians will also grow.[1931] As mentioned in the discussion of infrastructure technicians, if there is a shortage of technicians who can maintain and service HD ZEVs, employment in the industry may become more attractive (either due to higher wages because of the rarity of the skill set, more opportunities due to high demand for the skill set, or both), and workers willing to train, and companies willing to invest in those workers, is expected to increase. Also, it is not unreasonable to assume that technicians trained to work on HD vehicles will be uniquely qualified to retrain for ZEVs. Though ZEV maintenance requires additional skillsets beyond those learned by a traditional HD vehicle technician, there are aspects of the knowledge base acquired by working on HD vehicles that should transfer to ZEVs. In addition, as described above in Chapter 6.4.2, DOL, DOE and other groups are involved in existing and planned projects focused on training new and existing employees in green energy jobs, including maintenance and repair.

This action could also provide some positive impacts on driver employment in the HD trucking industry. As discussed in Preamble Section IV, the reduction in fuel costs from purchasing a ZEV instead of an ICE vehicle will be expected to not only reduce operational costs for ZEV owners and operators compared to an ICE vehicle, but it may also provide additional incentives to purchase a HD ZEV over a HD ICE vehicle. For example, comments submitted on the proposed rule stated that HD ZEVs are associated with increased driver satisfaction due to quieter operations, better visibility, a smoother ride, faster acceleration, less odor, and a smoother and safer experience when driving in high traffic or urban environments. The commenters state that these positive attributes have the possibility of decreasing truck driver shortages and increasing driver retention. Also, drivers of HD ZEVs, as well as other HD vehicles compliant with this rule, will benefit from the decreased emissions of the vehicle they are driving.

An additional factor to consider for employment impacts across all industries that might be affected by this rule under the potential compliance pathway, or by the increase in the share of HD ZEVs in the market, is that though more ZEVs are being introduced to the market, regardless of this rule, the vehicles on the road will still continue to be dominated by HD ICE vehicles, and many HD ICE vehicles will continue to be sold. This gradual shift avoids abrupt changes and will reduce impacts in acceptance, infrastructure availability, employment, supply chain, and more.

[1931] As discussed in Section 3.7 of the RTC, we account for a transition period during which extra training needs for ZEV maintenance and repair may be required in the first few years of the rule. To account for this, we use a decreasing scaling factor over 5 years, starting in 2027 for BEVs and 2031 for FCEVs, which, in effect, reduces the projected cost savings due to maintenance and repair in the early years compared to those in the later years.

6.5 Oil Imports and Electricity and Hydrogen Consumption

We project that the final emission standards will reduce not only GHG emissions but also liquid fuel consumption while simultaneously increasing electricity and hydrogen consumption. Reducing fuel consumption is a significant means of reducing GHG emissions from the transportation sector.

Table 6-1 shows the impacts on fossil fuel consumption. The diesel and gasoline gallons are straight gallons of retail liquid fuel, while the CNG reductions represent gasoline gallon equivalents. We do not include CNG reductions in our estimates of oil import reductions or our estimates of energy security benefits (see RIA Chapter 7.3). We do include CNG reductions in our estimate of monetized fuel savings (see RIA Chapter 3.5.3) where we apply gasoline fuel prices to the reduced gallons of gasoline equivalents.

Table 6-1 Fossil Fuel Reductions due to the Final Rule, Millions of Gallons

Calendar Year	Diesel	Gasoline	CNG (Gasoline Equivalents)
2027	-32	-23	0
2028	-84	-45	-1
2029	-160	-66	-1
2030	-300	-85	-2
2031	-610	-140	-4
2032	-1,200	-220	-8
2033	-1,800	-290	-11
2034	-2,300	-360	-15
2035	-2,800	-410	-18
2036	-3,300	-460	-22
2037	-3,800	-500	-25
2038	-4,200	-540	-28
2039	-4,600	-570	-32
2040	-4,900	-600	-35
2041	-5,200	-630	-39
2042	-5,400	-650	-42
2043	-5,600	-660	-45
2044	-5,800	-680	-49
2045	-5,900	-690	-52
2046	-6,000	-690	-55
2047	-6,100	-700	-58
2048	-6,100	-700	-61
2049	-6,100	-700	-65
2050	-6,200	-700	-68
2051	-6,200	-700	-72
2052	-6,200	-700	-75
2053	-6,300	-700	-78
2054	-6,300	-690	-82
2055	-6,300	-690	-86
Sum	-120,000	-15,000	-1,100

As discussed in Preamble Section V, we used an updated version of EPA's MOVES model to estimate the impact of the final standards on heavy-duty vehicle emissions, fuel consumption, electricity consumption, and hydrogen consumption. Table 6-2 shows the estimated reduction in U.S. oil imports under the final emission standards relative to the revised reference case scenario and, also, shows the projected increase in electricity and hydrogen consumption due to the final rule.

The oil import reductions are the result of reduced consumption (i.e., reduced liquid fuel demand) of both diesel fuel and gasoline and our estimate of 94.8 percent of reduced liquid fuel demand results in reduced imports. The 94.8 percent oil import factor is based upon revised refinery throughput assumptions for this final rule. See Chapter 7 of the RIA for a discussion of how the change in the refinery throughput estimate for this final rule results in the 94.8 percent oil import reduction factor. Thus, on balance, each gallon of petroleum reduced as a result of the final CO_2 emission standards is anticipated to reduce total U.S. imports of petroleum by 0.948 gallons.[1932]

To estimate how reductions in liquid fuel consumption translate to reductions in oil imports, we used the following factors:

- Every gallon of reduced retail gasoline (E10) consumption consists of 10 percent ethanol and 90 percent petroleum-based product (termed E0 for ease hereafter).
- Every gallon of reduced E0 has an energy density ratio of 0.881 relative to crude oil, based on the ratio of energy densities of E0 (114,200 BTU/gallon) to crude oil (129,670 BTU/gallon).
- Every gallon of reduced diesel consumption has an energy density ratio of 0.998 relative to crude oil, based on the ratio of energy densities of diesel fuel (129,488 BTU/gallon) to crude oil (129,670 BTU/gallon).
- 42 gallons per barrel of crude oil.

[1932] The estimated benefits from a reduction in U.S. oil imports are due to the U.S.'s decreased exposure to global oil price shocks. We characterized these energy security benefits in Chapter 7.3 of this RIA.

Table 6-2 Estimated U.S. Oil Import Reductions and Electricity and Hydrogen Consumption Increases due to the Final Rule*

Calendar Year	Imported Oil (Million Barrels per Year)	% of 2022 U.S. Imports of Crude	Electricity Consumption (GWh)	% of 2022 U.S. Electricity Consumption	Hydrogen Consumption (1000 metric tons per year)	% of 2020 U.S. Hydrogen Consumption
2027	-1	0.0%	620	0.0%	0	0.0%
2028	-3	-0.1%	1,600	0.0%	0	0.0%
2029	-5	-0.2%	3,100	0.1%	0	0.0%
2030	-8	-0.4%	5,700	0.1%	17	0.2%
2031	-16	-0.7%	12,000	0.3%	51	0.5%
2032	-31	-1.3%	22,000	0.5%	130	1.3%
2033	-45	-2.0%	32,000	0.8%	200	2.0%
2034	-58	-2.5%	43,000	1.1%	280	2.8%
2035	-71	-3.1%	53,000	1.3%	350	3.5%
2036	-83	-3.6%	62,000	1.5%	430	4.3%
2037	-94	-4.1%	71,000	1.7%	500	5.0%
2038	-100	-4.5%	79,000	1.9%	560	5.6%
2039	-110	-4.9%	86,000	2.1%	630	6.3%
2040	-120	-5.3%	93,000	2.3%	680	6.8%
2041	-130	-5.6%	99,000	2.4%	730	7.3%
2042	-130	-5.8%	100,000	2.6%	780	7.8%
2043	-140	-6.1%	110,000	2.7%	820	8.2%
2044	-140	-6.2%	110,000	2.8%	850	8.5%
2045	-150	-6.4%	110,000	2.8%	880	8.8%
2046	-150	-6.5%	120,000	2.9%	900	9.0%
2047	-150	-6.5%	120,000	2.9%	920	9.2%
2048	-150	-6.6%	120,000	2.9%	930	9.3%
2049	-150	-6.6%	120,000	2.9%	950	9.5%
2050	-150	-6.6%	120,000	3.0%	960	9.6%
2051	-150	-6.7%	120,000	3.0%	980	9.8%
2052	-150	-6.7%	120,000	3.0%	980	9.8%
2053	-150	-6.7%	120,000	3.0%	990	9.9%
2054	-150	-6.7%	120,000	3.0%	1,000	10%
2055	-150	-6.7%	120,000	3.0%	1,000	10%
Sum	-3,000		2,300,000		18,000	

*According to EIA, 2022 US crude oil imports were 6.28 million barrels per day, or 2.29 billion barrels for the year, 2022 U.S. electricity consumption was 4.05 trillion kWh, or 4.05 million GWh, and according to NREL in October 2020, U.S. hydrogen demand is 10 million metric tons annually.[1933] Note that the electricity consumption presented here reflects changes in battery electric vehicle consumption and is the consumption used in estimating fuel costs; it does not include changes in electricity generation to produce hydrogen.

We also conducted a sensitivity with respect to the impact on domestic refining in response to a demand reduction in domestic liquid fuel. That sensitivity and how it impacts refinery emissions is discussed in Chapter 4.10 of this RIA. Associated with that sensitivity is the impact on U.S. imports of oil because changes in domestic refining are likely to impact the level of

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[1933] See “2022_crude_oil_imports.pdf” and “2022_electricity_consumption.pdf” contained in the docket for this rule, both last accessed on November 22, 2023. See “H2_consumption_NREL.pdf” contained in the docket for this rule and last accessed on January 25, 2023.

imported oil. In our central analysis, we estimate that half of all reductions in domestic liquid fuel demand will result in reductions in domestic refining and, as a result, 94.8 percent of that reduced demand will result in reduced U.S. oil imports, as described above. In our sensitivity, we estimate that only 20 percent of the reduced domestic demand will result in reduced domestic refining. The result being a 97.9 percent reduction in U.S. oil imports. Under that scenario, the reductions in U.S. oil imports would be as shown in Table 6-3.

Table 6-3 Estimated U.S. Oil Import Reductions due to the Final Rule under the Refinery Sensitivity *

Calendar Year	**Imported Oil (Million Barrels per Year)**	**% of 2022 U.S. Imports of Crude**
2027	-1	-0.1%
2028	-3	-0.1%
2029	-5	-0.2%
2030	-9	-0.4%
2031	-17	-0.7%
2032	-32	-1.4%
2033	-46	-2.0%
2034	-60	-2.6%
2035	-74	-3.2%
2036	-86	-3.7%
2037	-97	-4.2%
2038	-110	-4.7%
2039	-120	-5.1%
2040	-120	-5.4%
2041	-130	-5.8%
2042	-140	-6.0%
2043	-140	-6.3%
2044	-150	-6.4%
2045	-150	-6.6%
2046	-150	-6.7%
2047	-150	-6.7%
2048	-160	-6.8%
2049	-160	-6.8%
2050	-160	-6.8%
2051	-160	-6.9%
2052	-160	-6.9%
2053	-160	-6.9%
2054	-160	-6.9%
2055	-160	-6.9%
Sum	-3,100	

*According to EIA, 2022 US crude oil imports were 6.28 million barrels per day, or 2.29 billion barrels for the year.

Chapter 7 Benefits

7.1 Benefits of GHG Reductions

Tables 7-1 through 7-4 present the estimated annual, undiscounted climate benefits of reduced GHG emissions, and consequently the annual quantified benefits (i.e., total GHG benefits), for each of the three SC-GHG values estimated within U.S. EPA (2023f)[1934] for the stream of years beginning with the first year of rule implementation, 2027, through 2055. Also shown are the present values (PV) and equivalent annualized values (AV) associated with each of the three SC-GHG values. In this analysis, to calculate the present and annualized values of climate benefits, EPA uses the same discount rate as the near-term target Ramsey rate used to discount the climate benefits from future GHG reductions. That is, future climate benefits estimated with the SC-GHG at the near-term 2 percent Ramsey rate are discounted to the base year of the analysis using the same 2 percent rate.[1935] Appendix C to this RIA contains the benefits of the final rule using the interim SC-GHG estimates calculated within the proposal.

[1934] U.S. Environmental Protection Agency (2023f). Supplementary Material for the Regulatory Impact Analysis for the Final Rulemaking, "Standards of Performance for New, Reconstructed, and Modified Sources and Emissions Guidelines for Existing Sources: Oil and Natural Gas Sector Climate Review": EPA Report on the Social Cost of Greenhouse Gases: Estimates Incorporating Recent Scientific Advances. Washington, DC: U.S. EPA

[1935] As discussed in U.S. EPA (2023f), the error associated with using a constant discount rate rather than the certainty-equivalent rate path to calculate the present value of a future stream of monetized climate benefits is small for analyses with moderate time frames (e.g., 30 years or less). (EPA 2023f) also provides an illustration of the amount that climate benefits from reductions in future emissions will be underestimated by using a constant discount rate relative to the more complicated certainty-equivalent rate path.

Table 7-1 Benefits of Reduced CO_2 Emissions from the Rule, Millions of 2022 dollars

Emissions Year	Near-Term Ramsey Discount Rate and Statistic		
	2.5% Average	2.0% Average	1.5% Average
2027	$43	$69	$120
2028	$94	$150	$250
2029	$150	$240	$400
2030	$180	$300	$490
2031	$280	$440	$730
2032	$400	$630	$1,000
2033	$500	$790	$1,300
2034	$580	$920	$1,500
2035	$630	$990	$1,600
2036	$1,700	$2,600	$4,300
2037	$3,000	$4,700	$7,700
2038	$4,700	$7,300	$12,000
2039	$6,700	$10,000	$17,000
2040	$8,900	$14,000	$22,000
2041	$9,500	$15,000	$24,000
2042	$10,000	$15,000	$25,000
2043	$10,000	$16,000	$26,000
2044	$11,000	$16,000	$26,000
2045	$11,000	$17,000	$27,000
2046	$12,000	$18,000	$28,000
2047	$12,000	$18,000	$29,000
2048	$12,000	$19,000	$29,000
2049	$13,000	$19,000	$30,000
2050	$13,000	$20,000	$31,000
2051	$13,000	$20,000	$31,000
2052	$14,000	$20,000	$32,000
2053	$14,000	$21,000	$32,000
2054	$14,000	$21,000	$32,000
2055	$14,000	$21,000	$33,000
PV	$130,000	$210,000	$370,000
AV	$6,200	$9,700	$16,000

Note: Climate benefits are based on changes (reductions) in CO_2 emissions and are calculated using updated estimates of the SC-CO_2 from (EPA 2023f). Climate benefits include changes in vehicle, EGU and refinery CO_2 emissions.

Table 7-2 Benefits of Reduced CH_4 Emissions from the Rule, Millions of 2022 dollars

Emissions Year	Near-Term Ramsey Discount Rate and Statistic		
	2.5% Average	2.0% Average	1.5% Average
2027	$0	$0	$0
2028	$0	$0	$0
2029	$0	$0	$0
2030	$0	$0	$0
2031	$0	$0	$0
2032	$0	$0	$0
2033	$0	$0	$0
2034	$0	$0	$0
2035	$0	$0	$0
2036	$1	$1	$1
2037	$2	$3	$4
2038	$5	$6	$7
2039	$7	$9	$11
2040	$10	$12	$15
2041	$12	$14	$18
2042	$14	$17	$21
2043	$16	$19	$24
2044	$18	$21	$27
2045	$20	$24	$30
2046	$22	$26	$33
2047	$24	$28	$35
2048	$26	$31	$38
2049	$28	$33	$41
2050	$30	$36	$44
2051	$32	$38	$47
2052	$34	$40	$50
2053	$36	$43	$53
2054	$38	$46	$57
2055	$41	$48	$60
PV	$240	$320	$440
AV	$12	$14	$19

Note: Climate benefits are based on changes (reductions) in GHG emissions and are calculated using updated estimates of the SC-CH_4 from (EPA 2023f). Climate benefits include changes in vehicle, EGU and refinery CH_4 emissions.

Table 7-3 Benefits of Reduced N_2O Emissions from the Rule, Millions of 2022 dollars

Emissions Year	**Near-Term Ramsey Discount Rate and Statistic**		
	2.5% Average	**2.0% Average**	**1.5% Average**
2027	$3	$4	$6
2028	$7	$10	$16
2029	$13	$19	$29
2030	$24	$36	$56
2031	$50	$75	$120
2032	$99	$150	$230
2033	$150	$220	$340
2034	$200	$290	$450
2035	$250	$360	$560
2036	$300	$440	$670
2037	$350	$510	$770
2038	$400	$580	$880
2039	$440	$640	$970
2040	$490	$710	$1,100
2041	$530	$760	$1,200
2042	$570	$820	$1,200
2043	$600	$870	$1,300
2044	$630	$910	$1,400
2045	$660	$940	$1,400
2046	$680	$970	$1,400
2047	$700	$1,000	$1,500
2048	$720	$1,000	$1,500
2049	$740	$1,000	$1,500
2050	$750	$1,100	$1,600
2051	$770	$1,100	$1,600
2052	$780	$1,100	$1,600
2053	$800	$1,100	$1,600
2054	$810	$1,100	$1,700
2055	$820	$1,200	$1,700
PV	$8,200	$13,000	$21,000
AV	$400	$590	$910

Note: Climate benefits are based on changes (reductions) in N2O emissions and are calculated using updated estimates of the SC-N_2O from (EPA 2023f). Climate benefits include changes in vehicle, EGU and refinery N_2O emissions.

Table 7-4 Benefits of Reduced GHG Emissions from the Final Rule, Millions of 2022 dollars

Emissions Year	Near-Term Ramsey Discount Rate and Statistic		
	2.5% Average	**2.0% Average**	**1.5% Average**
2027	$46	$73	$120
2028	$100	$160	$270
2029	$160	$260	$430
2030	$210	$330	$550
2031	$330	$510	$850
2032	$500	$770	$1,300
2033	$650	$1,000	$1,600
2034	$780	$1,200	$2,000
2035	$880	$1,400	$2,200
2036	$2,000	$3,100	$4,900
2037	$3,400	$5,300	$8,500
2038	$5,100	$7,900	$13,000
2039	$7,100	$11,000	$18,000
2040	$9,400	$15,000	$23,000
2041	$10,000	$15,000	$25,000
2042	$11,000	$16,000	$26,000
2043	$11,000	$17,000	$27,000
2044	$11,000	$17,000	$28,000
2045	$12,000	$18,000	$28,000
2046	$12,000	$19,000	$29,000
2047	$13,000	$19,000	$30,000
2048	$13,000	$20,000	$31,000
2049	$14,000	$20,000	$32,000
2050	$14,000	$21,000	$32,000
2051	$14,000	$21,000	$33,000
2052	$14,000	$21,000	$33,000
2053	$15,000	$22,000	$34,000
2054	$15,000	$22,000	$34,000
2055	$15,000	$22,000	$34,000
PV	$130,000	$220,000	$390,000
AV	$6,600	$10,000	$17,000

Note: Climate benefits are based on changes (reductions) in GHG emissions and are calculated using updated estimates of the SC-GHG from (EPA 2023f). Climate benefits include changes in vehicle, EGU and refinery GHG emissions.

Unlike many environmental problems where the causes and impacts are distributed more locally, GHG emissions are a global externality making climate change a true global challenge. GHG emissions contribute to damages around the world regardless of where they are emitted. Because of the distinctive global nature of climate change, in the RIA for this final rule the EPA centers attention on a global measure of climate benefits from GHG reductions. Consistent with all IWG recommended SC-GHG estimates to date, the SC-GHG values presented in Section 6 provide a global measure of monetized damages from CO_2, CH_4 and N_2O and Table 7-1 through Table 7-4 present the monetized global climate benefits of the CO_2, CH_4 and N_2O emission reductions expected from the final rule. This approach is the same as that taken in EPA regulatory analyses from 2009 through 2016 and since 2021. It is also consistent with OMB Circular A-4 guidance (2003) that states when a regulation is likely to have international effects, "these effects should be reported"[1936,1937]. EPA also notes that EPA's cost estimates in RIAs, including the cost estimates contained in this RIA, regularly do not differentiate between the share of compliance costs expected to accrue to U.S. firms versus foreign interests, such as to foreign investors in regulated entities[1938]. A global perspective on climate effects is therefore consistent with the approach EPA takes on costs. There are many reasons, as summarized in this section – and as articulated by OMB and in IWG assessments (IWG, 2010)[1939] (IWG, 2013)[1940] (IWG, 2016a)[1941] (IWG, 2016b)[1942] (IWG, 2021)[1943], the 2015 Response to Comments (IWG, 2015)[1944] and in detail in (EPA 2023f)[1945] and in Appendix A of the Response to Comments document for the December 2023 Final Oil and Gas NSPS/EG Rulemaking – why the EPA

[1936] Available online: https://obamawhitehouse.archives.gov/omb/circulars_a004_a-4.

[1937] While OMB Circular A-4 recommends that international effects we reported separately, the guidance also explains that "[d]ifferent regulations may call for different emphases in the analysis, depending on the nature and complexity of the regulatory issues". Circular A-4 (2023) states that "In certain contexts, it may be particularly appropriate to include effects experienced by noncitizens residing abroad in your primary analysis. Such contexts include, for example, when:

- assessing effects on noncitizens residing abroad provides a useful proxy for effects on U.S. citizens and residents that are difficult to otherwise estimate;
- assessing effects on noncitizens residing abroad provides a useful proxy for effects on U.S. national interests that are not otherwise fully captured by effects experienced by particular U.S. citizens and residents (e.g., national security interests, diplomatic interests, etc.);
- regulating an externality on the basis of its global effects supports a cooperative international approach to the regulation of the externality by potentially inducing other countries to follow suit or maintain existing efforts; or
- international or domestic legal obligations require or support a global calculation of regulatory effects".

[1938] For example, in the RIA for the 2018 Proposed Reconsideration of the Oil and Natural Gas Sector Emission Standards for New, Reconstructed, and Modified Sources, the EPA acknowledged that some portion of regulatory costs will likely "accru[e] to entities outside U.S. borders" through foreign ownership, employment, or consumption (EPA 2018). In general, a significant share of U.S. corporate debt and equities are foreign-owned, including in the oil and gas industry.

[1939] IWG. 2010. Technical Support Document: Social Cost of Carbon for Regulatory Impact Analysis under Executive Order 12866. Accessed 2023. https://www.epa.gov/sites/default/files/2016-12/documents/scc_tsd_2010.pdf.

[1940] —. 2013. Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866. https://www.ourenergypolicy.org/wp-content/uploads/2013/06/social_cost_of_carbon_for_ria_2013_update.pdf.

[1941] —. 2016a. Addendum to Technical Support Document on Social Cost of Carbon for Regulatory Impact Analysis under Executive Order 12866: Application of the Methodology to Estimate the Social Cost of Methane and the Social Cost of Nitrous Oxide. https://www.epa.gov/sites/default/files/2016-12/documents/addendum_to_sc-ghg_tsd_august_2016.pdf.

[1942] —. 2016b. Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866. Accessed 2023. https://www.epa.gov/sites/default/files/2016-12/documents/sc_CO2_tsd_august_2016.pdf.

[1943] —. 2021. Technical Support Document: Social Cost of Carbon, Methane, and Nitrous Oxide Interim Estimates under Executive Order 13990. Accessed 2023. https://www.whitehouse.gov/wp-content/uploads/2021/02/TechnicalSupportDocument_SocialCostofCarbonMethaneNitrouSOXide.pdf.

[1944] IWG. 2015. Response to comments: social cost of carbon for regulatory impact analysis under executive order 12866. Response to Comments, United States Government. https://obamawhitehouse.archives.gov/sites/default/files/omb/inforeg/scc-responseto-comments-final-july-2015.pdf.

[1945] EPA. 2023f. "Supplementary Material for the Regulatory Impact Analysis for the Final Rulemaking: Standards of Performance for New, Reconstructed, and Modified Sources and Emissions Guidelines for Existing Sources: Oil and Natural Gas Sector Climate Review." EPA Report on the Social Cost of Greenhouse Gases: Estimates Incorporating Recent Scientific Advances, Washington, DC. doi:Docket ID No. EPA-HQ-OAR-2021-0317.

focuses on the global value of climate change impacts when analyzing policies that affect GHG emissions.

International cooperation and reciprocity are essential to successfully addressing climate change, as the global nature of greenhouse gases means that a ton of GHGs emitted in any other country harms those in the U.S. just as much as a ton emitted within the territorial U.S. Assessing the benefits of U.S. GHG mitigation activities requires consideration of how those actions may affect mitigation activities by other countries, as those international mitigation actions will provide a benefit to U.S. citizens and residents by mitigating climate impacts that affect U.S. citizens and residents. This is a classic public goods problem because each country's reductions benefit everyone else, and no country can be excluded from enjoying the benefits of other countries' reductions. The only way to achieve an efficient allocation of resources for emissions reduction on a global basis — and so benefit the U.S. and its citizens and residents — is for all countries to base their policies on global estimates of damages. A wide range of scientific and economic experts have emphasized the issue of international cooperation and reciprocity as support for assessing global damages of GHG emission in domestic policy analysis. Using a global estimate of damages in U.S. analyses of regulatory actions allows the U.S. to continue to actively encourage other nations, including emerging major economies, to also assess global climate damages of their policies and to take steps to reduce emissions. For example, many countries and international institutions have already explicitly adapted the global SC-GHG estimates used by EPA in their domestic analyses (e.g., Canada, Israel) or developed their own estimates of global damages (e.g., Germany), and recently, there has been renewed interest by other countries to update their estimates since the draft release of the updated SC-GHG estimates presented in the December 2022 Oil and Gas NSPS/EG Supplemental Proposal RIA[1946]. Several recent studies have empirically examined the evidence on international GHG mitigation reciprocity, through both policy diffusion and technology diffusion effects. See U.S. EPA (EPA 2023f)[1947] for more discussion.

For all of these reasons, the EPA believes that a global metric is appropriate for assessing the climate benefits of avoided GHG emissions in this final RIA. In addition, as emphasized in the (National Academies, 2017)[1948] recommendations, "[i]t is important to consider what constitutes a domestic impact in the case of a global pollutant that could have international implications that impact the United States." The global nature of GHG pollution and its impacts means that U.S. interests are affected by climate change impacts through a multitude of pathways and these need to be considered when evaluating the benefits of GHG mitigation to U.S. citizens and residents. The increasing interconnectedness of global economy and populations means that impacts

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1946 In April 2023, the government of Canada announced the publication of an interim update to their SC-GHG guidance, recommending SC-GHG estimates identical to the EPA's updated estimates presented in the December 2022 Supplemental Proposal RIA. The Canadian interim guidance will be used across all Canadian federal departments and agencies, with the values expected to be finalized by the end of the year. See more at https://www.canada.ca/en/environment-climate-change/services/climate-change/science-research-data/social-cost-ghg.html.

[1947] EPA. 2023f. "Supplementary Material for the Regulatory Impact Analysis for the Final Rulemaking: Standards of Performance for New, Reconstructed, and Modified Sources and Emissions Guidelines for Existing Sources: Oil and Natural Gas Sector Climate Review." EPA Report on the Social Cost of Greenhouse Gases: Estimates Incorporating Recent Scientific Advances, Washington, DC. doi:Docket ID No. EPA-HQ-OAR-2021-0317.

[1948] National Academies. 2017. Valuing Climate Damages: Updating Estimation of the Social Cost of Carbon Dioxide. Washington, D.C.: The National Academies Press.

occuring outside of U.S. borders can have significant impacts on U.S. interests. Examples of affected interests include direct effects on U.S. citizens and assets located abroad, international trade, and tourism, and spillover pathways such as economic and political destabilization and global migration that can lead to adverse impacts on U.S. national security, public health, and humanitarian concerns. Those impacts point to the global nature of the climate change problem and are better captured within global measures of the social cost of greenhouse gases.

In the case of these global pollutants, for the reasons articulated in this section, the assessment of global net damages of GHG emissions allows EPA to fully disclose and contextualize the net climate benefits of GHG emission reductions expected from this final rule. The EPA disagrees with public comments received on the December 2022 Oil and Gas NSPS/EG Supplemental Proposal that suggested that the EPA can or should use a metric focused on benefits resulting solely from changes in climate impacts occuring within U.S. borders. The global models used in the SC-GHG modeling described above do not lend themselves to be disaggregated in a way that could provide sufficiently robust information about the distribution of the rule's climate benefits to citizens and residents of particular countries, or population groups across the globe and within the U.S. Two of the models used to inform the damage module, the GIVE and DSCIM models, have spatial resolution that allows for some geographic disaggregation of future climate impacts across the world. This permits the calculation of a partial GIVE and DSCIM-based SC-GHG measuring the damages from four or five climate impact categories projected to physically occur within the U.S., respectively, subject to caveats. As discussed at length in (EPA 2023f)[1949] these damage modules are only a partial accounting and do not capture all of the pathways through which climate change affects public health and welfare. For example, this modeling omits most of the consequences of changes in precipitation, damages from extreme weather events (e.g., wildfires), the potential for nongradual damages from passing critical thresholds (e.g., tipping elements) in natural or socioeconomic systems, and non-climate mediated effects of GHG emissions other than CO_2 fertilization (e.g., tropospheric ozone formation due to CH_4 emissions). Thus, they only cover a subset of potential climate change impacts. Furthermore, as discussed at length in (EPA 2023f), the damage modules do not capture spillover or indirect effects whereby climate impacts in one country or region can affect the welfare of residents in other countries or regions— through the effect of climate change on international markets, trade, tourism, and other activities. Supply chain disruptions are a prominent pathway through which U.S. business and consumers can be affected by climate change impacts abroad. Additional climate change-induced international spillovers can occur through pathways such as damages across transboundary resources, economic and political destabilization, and global migration that can lead to adverse impacts on U.S. national security, public health, and humanitarian concerns.

Additional modeling efforts can and have shed further light on some omitted damage categories. For example, the Framework for Evaluating Damages and Impacts (FrEDI) is an open-source modeling framework developed by the EPA[1950] to facilitate the characterization of

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[1949] EPA. 2023f. "Supplementary Material for the Regulatory Impact Analysis for the Final Rulemaking: Standards of Performance for New, Reconstructed, and Modified Sources and Emissions Guidelines for Existing Sources: Oil and Natural Gas Sector Climate Review." EPA Report on the Social Cost of Greenhouse Gases: Estimates Incorporating Recent Scientific Advances, Washington, DC. doi:Docket ID No. EPA-HQ-OAR-2021-0317.

1950 The FrEDI framework and Technical Documentation have been subject to a public review comment period and an independent external peer review, following guidance in the EPA Peer-Review Handbook for Influential Scientific Information (ISI). Information on the FrEDI peer-review is available at the EPA Science Inventory.

net annual climate change impacts in numerous impact categories within the contiguous U.S. and monetize the associated distribution of modeled damages (Hartin, et al., 2023)[1951] (EPA, 2021)[1952]. The additional impact categories included in FrEDI reflect the availability of U.S.-specific data and research on climate change effects. As discussed in U.S. EPA (EPA, 2023f) [1953] results from FrEDI show that annual damages resulting from climate change impacts within the contiguous U.S. (CONUS) (i.e., excluding Hawaii, Alaska, and U.S. territories) and for impact categories not represented in GIVE and DSCIM are expected to be substantial. As discussed in U.S. EPA (EPA, 2021)[1954], results from FrEDI show that annual damages resulting from climate change impacts within the contiguous U.S. (CONUS) (i.e., excluding Hawaii, Alaska, and U.S. territories) and for impact categories not represented in GIVE and DSCIM are expected to be substantial. For example, FrEDI estimates a partial SC-CO_2 of $41/mtCO2 for damages physically occurring within CONUS for 2030 emissions (under a 2 percent near-term Ramsey discount rate) (Hartin, et al., 2023)[1955], compared to a GIVE and DSCIM-based U.S.-specific SC-CO_2 of $18/mt$CO_2$ and $16/mt$CO_2$, respectively, for 2030 emissions (2022 USD). While the FrEDI results help to illustrate how monetized damages physically occurring within CONUS increase as more impacts are reflected in the modeling framework, they are still subject to many of the same limitations associated with the DSCIM and GIVE damage modules, including the

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[1951] Hartin, C. 2023. "Advancing the estimation of future climate impacts within the United States." Earth System Dynamics 14: 1015-1037. https://dio.org/10.5194/esd-14-1015-2023.

[1952] EPA. 2021. "Technical Documentation on the framework for evaluating damages and impacts (FrEDI)." EPA Science Inventory.
https://cfpub.epa.gov/si/si_public_record_report.cfm?dirEntryId=351316&Lab=OAP&simplesearch=0&showcriteria=2&sortby=pubDate&searchall=fredi&timstype=&datebeginpublishedpresented=02/14/2021.
Technical Documentation on The Framework for Evaluating Damages and Impacts (FrEDI) | Science Inventory | US EPA

[1953] EPA. 2023f. "Supplementary Material for the Regulatory Impact Analysis for the Final Rulemaking: Standards of Performance for New, Reconstructed, and Modified Sources and Emissions Guidelines for Existing Sources: Oil and Natural Gas Sector Climate Review." EPA Report on the Social Cost of Greenhouse Gases: Estimates Incorporating Recent Scientific Advances, Washington, DC. doi:Docket ID No. EPA-HQ-OAR-2021-0317.

[1954] EPA. 2021. "Technical Documentation on the framework for evaluating damages and impacts (FrEDI)." EPA Science Inventory.
https://cfpub.epa.gov/si/si_public_record_report.cfm?dirEntryId=351316&Lab=OAP&simplesearch=0&showcriteria=2&sortby=pubDate&searchall=fredi&timstype=&datebeginpublishedpresented=02/14/2021.
Technical Documentation on The Framework for Evaluating Damages and Impacts (FrEDI) | Science Inventory | US EPA

[1955] Hartin, C. 2023. "Advancing the estimation of future climate impacts within the United States." Earth System Dynamics 14: 1015-1037. https://dio.org/10.5194/esd-14-1015-2023.

omission or partial modeling of important damage categories[1956,1957]. Finally, none of these modeling efforts – GIVE, DSCIM, and FrEDI – reflect non-climate mediated effects of GHG emissions experienced by U.S. populations (other than CO_2 fertilization effects on agriculture). In addition to its climate impacts, methane also contributes to the chemical formation of tropospheric ozone, which contributes to mortality. One recent paper on this effect (McDuffie, et al., 2023)[1958] estimated the monetized increase in respiratory-related human mortality risk from the ozone produced from a marginal pulse of methane emissions. Using the socioeconomics from the RFF-SPs and the 2 percent near-term Ramsey discounting approach, this additional health risk to U.S. populations is on the order of approximately $360/mtCH4 (2022 USD) for 2030 emissions.

Applying the U.S.-specific partial SC-GHG estimates derived from the multiple lines of evidence described above to the GHG emissions reduction expected under the final rule would yield substantial benefits. For example, the present value of the climate benefits of the final rule as measured by FrEDI from climate change impacts in CONUS are estimated to be $33 billion (under a 2 percent near-term Ramsey discount rate)[1959]. However, the numerous explicitly omitted damage categories and other modeling limitations discussed above and throughout (EPA 2023f) make it likely that these estimates underestimate the benefits to U.S. citizens and residents of the GHG reductions from the final rule; the limitations in developing a U.S.-specific estimate that accurately captures direct and spillover effects on U.S. citizens and residents further demonstrates that it is more appropriate to use a global measure of climate benefits from GHG reductions. The EPA will continue to review developments in the literature, including more robust methodologies for estimating the magnitude of the various damages to U.S. populations from climate impacts and reciprocal international mitigation activities, and explore ways to better inform the public of the full range of GHG impacts.

[1956] Another method that has produced estimates of the effect of climate change on U.S.-specific outcomes uses a top-down approach to estimate aggregate damage functions. Published research using this approach include total-economy empirical studies that econometrically estimate the relationship between GDP and a climate variable, usually temperature. As discussed in U.S. EPA (EPA 2023f) the modeling framework used in the existing published studies using this approach differ in important ways from the inputs underlying the SC-GHG estimates described above (e.g., discounting, risk aversion, and scenario uncertainty) and focus solely on SC-CO2. Hence, we do not consider this line of evidence in the analysis for this RIA. Updating the framework of total-economy empirical damage functions to be consistent with the methods described in this RIA and (EPA 2023f) would require new analysis. Finally, because total-economy empirical studies estimate market impacts, they do not include any non-market impacts of climate change (e.g., heat related mortality) and therefore are also only a partial estimate. The EPA will continue to review developments in the literature and explore ways to better inform the public of the full range of GHG impacts.

[1957] FrEDI estimates a partial SC-CH_4 (N_2O) of $660/mtCH4 ($12,000/mtN_2O) for damages physically occurring within CONUS for 2030 emissions (under a 2 percent near-term Ramsey discount rate) (Hartin et al. 2023) compared to a GIVE and DSCIM-based U.S.-specific SC-CH_4 of $310/mtCH4 ($5,600/mtN_2O) and $84/mt$CH_4$ ($4,300/mt$N_2O$), respectively, for 2030 emissions (2022 USD).

[1958] McDuffie, EE, MC Sarofim, W Raich, M Jackson, H Roman, K Seltzer, BH Henderson, et al. 2023. "The social cost of ozone-related mortality impacts from methane emissions." Earth's Future 11(9). doi:https://doi.org/10.1029/2023EF003853.

1959 DCIM and GIVE use global damage functions. Damage functions based on only U.S.-data and research, but not for other parts of the world, were not included in those models. FrEDI does make use of some of this U.S.-specific data and research and as a result has a broader coverage of climate impact categories.

7.2 Estimated Human Health Benefits of Non-GHG Emission Reductions

This section discusses the economic benefits from reductions in health and environmental impacts resulting from criteria pollutant emission reductions that can be expected to occur as a result of the final rule standards, or under the alternative standards. GHG emissions are predominantly the byproduct of fossil fuel combustion processes that also produce criteria and hazardous air pollutant emissions. The heavy-duty vehicles and engines that are subject to the final standards are also significant sources of mobile source air pollution such as directly-emitted PM, NO_X, VOCs and air toxics. Our projected emission reductions, monetized here, reflect the projected compliance pathway presented in Section II of the preamble that accompanies this rule. However, as noted elsewhere, there are other means of achieving the standards, including pathways not utilizing ZEV technologies. Resulting emission reductions would differ from those presented here in such cases (EPA expects that different manufacturers will choose different compliance pathways) (see RIA Chapter 4). Under the modeled pathway, zero-emission technologies will also affect emissions from upstream sources that occur during, for example, electricity generation and from the refining and distribution of fuel (see RIA Chapter 4).[1960] This final rule's benefits analysis includes added emissions due to increased electricity generation and emissions reductions from reduced petroleum refining.

Changes in ambient concentrations of ozone, $PM_{2.5}$, and air toxics that will result from the final CO_2 emission standards under the modeled pathway are expected to affect human health by reducing premature deaths and other serious human health effects, and they are also expected to result in other important improvements in public health and welfare. Children, especially, benefit from reduced exposures to criteria and toxic pollutants because they tend to be more sensitive to the effects of these respiratory pollutants. Ozone and particulate matter have been associated with increased incidence of asthma and other respiratory effects in children, and particulate matter has been associated with a decrease in lung maturation.

When feasible, EPA conducts full-scale photochemical air quality modeling to demonstrate how its national mobile source regulatory actions affect ambient concentrations of regional pollutants throughout the United States. The estimation of the human health impacts of a regulatory action requires national-scale photochemical air quality modeling to conduct a full-scale assessment of $PM_{2.5}$- and ozone-related health benefits. Air quality modeling and associated analyses are not available for this rule.

For the analysis of the final CO_2 and alternative CO_2 emission standards, we instead use a reduced-form "benefit-per-ton" (BPT) approach to estimate the monetized $PM_{2.5}$-related health benefits of this final rule. The BPT approach estimates the monetized economic value of $PM_{2.5}$-related emission reductions (such as direct PM, NOx and SO_2) due to implementation of the final program. Similar to the SC-GHG approach for monetizing reductions in GHGs, the BPT approach estimates monetized health benefits of avoiding one ton of $PM_{2.5}$-related emissions from a particular source sector. The value of health benefits from reductions (or increases) in $PM_{2.5}$ emissions associated with this final rule was estimated by multiplying $PM_{2.5}$-related BPT

[1960] Like downstream emissions, the upstream emission impacts also depend on the compliance pathway chosen by manufacturers. Should they comply, for example, by using more ICE technologies, the increased upstream emissions would be smaller.

values by the corresponding annual reduction (or increase) in tons of directly-emitted $PM_{2.5}$ and $PM_{2.5}$ precursor emissions (NO_X and SO_2).

The BPT approach monetizes avoided premature deaths and illnesses that are expected to occur as a result of reductions in directly-emitted $PM_{2.5}$ and $PM_{2.5}$ precursors. A chief limitation to using $PM_{2.5}$-related BPT values is that they do not reflect benefits associated with reducing ambient concentrations of ozone, direct exposure to NO_2, or exposure to mobile source air toxics, nor do they account for improved ecosystem effects or visibility. The estimated benefits of this final rule would be larger if we were able to monetize these unquantified benefits at this time.

Using the BPT approach, we estimate the annualized value of the benefits of the final program (over the analysis period from 2027 to 2055) to be \$120 to \$22 million at a 3% discount rate and -\$32 to -\$9.1 million at a 7% discount rate.[1961,1962] Benefits are reported in year 2022 dollars and reflect the $PM_{2.5}$-related benefits associated with reductions in NOx, SO_2, and direct $PM_{2.5}$ emissions. The monetized criteria pollutant health benefits include reductions in $PM_{2.5}$-related emissions from HD vehicles. Monetized upstream health impacts associated with the standards also include benefits associated with reduced $PM_{2.5}$-related emissions from refineries and health disbenefits associated with increased $PM_{2.5}$-related emissions from EGUs. Negative monetized values are associated with health disbenefits related to increases in estimated emissions from EGUs. Depending on the discount rate used, the annualized value of the stream of $PM_{2.5}$-related benefits may either be positive or negative.

7.2.1 Approach to Estimating Human Health Benefits

This section summarizes EPA's approach to estimating the economic value of the $PM_{2.5}$-related benefits for this final rule. We use a BPT approach that is conceptually consistent with EPA's use of BPT estimates in its regulatory analyses.[1963,1964] In this approach, the $PM_{2.5}$-related BPT values are the total monetized human health benefits (the sum of the economic value of the reduced risk of premature death and illness) that are expected from reducing one ton of NOx, SO_2 or directly-emitted $PM_{2.5}$.

[1961] We note that the $PM_{2.5}$-related health benefits of the final rule are smaller than those estimated for the proposal for a number of reasons. First, the updates to the reference (no-action) case lead to a cleaner no-action scenario and thus less incremental impact of the final standards. Second, there are other methodological changes and updates that are included in the emissions modeling for the final rule, which are explained in RIA Chapter 4. Finally, there was an error in the proposed criteria pollutant benefits calculation that resulted in an overestimate of the benefits associated with reductions in direct PM emissions. The difference in criteria pollutant benefits between the proposed and final rules does not reflect changes in the stringency of the standard, nor does it affect our consideration of the proposed and final standards.

[1962] Because premature mortality typically constitutes the vast majority of monetized benefits in a $PM_{2.5}$ benefits assessment, we present PM benefits based on risk estimates reported from two different long-term exposure studies using different cohorts to account for uncertainty in the benefits associated with avoiding PM-related premature deaths (see RIA Chapter 7.2.2).

[1963] U.S. Environmental Protection Agency (U.S. EPA). 2018. Estimating the Benefit per Ton of Reducing $PM_{2.5}$ Precursors from 17 Sectors. Available at: https://www.epa.gov/sites/default/files/2018-02/documents/sourceapportionmentbpttsd_2018.pdf.

[1964] U.S. Environmental Protection Agency (U.S. EPA). 2023.Estimating the Benefit per Ton of Reducing Directly-Emitted $PM_{2.5}$, $PM_{2.5}$ Precursors and Ozone Precursors from 21 Sectors. January. Available at: https://www.epa.gov/system/files/documents/2021-10/source-apportionment-tsd-oct-2021_0.pdf

The mobile sector BPT estimates used in this final rule were published in 2019 but have been updated to be consistent with the health benefits Technical Support Document (Benefits TSD) that accompanied the 2023 PM NAAQS Reconsideration Proposal.[1965 ,1966,1967,1968] The Benefits TSD details the approach used to estimate the $PM_{2.5}$-related benefits reflected in these BPTs. The upstream EGU BPT estimates used in this final rule were also recently updated to be consistent with the Benefits TSD.[1969] We multiply these BPT values by national reductions in annual emissions in tons to estimate the total monetized human health benefits associated with the final rule.

Our procedure for calculating BPT values follows three steps:

1. Using source apportionment photochemical modeling, predict annual average ambient concentrations of NO_X, SO_2 and primary $PM_{2.5}$ that are attributable to each source sector (Onroad Heavy-Duty Diesel, Onroad Heavy-Duty Gas, EGUs, and refineries), for the Continental U.S. (48 states). This yields the estimated ambient pollutant concentrations to which the U.S. population is exposed.
2. For each sector, estimate the health impacts, and economic value of those impacts, associated with the attributable ambient concentrations of NO_X, SO_2 and primary $PM_{2.5}$ using the environmental Benefits Mapping and Analysis Program-Community Edition (BenMAP-CE). [1970] This yields the estimated total monetized value of health effects associated with exposure to the relevant pollutants by sector.
3. For each sector, divide the monetary value of health impacts by the inventory of associated precursor emissions. That is, primary $PM_{2.5}$ benefits for a given sector are divided by direct $PM_{2.5}$ emissions from that same sector, sulfate benefits are divided by SO_2 emissions, and nitrate benefits are divided by NO_X emissions. This yields the estimated monetary value of one ton of sector-specific direct $PM_{2.5}$ SO_2 or NO_X emissions.

The quantified and monetized $PM_{2.5}$ health categories that are included in the BPT values are summarized in Table 7-5. Table 7-17 in Section 7.2.6 lists a sampling of the $PM_{2.5}$, ozone, and

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[1965] Note that the Final PM NAAQS Reconsideration, released in February 2024, based its benefits analysis on the same Benefits TSD that accompanied the PM NAAQS Reconsideration proposal.

[1966] Wolfe, P.; Davidson, K.; Fulcher, C.; Fann, N.; Zawacki, M.; Baker, K. R. 2019. Monetized Health Benefits Attributable to Mobile Source Emission Reductions across the United States in 2025. Sci. Total Environ. 650, 2490–2498. Available at: https://doi.org/10.1016/J.SCITOTENV.2018.09.273.

[1967] U.S. Environmental Protection Agency (U.S. EPA). 2022. 2022 PM NAAQS Reconsideration Proposal RIA. EPA-HQ-OAR-2019-0587.

[1968] U.S. Environmental Protection Agency (U.S. EPA). 2021. Estimating $PM_{2.5}$- and Ozone-Attributable Health Benefits. Technical Support Document (TSD) for the 2023 PM NAAQS Reconsideration Proposal." EPA-HQ-OAR-2019-0587.

[1969] U.S. Environmental Protection Agency (U.S. EPA). 2023. Technical Support Document: Estimating the Benefit per Ton of Reducing Directly-Emitted $PM_{2.5}$, $PM_{2.5}$ Precursors and Ozone Precursors from 21 Sectors.

[1970] BenMAP-CE is an open-source computer program developed by the EPA that calculates the number and economic value of air pollution-related deaths and illnesses. The software incorporates a database that includes many of the concentration-response relationships, population files, and health and economic data needed to quantify these impacts. Information on BenMAP is found at: https://www.epa.gov/benmap/benmap-community-edition, and the source code is available at: https://github.com/BenMAPCE/BenMAP-CE.

air toxics health categories that are not quantified and monetized by the BPT approach and are therefore not included in the estimated benefits analysis for this rulemaking.

Table 7-5 Human Health Effects of $PM_{2.5}$

Pollutant	Effect (age)	Effect Quantified	Effect Monetized	More Information
$PM_{2.5}$	Adult premature mortality based on cohort study estimates (>17 or >64)	✓	✓	PM ISA
	Infant mortality (<1)	✓	✓	PM ISA
	Non-fatal heart attacks (>18)	✓	✓	PM ISA
	Hospital admissions - cardiovascular (all)	✓	✓	PM ISA
	Hospital admissions - respiratory (<19 and >64)	✓	✓	PM ISA
	Hospital admissions - Alzheimer's disease (>64)	✓	✓	PM ISA
	Hospital admissions - Parkinson's disease (>64)	✓	✓	PM ISA
	Emergency department visits – cardiovascular (all)	✓	✓	PM ISA
	Emergency department visits – respiratory (all)	✓	✓	PM ISA
	Emergency hospital admissions (>65)	✓	✓	PM ISA
	Non-fatal lung cancer (>29)	✓	✓	PM ISA
	Stroke incidence (50-79)	✓	✓	PM ISA
	New onset asthma (<12)	✓	✓	PM ISA
	Exacerbated asthma – albuterol inhaler use (asthmatics, 6-13)	✓	✓	PM ISA
	Lost work days (18-64)	✓	✓	PM ISA
	Other cardiovascular effects (e.g., doctor's visits, prescription medication)	—	—	PM ISA[1]
	Other respiratory effects (e.g., pulmonary function, other ages)	—	—	PM ISA[1]
	Other cancer effects (e.g., mutagenicity, genotoxicity)	—	—	PM ISA[1]
	Other nervous system effects (e.g., dementia)	—	—	PM ISA[1]
	Metabolic effects (e.g., diabetes, metabolic syndrome)	—	—	PM ISA[1]
	Reproductive and developmental effects (e.g., low birth weight, pre-term births)	—	—	PM ISA[1]

[1] We assess these benefits qualitatively due to epidemiological or economic data limitations.

Of the PM-related health endpoints listed in Table 7-5, EPA estimates the incidence of air pollution effects for only those classified as either "causal" or "likely-to-be-causal" in the 2019

PM Integrated Science Assessment (ISA) and the 2022 PM ISA update.[1971,1972,1973] The full complement of human health effects associated with PM remains unquantified because of current limitations in methods or available data. Thus, our quantified PM-related benefits omit a number of known or suspected health effects linked with PM, either because appropriate health impact functions are not available or because outcomes are not easily interpretable (e.g., changes in heart rate variability).

We anticipate the final program will also yield benefits from reduced exposure to ambient concentrations of ozone. However, the complex, non-linear photochemical processes that govern ozone formation prevent us from developing reduced-form ozone BPT values for mobile sources. This BPT approach also omits health effects associated with ambient concentrations of NO_2 as well as criteria pollutant-related welfare effects such as improvements in visibility, reductions in materials damage, ecological effects from reduced PM deposition, ecological effects from reduced nitrogen emissions, and vegetation effects from reduced ozone exposure. A list of these unquantified benefits can be found in Table 7-17.

We also do not provide estimated monetized benefits due to reductions in mobile source air toxics. This is because currently available tools and methods to assess air toxics risk from mobile sources at the national scale are not adequate for extrapolation to incidence estimation or benefits assessment.

7.2.2 Estimating $PM_{2.5}$-attributable Adult Premature Death

Of the $PM_{2.5}$-related health endpoints listed in Table 7-5, adult premature deaths typically account for the majority of total monetized PM benefits and are thus the primary component of the $PM_{2.5}$-related BPT values. In this section, we provide more detail on PM mortality effect coefficients and the concentration-response functions that underlie the BPT values.

A substantial body of published scientific literature documents the association between $PM_{2.5}$ concentrations and the risk of premature death.[1974,1975] This body of literature reflects thousands

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[1971] U.S. EPA. 2019. Integrated Science Assessment (ISA) for Particulate Matter (Final Report). U.S. Environmental Protection Agency, Office of Research and Development, Center for Public Health and Environmental Assessment. Research Triangle Park, NC. U.S. EPA. EPA/600/R-19/188. December 2019. Available at: https://www.epa.gov/naaqs/particulate-matter-pm-standards-integrated-science-assessments-current-review.

[1972] U.S. EPA. 2022. Supplement to the 2019 Integrated Science Assessment for Particulate Matter (Final Report). U.S. Environmental Protection Agency, Office of Research and Development, Center for Public Health and Environmental Assessment. Research Triangle Park, NC. U.S. EPA. EPA/600/R-22/028. May 2022. Available at: https://www.epa.gov/isa/integrated-science-assessment-isa-particulate-matter.

[1973] The ISA synthesizes the toxicological, clinical and epidemiological evidence to determine whether each pollutant is causally related to an array of adverse human health outcomes associated with either acute (i.e., hours- or days-long) or chronic (i.e., years-long) exposure. For each outcome, the ISA reports this relationship to be causal, likely to be causal, suggestive of a causal relationship, inadequate to infer a causal relationship, or not likely to be a causal relationship.

[1974] U.S. EPA. 2019. Integrated Science Assessment (ISA) for Particulate Matter (Final Report). U.S. Environmental Protection Agency, Office of Research and Development, Center for Public Health and Environmental Assessment. Research Triangle Park, NC. U.S. EPA. EPA/600/R-19/188. December 2019. Available at: https://www.epa.gov/naaqs/particulate-matter-pm-standards-integrated-science-assessments-current-review.

[1975] U.S. EPA. 2022. Supplement to the 2019 Integrated Science Assessment for Particulate Matter (Final Report). U.S. Environmental Protection Agency, Office of Research and Development, Center for Public Health and Environmental Assessment. Research Triangle Park, NC. U.S. EPA. EPA/600/R-22/028. May 2022. Available at: https://www.epa.gov/isa/integrated-science-assessment-isa-particulate-matter.

of epidemiology, toxicology, and clinical studies. The PM ISA, completed as part of the review of the recently finalized PM NAAQS reconsideration and reviewed by the Clean Air Scientific Advisory Committee (CASAC),[1976] concluded that there is a causal relationship between mortality and both long-term and short-term exposure to $PM_{2.5}$ based on the full body of scientific evidence. The size of the mortality effect estimates from epidemiologic studies, the serious nature of the effect itself, and the high monetary value ascribed to prolonging life make mortality risk reduction the most significant health endpoint quantified in this analysis. EPA selects Hazard Ratios from cohort studies to estimate counts of PM-related premature death, following a systematic approach detailed in the Benefits TSD.

For adult PM-related mortality, the BPT values are based on the risk estimates from two alternative long-term exposure mortality studies: the National Health Interview Survey (NHIS) cohort study (Pope III et al., 2019) and an extended analysis of the Medicare cohort (Wu et al., 2020).[1977,1978] In past analyses, EPA has used two alternate estimates of mortality: one from the American Cancer Society cohort and one from the Medicare cohort (Turner et al., 2016 and Di et al., 2017, respectively).[1979,1980] We use a risk estimate from Pope III et al., 2019 study in place of the risk estimate from the Turner et al., 2016 analysis, as it: (1) includes a longer follow-up period that includes more recent (and lower) $PM_{2.5}$ concentrations; (2) the NHIS cohort is more representative of the U.S. population than is the ACS cohort with respect to the distribution of individuals by race, ethnicity, income and education.

Based on the 2022 Supplement to the PM ISA, [1981] EPA substituted a risk estimate from Wu et al., 2020 in place of a risk estimate from Di et al., 2017. These two epidemiologic studies share many attributes, including the cohort and model used to characterize population exposure to $PM_{2.5}$. As compared to Di et al., 2017, Wu et al., 2020 includes a longer follow-up period and reflects more recent $PM_{2.5}$ concentrations.

The PM ISA also concluded that the scientific literature supports the use of a no-threshold log-linear model to portray the PM-mortality concentration-response relationship while recognizing potential uncertainty about the exact shape of the concentration-response relationship. The 2019 PM ISA, which informed the final 2024 PM NAAQS Reconsideration, reviewed available studies that examined the potential for a population-level threshold to exist in

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[1976] Sheppard, EL (2022). Letter from Elizabeth A. (Lianne) Sheppard, Chair, Clean Air Scientific Advisory Committee, to Administrator Michale Regan. Re:CASAC Review of the EPA's Supplement to the 2019 Integrated Science Assessment for Particulate Matter (External Review Draft – October 2021). March 18, 2022. EPA-CASAC-22-001. Office of the Adminstrator, Science Advisory Board Washington, DC.

[1977] Pope III, CA, Lefler, JS, Ezzati, M, Higbee, JD, Marshall, JD, Kim, S-Y, Bechle, M, Gilliat, KS, Vernon, SE and Robinson, AL (2019). Mortality risk and fine particulate air pollution in a large, representative cohort of US adults. Environmental health perspectives 127(7): 077007.

[1978] Wu, X, Braun, D, Schwartz, J, Kioumourtzoglou, M and Dominici, F (2020). Evaluating the impact of long-term exposure to fine particulate matter on mortality among the elderly. Science advances 6(29): eaba5692.

[1979] Turner, MC, Jerrett, M, Pope, A, III, Krewski, D, Gapstur, SM, Diver, WR, Beckerman, BS, Marshall, JD, Su, J, Crouse, DL and Burnett, RT (2016). Long-term ozone exposure and mortality in a large prospective study. American Journal of Respiratory and Critical Care Medicine 193(10): 1134-1142.

[1980] Di, Q, Wang, Y, Zanobetti, A, Wang, Y, Koutrakis, P, Choirat, C, Dominici, F and Schwartz, JD (2017). Air pollution and mortality in the Medicare population. New England Journal of Medicine 376(26): 2513-2522.

[1981] U.S. EPA. 2022. Supplement to the 2019 Integrated Science Assessment for Particulate Matter (Final Report). U.S. Environmental Protection Agency, Office of Research and Development, Center for Public Health and Environmental Assessment. Research Triangle Park, NC. U.S. EPA. EPA/600/R-22/028. May 2022. Available at: https://www.epa.gov/isa/integrated-science-assessment-isa-particulate-matter.

the concentration-response relationship. Based on such studies, the ISA concluded that "evidence from recent studies reduce uncertainties related to potential co-pollutant confounding and continues to provide strong support for a linear, no-threshold concentration-response relationship." [1982] Consistent with this evidence, the Agency historically has estimated health impacts above and below the prevailing NAAQS.

7.2.3 Economic Value of Health Benefits

The BPT values used in this analysis are a reduced-form approach for relating emission reductions to reductions in ambient concentrations of $PM_{2.5}$ and associated improvements in human health. Reductions in ambient concentrations of air pollution generally decrease the risk of future adverse health effects by a small amount for a large population. To monetize these benefits, the appropriate economic measure is willingness to pay (WTP) for changes in risk of a health effect. For some health effects, such as hospital admissions, WTP estimates are generally not available, so we use the cost of treating or mitigating the effect. These cost-of-illness (COI) estimates generally (although not necessarily in every case) understate the true value of reductions in risk of a health effect. They tend to reflect the direct expenditures related to treatment, but not the value of avoided pain and suffering from the health effect. The WTP and COI unit values for each endpoint are provided in the Benefits TSD. These unit values were used to monetize the underlying health effects included in the $PM_{2.5}$ BPT values.

Avoided premature deaths typically account for the majority of monetized $PM_{2.5}$-related benefits. The economics literature concerning the appropriate methodology for valuing reductions in premature mortality risk is still developing and is the subject of continuing discussion within the economics and public policy analysis community. Following the advice of the SAB's Environmental Economics Advisory Committee (SAB-EEAC), EPA currently uses the value of statistical life (VSL) approach in calculating estimates of mortality benefits. This calculation provides the most reasonable single estimate of an individual's WTP for reductions in mortality risk.[1983] The VSL approach is a summary measure for the value of small changes in mortality risk experienced by a large number of people.

EPA consulted several times with the SAB-EEAC on valuing mortality risk reductions and continues work to update the Agency's guidance on the issue. Until updated guidance is available, EPA determined that a single, peer-reviewed estimate applied consistently best reflects the SAB-EEAC advice we have received. Therefore, EPA applies the VSL that was vetted and endorsed by the SAB in the Agency's Guidelines for Preparing Economic Analyses.[1984] The mean VSL across these studies is $4.8 million (1990$). We then adjust this VSL to account for the currency year and to account for income growth from 1990 to the analysis year. Specifically, the VSL applied in this analysis in 2022 dollars after adjusting for income growth to 2022 is $12.6 million.

[1982] U.S. EPA. 2019. Integrated Science Assessment (ISA) for Particulate Matter (Final Report). U.S. Environmental Protection Agency, Office of Research and Development, Center for Public Health and Environmental Assessment. Research Triangle Park, NC. U.S. EPA. EPA/600/R-19/188. December 2019. Available at: https://www.epa.gov/naaqs/particulate-matter-pm-standards-integrated-science-assessments-current-review.

[1983] U.S. EPA-SAB. 2000. An SAB Report on EPA's White Paper Valuing the Benefits of Fatal Cancer Risk Reduction. Available at: https://www.epa.gov/system/files/documents/2022-03/86189901_0.pdf.

[1984] U.S. EPA. 2016. Guidelines for Preparing Economic Analyses. Available at: https://www.epa.gov/sites/default/files/2017-08/documents/ee-0568-50.pdf.

EPA is committed to using scientifically sound, appropriately reviewed evidence in valuing changes in the risk of premature death and continues to engage with the SAB to identify scientifically sound approaches to update its mortality risk valuation estimates. Most recently, the Agency proposed new meta-analytic approaches for updating its estimates, which were subsequently reviewed by the SAB-EEAC.[1985] EPA is taking the SAB's formal recommendations under advisement.

7.2.4 Health Benefits Results

The value of health benefits from reductions in $PM_{2.5}$ emissions associated with this final rule were estimated by multiplying $PM_{2.5}$-related BPT values by the corresponding annual reduction in tons of directly-emitted $PM_{2.5}$ and $PM_{2.5}$ precursor emissions (NO_X and SO_2). As explained above, the $PM_{2.5}$ BPT values represent the monetized value of human health benefits, including reductions in both premature mortality and nonfatal illnesses. Table 7-6 presents the $PM_{2.5}$ BPT values estimated from two different PM-related premature mortality cohort studies, Wu et al., 2020 (the Medicare cohort study) and Pope III et al., 2019 (the NHIS cohort study). The table reports different values by source and pollutant because different pollutant emissions do not equally contribute to ambient $PM_{2.5}$ formation and different emissions sources do not equally contribute to population exposure and associated health impacts. BPT values are also estimated using either a 3-percent or 7-percent discount rate to account for avoided health outcomes that are expected to accrue over more than a single year (the "cessation lag" between the change in PM exposures and the total realization of changes in health effects). The source sectors include: onroad heavy-duty diesel trucks, onroad heavy-duty gasoline trucks, electricity generating units (EGUs), and refineries.

Table 7-7 and Table 7-8 present the NO_X, SO_2 and direct $PM_{2.5}$ emission reductions, and associated monetized $PM_{2.5}$-related health benefits, of the final program for heavy-duty diesel and heavy-duty gasoline vehicles, respectively. Benefits for each heavy-duty vehicle type (diesel or gasoline engine) are presented for the stream of years beginning with the first year of rule implementation, 2027, through 2055. The tables also include the present value (PV) and annualized value (AV) of the stream of benefits over this time series, discounted using both 3-percent and 7-percent discount rates. Table 7-9 presents the NO_X, SO_2, and direct $PM_{2.5}$ emissions increases, and associated monetized $PM_{2.5}$-related health impacts, for EGUs for the final rule. Table 7-10presents the NO_X, SO_2, and direct $PM_{2.5}$ emissions reductions, and associated monetized $PM_{2.5}$-related health benefits, from refineries for the final rule.

Table 7-11 presents the total net $PM_{2.5}$-related benefits (onroad heavy-duty vehicles and upstream) for the final rule. Table 7-12 through Table 7-16 present similar results for the alternative.

[1985] U.S. EPA. 2017. SAB Review of EPA's Proposed Methodology for Updating Mortality Risk Valuation Estimates for Policy Analysis. Available at: https://nepis.epa.gov/Exe/ZyPDF.cgi/P100ROQR.PDF?Dockey=P100ROQR.PDF.

Table 7-6 PM$_{2.5}$-related Benefit Per Ton values (2022$) associated with the changes of NO$_X$, SO$_2$ and directly emitted PM$_{2.5}$ emissions for (A) Onroad Heavy-Duty Diesel Vehicles, (B) Onroad Heavy-Duty Gasoline Vehicles, (C) Electricity Generating Units, and (D) Refineries.

A. Onroad Heavy-Duty Diesel

	NO$_X$				SO$_2$				Direct PM			
	3% Discount Rate		7% Discount Rate		3% Discount Rate		7% Discount Rate		3% Discount Rate		7% Discount Rate	
	Wu	Pope	Wu	Pope	Wu	Pope	Wu	Pope	Wu	Pope	Wu	Pope
2025	$7,070	$15,000	$6,350	$13,500	$299,000	$ 643,000	$269,000	$578,000	$468,000	$1,010,000	$420,000	$ 904,000
2030	$7,950	$16,400	$7,140	$14,700	$341,000	$ 709,000	$306,000	$637,000	$534,000	$1,110,000	$479,000	$ 996,000
2035	$8,930	$18,000	$8,020	$16,200	$390,000	$ 790,000	$350,000	$710,000	$609,000	$1,230,000	$547,000	$1,110,000
2040	$9,740	$19,300	$8,750	$17,300	$436,000	$ 867,000	$392,000	$780,000	$680,000	$1,350,000	$611,000	$1,220,000
2045	$10,300	$20,200	$9,270	$18,200	$476,000	$ 936,000	$428,000	$842,000	$741,000	$1,460,000	$666,000	$1,310,000
2050	$10,700	$20,700	$9,590	$18,700	$510,000	$ 991,000	$458,000	$892,000	$792,000	$1,540,000	$711,000	$1,380,000
2055	$11,100	$21,400	$9,970	$19,200	$547,000	$1,050,000	$491,000	$947,000	$846,000	$1,630,000	$760,000	$1,460,000

B. Onroad Heavy-Duty Gasoline

	NO$_X$				SO$_2$				Direct PM			
	3% Discount Rate		7% Discount Rate		3% Discount Rate		7% Discount Rate		3% Discount Rate		7% Discount Rate	
	Wu	Pope	Wu	Pope	Wu	Pope	Wu	Pope	Wu	Pope	Wu	Pope
2025	$6,970	$14,800	$6,260	$13,300	$161,000	$344,000	$144,000	$310,000	$614,000	$1,310,000	$551,000	$1,180,000
2030	$7,850	$16,100	$7,050	$14,500	$183,000	$379,000	$164,000	$340,000	$700,000	$1,450,000	$629,000	$1,300,000
2035	$8,840	$17,700	$7,940	$16,000	$208,000	$421,000	$187,000	$379,000	$801,000	$1,620,000	$720,000	$1,450,000
2040	$9,670	$19,100	$8,690	$17,200	$232,000	$461,000	$209,000	$415,000	$895,000	$1,770,000	$804,000	$1,590,000
2045	$10,300	$20,100	$9,240	$18,100	$253,000	$496,000	$227,000	$446,000	$976,000	$1,910,000	$877,000	$1,720,000
2050	$10,700	$20,700	$9,600	$18,600	$269,000	$523,000	$242,000	$471,000	$1,040,000	$2,020,000	$936,000	$1,820,000
2055	$11,100	$21,500	$10,000	$19,300	$288,000	$554,000	$259,000	$498,000	$1,110,000	$2,130,000	$997,000	$1,920,000

C. Electricity Generating Units (EGUs)

	NO$_X$				SO$_2$				Direct PM			
	3% Discount Rate		7% Discount Rate		3% Discount Rate		7% Discount Rate		3% Discount Rate		7% Discount Rate	
	Wu	Pope	Wu	Pope	Wu	Pope	Wu	Pope	Wu	Pope	Wu	Pope
2025	$8,450	$17,900	$7,590	$16,100	$62,400	$133,000	$56,200	$120,000	$124,000	$266,000	$111,000	$239,000
2030	$9,460	$19,300	$8,510	$17,400	$70,400	$146,000	$63,300	$131,000	$141,000	$292,000	$127,000	$262,000
2035	$10,600	$21,100	$9,520	$19,100	$79,000	$159,000	$71,100	$144,000	$161,000	$325,000	$145,000	$292,000
2040	$11,500	$22,600	$10,300	$20,400	$86,400	$172,000	$77,700	$154,000	$179,000	$355,000	$161,000	$320,000

D. Refineries

	NO$_X$				SO$_2$				Direct PM			
	3% Discount Rate		7% Discount Rate		3% Discount Rate		7% Discount Rate		3% Discount Rate		7% Discount Rate	
	Wu	Pope	Wu	Pope	Wu	Pope	Wu	Pope	Wu	Pope	Wu	Pope
2025	$25,400	$54,600	$22,800	$49,100	$56,100	$121,000	$50,300	$109,000	$405,000	$878,000	$364,000	$789,000
2030	$28,000	$58,200	$25,200	$52,400	$62,000	$129,000	$55,600	$116,000	$447,000	$934,000	$401,000	$840,000
2035	$32,200	$65,000	$28,900	$58,600	$70,900	$144,000	$63,800	$130,000	$512,000	$1,040,000	$460,000	$940,000
2040	$36,100	$71,600	$32,500	$64,300	$79,300	$158,000	$71,200	$142,000	$576,000	$1,150,000	$518,000	$1,030,000

Notes: All estimates are rounded to three significant figures. The benefit-per-ton (BPT) estimates presented in this table assume either a 3 percent or 7 percent discount rate in the valuation of premature mortality to account for a twenty-year segmented cessation lag. BPT values were estimated for the years 2025, 2030, 2035, 2040, 2045, 2050, and 2055 for mobile sources, and for years 2025, 2030, 2035, and 2040 for EGUs and refineries. We interpolate values for intervening years (e.g., the 2032 BPT values are linearly interpolated using BPT values for 2030 and 2035) and hold values constant past 2040 for EGU and refinery BPTs.

Table 7-7 Summary of the estimated tons of reduced NO_X, SO_2 and direct $PM_{2.5}$ per year from Heavy-Duty Diesel Vehicles and the associated monetized $PM_{2.5}$-related health benefits (millions, 2022$) for the final program

	NOx Reduction Benefits			**SO_2 Reduction Benefits**			**Direct PM Reduction Benefits**		
	Emissions (tons)	**3% Discount Rate**	**7% Discount Rate**	**Emissions (tons)**	**3% Discount Rate**	**7% Discount Rate**	**Emissions (tons)**	**3% Discount Rate**	**7% Discount Rate**
2027	97	$0.72-1.5	$0.65-1.4	1.2	$0.37-0.79	$0.34-0.71	1.5	$0.72-1.5	$0.64-1.4
2028	260	$2.0-4.1	$1.8-3.7	3.1	$1.0-2.1	$0.91-1.9	3.2	$1.6-3.5	$1.5-3.1
2029	480	$3.7-7.7	$3.4-7	5.8	$1.9-4	$1.7-3.6	5.3	$2.8-5.8	$2.5-5.2
2030	890	$7.1-15	$6.4-13	11	$3.8-7.9	$3.4-7.1	9.0	$4.8-9.9	$4.3-8.9
2031	1,800	$15-30	$13-27	23	$8.1-17	$7.2-15	17	$9.4-19	$8.4-17
2032	3,500	$29-60	$26-54	44	$16-33	$14-30	32	$18-37	$16-33
2033	5,200	$45-91	$40-82	66	$24-50	$22-45	46	$27-54	$24-49
2034	7,200	$63-130	$57-110	86	$33-67	$29-60	60	$36-72	$32-65
2035	9,700	$87-170	$78-160	110	$41-84	$37-75	74	$45-91	$41-82
2036	13,000	$120-240	$110-210	120	$50-100	$45-90	88	$55-110	$49-100
2037	17,000	$160-310	$140-280	140	$58-120	$52-100	100	$65-130	$58-120
2038	22,000	$200-410	$180-370	160	$65-130	$59-120	120	$76-150	$68-140
2039	26,000	$250-500	$230-450	170	$73-140	$65-130	130	$86-170	$78-150
2040	30,000	$300-590	$270-530	180	$79-160	$71-140	140	$97-190	$87-170
2041	34,000	$340-670	$300-600	190	$86-170	$77-150	150	$110-210	$96-190
2042	38,000	$380-740	$340-670	200	$92-180	$82-160	160	$120-230	$100-210
2043	41,000	$410-800	$370-720	210	$97-190	$87-170	170	$120-240	$110-220
2044	43,000	$440-860	$390-770	220	$100-200	$91-180	180	$130-260	$120-230
2045	45,000	$460-900	$410-810	220	$110-210	$95-190	190	$140-270	$120-240
2046	46,000	$480-940	$430-850	220	$110-210	$97-190	190	$140-280	$130-250
2047	47,000	$500-970	$450-870	230	$110-220	$100-200	190	$150-290	$130-260
2048	48,000	$510-990	$460-890	230	$110-220	$100-200	190	$150-290	$130-260
2049	49,000	$520-1000	$470-910	230	$120-230	$100-200	200	$150-300	$140-270
2050	50,000	$530-1000	$480-930	230	$120-230	$110-210	200	$160-300	$140-270
2051	50,000	$540-1100	$490-950	230	$120-230	$110-210	200	$160-310	$140-280
2052	51,000	$550-1100	$500-960	230	$120-240	$110-210	200	$160-320	$150-280
2053	51,000	$560-1100	$500-980	230	$120-240	$110-220	200	$170-320	$150-290
2054	52,000	$570-1100	$510-990	230	$130-240	$110-220	200	$170-330	$150-290
2055	52,000	$570-1100	$520-1000	230	$130-250	$110-220	200	$170-330	$150-300
PV		$4,700-9,200	$2,000-4,000		$1,200-2,400	$540-1,100		$1,500-3,000	$680-1,300
AV		$250-480	$170-320		$62-120	$44-87		$79-160	$55-110

Notes: The range of benefits in this table reflect the range of premature mortality estimates derived from the Medicare study (Wu et al., 2020) and the NHIS study (Pope III et al., 2019). All benefits estimates are rounded to two significant figures. Annual benefit values presented here are not discounted. The present value of benefits is the total aggregated value of the series of discounted annual benefits that occur between 2027-2055 (in 2022 dollars) using either a 3% or 7% discount rate.

Table 7-8 Summary of the estimated tons of reduced NO_X, SO_2 and direct $PM_{2.5}$ per year from Heavy-Duty Gasoline Vehicles and the associated monetized $PM_{2.5}$-related health benefits (millions, 2022$) for the final program

	NOx Reduction Benefits			SO_2 Reduction Benefits			Direct PM Reduction Benefits		
	Emissions (tons)	**3% Discount Rate**	**7% Discount Rate**	**Emissions (tons)**	**3% Discount Rate**	**7% Discount Rate**	**Emissions (tons)**	**3% Discount Rate**	**7% Discount Rate**
2027	49	$0.36-0.75	$0.32-0.67	1.1	$0.19-0.4	$0.17-0.36	2.4	$1.5-3.2	$1.4-2.9
2028	100	$0.75-1.6	$0.68-1.4	2.2	$0.38-0.8	$0.34-0.72	4.7	$3.1-6.5	$2.8-5.9
2029	150	$1.2-2.4	$1-2.2	3.2	$0.57-1.2	$0.51-1.1	7.0	$4.8-9.9	$4.3-8.9
2030	200	$1.6-3.3	$1.4-3	4.2	$0.76-1.6	$0.68-1.4	9.3	$6.5-13	$5.9-12
2031	340	$2.7-5.6	$2.5-5	6.6	$1.2-2.6	$1.1-2.3	16	$12-24	$10-21
2032	540	$4.5-9.1	$4-8.2	11	$2.1-4.2	$1.9-3.8	26	$19-39	$17-35
2033	740	$6.2-13	$5.6-11	14	$2.9-5.8	$2.6-5.2	35	$27-54	$24-49
2034	920	$7.9-16	$7.1-14	18	$3.6-7.3	$3.2-6.5	43	$34-68	$30-61
2035	1,100	$9.7-19	$8.7-17	20	$4.2-8.5	$3.8-7.7	52	$42-84	$38-76
2036	1,300	$12-23	$10-21	23	$4.8-9.7	$4.4-8.8	62	$51-100	$46-92
2037	1,500	$13-27	$12-24	25	$5.4-11	$4.9-9.8	72	$60-120	$54-110
2038	1,600	$15-30	$14-27	27	$6-12	$5.4-11	81	$69-140	$62-120
2039	1,800	$17-33	$15-30	29	$6.5-13	$5.8-12	88	$77-150	$69-140
2040	1,900	$18-36	$17-33	30	$7-14	$6.3-13	95	$85-170	$76-150
2041	2,000	$20-39	$18-35	31	$7.4-15	$6.7-13	100	$92-180	$83-160
2042	2,100	$21-41	$19-37	33	$7.8-16	$7.1-14	110	$99-200	$89-180
2043	2,200	$22-43	$20-39	34	$8.2-16	$7.4-15	110	$110-210	$95-190
2044	2,300	$23-45	$21-41	34	$8.5-17	$7.6-15	120	$110-220	$100-200
2045	2,300	$24-47	$21-42	35	$8.8-17	$7.9-16	120	$120-230	$100-200
2046	2,400	$25-48	$22-43	35	$9-18	$8.1-16	120	$120-230	$110-210
2047	2,400	$25-49	$23-44	36	$9.2-18	$8.3-16	120	$120-240	$110-220
2048	2,400	$26-50	$23-45	36	$9.4-18	$8.4-16	130	$130-250	$110-220
2049	2,500	$26-51	$24-46	36	$9.6-19	$8.6-17	130	$130-250	$120-230
2050	2,500	$27-52	$24-46	36	$9.7-19	$8.8-17	130	$130-260	$120-230
2051	2,500	$27-52	$24-47	36	$9.9-19	$8.9-17	130	$140-260	$120-240
2052	2,500	$27-53	$25-48	36	$10-19	$9.1-18	130	$140-270	$130-240
2053	2,500	$28-54	$25-48	36	$10-20	$9.2-18	130	$140-270	$130-250
2054	2,500	$28-54	$25-49	36	$10-20	$9.3-18	130	$140-280	$130-250
2055	2,500	$28-54	$25-49	36	$10-20	$9.4-18	130	$140-280	$130-250
PV		$280-540	$130-250		$110-210	$49-98		$1,300-2,600	$600-1,200
AV		$14-28	$10-20		$5.5-11	$4.0-8.0		$69-140	$49-96

Notes: The range of benefits in this table reflect the range of premature mortality estimates derived from the Medicare study (Wu et al., 2020) and the NHIS study (Pope III et al., 2019). All benefits estimates are rounded to two significant figures. Annual benefit values presented here are not discounted. The present value of benefits is the total aggregated value of the series of discounted annual benefits that occur between 2027-2055 (in 2022 dollars) using either a 3% or 7% discount rate.

Table 7-9 Summary of the estimated tons of increased NO$_X$, SO$_2$ and direct PM$_{2.5}$ per year from EGUs and the associated monetized PM$_{2.5}$-related health impacts (millions, 2022$) for the final program

	NOx Reduction Benefits			**SO$_2$ Reduction Benefits**			**Direct PM Reduction Benefits**		
	Emissions (tons)	**3% Discount Rate**	**7% Discount Rate**	**Emissions (tons)**	**3% Discount Rate**	**7% Discount Rate**	**Emissions (tons)**	**3% Discount Rate**	**7% Discount Rate**
2027	83	$(0.73)-(1.5)	$(0.66)-(1.4)	100	$(6.5)-(14)	$(5.9)-(12)	12	$(1.6)-(3.3)	$(1.4)-(3.0)
2028	220	$(2.0)-(4.1)	$(1.8)-(3.7)	260	$(18)-(37)	$(16)-(34)	32	$(4.3)-(9.0)	$(3.9)-(8.1)
2029	410	$(3.8)-(7.8)	$(3.4)-(7.1)	500	$(34)-(71)	$(31)-(64)	60	$(8.3)-(17)	$(7.4)-(15)
2030	890	$(8.4)-(17)	$(7.6)-(15)	1,100	$(75)-(160)	$(68)-(140)	130	$(18)-(38)	$(16)-(34)
2031	1,900	$(19)-(38)	$(17)-(34)	2,300	$(170)-(350)	$(150)-(310)	280	$(41)-(84)	$(37)-(76)
2032	3,900	$(39)-(79)	$(35)-(71)	4,700	$(350)-(710)	$(310)-(640)	570	$(85)-(170)	$(76)-(160)
2033	5,900	$(60)-(120)	$(54)-(110)	7,100	$(540)-(1100)	$(480)-(980)	860	$(130)-(270)	$(120)-(240)
2034	7,800	$(81)-(160)	$(73)-(150)	9,400	$(730)-(1500)	$(660)-(1300)	1,100	$(180)-(360)	$(160)-(330)
2035	9,700	$(100)-(210)	$(93)-(190)	12,000	$(930)-(1900)	$(830)-(1700)	1,400	$(230)-(460)	$(210)-(410)
2036	9,500	$(100)-(200)	$(92)-(180)	11,000	$(910)-(1800)	$(820)-(1700)	1,400	$(230)-(470)	$(210)-(420)
2037	8,700	$(95)-(190)	$(85)-(170)	10,000	$(830)-(1700)	$(750)-(1500)	1,300	$(220)-(440)	$(200)-(400)
2038	7,100	$(80)-(160)	$(71)-(140)	8,000	$(670)-(1300)	$(600)-(1200)	1,100	$(190)-(380)	$(170)-(350)
2039	5,000	$(57)-(110)	$(51)-(100)	5,200	$(440)-(880)	$(400)-(790)	850	$(150)-(300)	$(130)-(270)
2040	2,400	$(28)-(55)	$(25)-(49)	1,800	$(150)-(300)	$(140)-(270)	510	$(92)-(180)	$(82)-(160)
2041	2,300	$(27)-(53)	$(24)-(47)	1,600	$(140)-(280)	$(130)-(250)	540	$(96)-(190)	$(87)-(170)
2042	2,200	$(25)-(50)	$(23)-(45)	1,400	$(120)-(250)	$(110)-(220)	560	$(100)-(200)	$(90)-(180)
2043	2,000	$(23)-(46)	$(21)-(41)	1,200	$(100)-(210)	$(93)-(180)	580	$(100)-(210)	$(93)-(190)
2044	1,800	$(21)-(41)	$(19)-(37)	940	$(81)-(160)	$(73)-(140)	590	$(110)-(210)	$(95)-(190)
2045	1,600	$(18)-(36)	$(16)-(32)	650	$(56)-(110)	$(50)-(100)	600	$(110)-(210)	$(96)-(190)
2046	1,600	$(18)-(36)	$(16)-(32)	540	$(47)-(93)	$(42)-(83)	580	$(100)-(210)	$(94)-(190)
2047	1,600	$(18)-(35)	$(16)-(32)	430	$(37)-(74)	$(33)-(66)	570	$(100)-(200)	$(91)-(180)
2048	1,500	$(18)-(35)	$(16)-(31)	310	$(27)-(53)	$(24)-(48)	550	$(98)-(190)	$(88)-(170)
2049	1,500	$(18)-(34)	$(16)-(31)	190	$(16)-(33)	$(15)-(29)	530	$(94)-(190)	$(84)-(170)
2050	1,500	$(17)-(34)	$(15)-(30)	68	$(5.8)-(12)	$(5.3)-(10)	500	$(90)-(180)	$(81)-(160)
2051	1,500	$(17)-(34)	$(16)-(31)	68	$(5.9)-(12)	$(5.3)-(10)	510	$(91)-(180)	$(82)-(160)
2052	1,500	$(17)-(34)	$(16)-(31)	68	$(5.9)-(12)	$(5.3)-(11)	510	$(91)-(180)	$(82)-(160)
2053	1,500	$(17)-(34)	$(16)-(31)	69	$(5.9)-(12)	$(5.3)-(11)	510	$(91)-(180)	$(82)-(160)
2054	1,500	$(18)-(34)	$(16)-(31)	69	$(5.9)-(12)	$(5.3)-(11)	510	$(92)-(180)	$(82)-(160)
2055	1,500	$(18)-(34)	$(16)-(31)	69	$(5.9)-(12)	$(5.3)-(11)	510	$(92)-(180)	$(82)-(160)
PV		$(670)-(1,300)	$(600)-(1,200)		$(4,800)-(9,700)	$(4,300)-(8,700)		$(2,000)-(3,900)	$(1,800)-(3,500)
AV		$(35)-(69)	$(31)-(62)		$(250)-(510)	$(230)-(460)		$(100)-(200)	$(92)-(180)

Notes: The range of benefits in this table reflect the range of premature mortality estimates derived from the Medicare study (Wu et al., 2020) and the NHIS study (Pope III et al., 2019). A negative benefit value (in parentheses) implies an increase in adverse health outcomes. All benefits estimates are rounded to two significant figures. Annual benefit values presented here are not discounted. The present value of benefits is the total aggregated value of the series of discounted annual benefits that occur between 2027-2055 (in 2022 dollars) using either a 3% or 7% discount rate.

Table 7-10 Summary of the estimated tons of reduced NO_X, SO_2 and direct $PM_{2.5}$ per year from Refineries and the associated monetized $PM_{2.5}$-related health benefits (millions, 2022$) for the final program

	NOx Reduction Benefits			SO_2 Reduction Benefits			Direct PM Reduction Benefits		
	Emissions (tons)	3% Discount Rate	7% Discount Rate	Emissions (tons)	3% Discount Rate	7% Discount Rate	Emissions (tons)	3% Discount Rate	7% Discount Rate
2027	4.6	$0.12-0.26	$0.11-0.23	1.4	$0.081-0.17	$0.073-0.16	1.1	$0.46-0.98	$0.41-0.88
2028	9.5	$0.26-0.54	$0.23-0.49	2.9	$0.17-0.36	$0.15-0.33	2.3	$0.97-2.1	$0.87-1.8
2029	15	$0.41-0.85	$0.37-0.77	4.5	$0.27-0.57	$0.25-0.52	3.5	$1.5-3.2	$1.4-2.9
2030	22	$0.62-1.3	$0.55-1.1	6.7	$0.42-0.87	$0.37-0.78	5.1	$2.3-4.8	$2.1-4.3
2031	39	$1.1-2.3	$1.0-2.1	12	$0.77-1.6	$0.69-1.4	9.1	$4.2-8.7	$3.8-7.9
2032	69	$2.0-4.2	$1.8-3.8	21	$1.4-2.9	$1.3-2.6	16	$7.6-16	$6.8-14
2033	97	$3.0-6.0	$2.7-5.4	30	$2.0-4.1	$1.8-3.7	23	$11-23	$9.9-20
2034	120	$3.9-7.9	$3.5-7.1	38	$2.6-5.4	$2.4-4.9	29	$14-29	$13-26
2035	150	$4.8-9.6	$4.3-8.7	46	$3.2-6.6	$2.9-6.0	34	$18-36	$16-32
2036	170	$5.6-11	$5.0-10	53	$3.8-7.7	$3.4-7.0	39	$21-42	$19-38
2037	190	$6.4-13	$5.8-12	59	$4.4-8.8	$3.9-8.0	44	$24-48	$21-43
2038	210	$7.2-14	$6.5-13	65	$4.9-9.9	$4.4-8.9	48	$27-54	$24-48
2039	230	$8.0-16	$7.2-14	70	$5.4-11	$4.9-9.8	52	$29-59	$27-53
2040	240	$8.7-17	$7.8-16	75	$5.9-12	$5.3-11	56	$32-64	$29-58
2041	250	$9.2-18	$8.3-16	79	$6.2-12	$5.6-11	59	$34-68	$30-61
2042	270	$9.6-19	$8.6-17	82	$6.5-13	$5.9-12	61	$35-71	$32-64
2043	280	$9.9-20	$8.9-18	85	$6.7-13	$6.1-12	64	$37-73	$33-66
2044	280	$10-20	$9.2-18	87	$6.9-14	$6.2-12	65	$38-75	$34-67
2045	290	$10-21	$9.3-19	89	$7.1-14	$6.3-13	66	$38-77	$34-69
2046	290	$11-21	$9.5-19	90	$7.2-14	$6.4-13	68	$39-78	$35-70
2047	300	$11-21	$9.6-19	92	$7.3-15	$6.5-13	68	$39-79	$35-71
2048	300	$11-21	$9.7-19	92	$7.3-15	$6.6-13	69	$40-80	$36-71
2049	300	$11-22	$9.8-19	93	$7.4-15	$6.6-13	69	$40-80	$36-72
2050	300	$11-22	$9.9-20	94	$7.4-15	$6.7-13	70	$40-81	$36-72
2051	300	$11-22	$9.9-20	94	$7.4-15	$6.7-13	70	$40-81	$36-73
2052	310	$11-22	$9.9-20	94	$7.5-15	$6.7-13	70	$41-81	$36-73
2053	310	$11-22	$9.9-20	94	$7.5-15	$6.7-13	70	$41-81	$36-73
2054	300	$11-22	$9.9-20	94	$7.4-15	$6.7-13	70	$40-81	$36-73
2055	300	$11-22	$9.9-20	94	$7.4-15	$6.7-13	70	$40-81	$36-72
PV		$120-240	$110-220		$82-160	$74-150		$450-900	$400-800
AV		$6.3-13	$5.7-11		$4.3-8.6	$3.8-7.7		$23-47	$21-42

Notes: The range of benefits in this table reflect the range of premature mortality estimates derived from the Medicare study (Wu et al., 2020) and the NHIS study (Pope III et al., 2019). All benefits estimates are rounded to two significant figures. Annual benefit values presented here are not discounted. The present value of benefits is the total aggregated value of the series of discounted annual benefits that occur between 2027-2055 (in 2022 dollars) using either a 3% or 7% discount rate.

Table 7-11 Year-over-year monetized $PM_{2.5}$-related health benefits (millions, 2022$) associated with Onroad Heavy-Duty Vehicle and upstream (EGU plus refinery) emissions from the final program

	Total Onroad Benefits		Upstream Benefits		Net Benefits	
	3% Discount Rate	**7% Discount Rate**	**3% Discount Rate**	**7% Discount Rate**	**3% Discount Rate**	**7% Discount Rate**
2027	$3.9-8.2	$3.5-7.4	$(8.2)-(17)	$(7.4)-(15)	$(4.3)-(9.0)	$(3.9)-(8.1)
2028	$8.9-19	$8.0-17	$(23)-(47)	$(20)-(43)	$(14)-(29)	$(12)-(26)
2029	$15-31	$13-28	$(44)-(92)	$(40)-(82)	$(29)-(61)	$(26)-(54)
2030	$25-51	$22-46	$(99)-(200)	$(89)-(180)	$(74)-(150)	$(67)-(140)
2031	$48-98	$43-88	$(220)-(460)	$(200)-(410)	$(180)-(360)	$(160)-(320)
2032	$89-180	$80-160	$(460)-(940)	$(420)-(850)	$(370)-(760)	$(340)-(690)
2033	$130-270	$120-240	$(710)-(1,400)	$(640)-(1,300)	$(580)-(1,200)	$(520)-(1,100)
2034	$180-360	$160-320	$(970)-(2,000)	$(870)-(1,800)	$(790)-(1,600)	$(710)-(1,400)
2035	$230-460	$210-420	$(1,200)-(2,500)	$(1,100)-(2,200)	$(1,000)-(2,000)	$(900)-(1,800)
2036	$290-580	$260-520	$(1,200)-(2,500)	$(1,100)-(2,200)	$(930)-(1,900)	$(840)-(1,700)
2037	$360-720	$320-640	$(1,100)-(2,200)	$(1,000)-(2,000)	$(750)-(1,500)	$(680)-(1,400)
2038	$440-870	$390-780	$(900)-(1,800)	$(810)-(1,600)	$(470)-(940)	$(420)-(840)
2039	$510-1,000	$460-910	$(610)-(1,200)	$(550)-(1,100)	$(96)-(190)	$(87)-(170)
2040	$580-1,200	$520-1,000	$(230)-(450)	$(200)-(400)	$360-710	$320-640
2041	$650-1,300	$580-1,200	$(210)-(420)	$(190)-(380)	$440-860	$390-770
2042	$710-1,400	$640-1,300	$(200)-(390)	$(180)-(350)	$510-1,000	$460-910
2043	$760-1,500	$690-1,400	$(180)-(350)	$(160)-(320)	$590-1,200	$530-1,000
2044	$810-1,600	$730-1,400	$(150)-(300)	$(140)-(270)	$660-1,300	$590-1,200
2045	$850-1,700	$770-1,500	$(130)-(250)	$(110)-(220)	$730-1,400	$650-1,300
2046	$880-1,700	$800-1,600	$(110)-(220)	$(100)-(200)	$770-1,500	$690-1,400
2047	$910-1,800	$820-1,600	$(99)-(200)	$(89)-(180)	$810-1,600	$730-1,400
2048	$940-1,800	$840-1,600	$(84)-(170)	$(76)-(150)	$850-1,700	$770-1,500
2049	$960-1,900	$860-1,700	$(70)-(140)	$(62)-(120)	$890-1,700	$800-1,600
2050	$980-1,900	$880-1,700	$(55)-(110)	$(49)-(97)	$920-1,800	$830-1,600
2051	$1,000-1,900	$900-1,700	$(55)-(110)	$(49)-(98)	$940-1,800	$850-1,600
2052	$1,000-2,000	$910-1,800	$(56)-(110)	$(50)-(99)	$960-1,900	$860-1,700
2053	$1,000-2,000	$930-1,800	$(56)-(110)	$(50)-(99)	$970-1,900	$880-1,700
2054	$1,000-2,000	$940-1,800	$(56)-(110)	$(50)-(100)	$990-1,900	$890-1,700
2055	$1,100-2,000	$950-1,800	$(56)-(110)	$(51)-(100)	$1,000-1,900	$900-1,700
PV	$9,100-18,000	$4,000-7,900	$(6,800)-(14,000)	$(4,100)-(8,300)	$2,300-4,200	$(110)-(400)
AV	$480-930	$330-650	$(350)-(710)	$(340)-(680)	$120-220	$(9.1)-(32)

Notes:
The range of benefits in this table reflect the range of premature mortality estimates derived from the Medicare study (Wu et al., 2020) and the NHIS study (Pope et al., 2019), respectively. All benefits estimates are rounded to two significant figures. Annual benefit values presented here are not discounted. Negative values in parentheses are health disbenefits related to increases in estimated emissions. The present value of benefits is the total aggregated value of the series of discounted annual benefits that occur between 2027-2055 (in 2022 dollars) using either a 3% or 7% discount rate. Depending on the discount rate used, the present and annualized value of the stream of $PM_{2.5}$ health benefits may either be positive or negative. The upstream impacts associated with the standards presented here include health benefits associated with reduced criteria pollutant emissions from refineries and health disbenefits associated with increased criteria pollutant emissions from EGUs. The benefits in this table also do not include the full complement of health and environmental benefits (such as health benefits related to reduced ozone exposure) that, if quantified and monetized, would increase the total monetized benefits.

Table 7-12 Summary of the estimated tons of reduced NO$_X$, SO$_2$ and direct PM$_{2.5}$ per year from Heavy-Duty Diesel Vehicles and the associated monetized PM$_{2.5}$-related health benefits (millions, 2022$) for the alternative program

	NOx Reduction Benefits			SO$_2$ Reduction Benefits			Direct PM Reduction Benefits		
	Emissions (tons)	**3% Discount Rate**	**7% Discount Rate**	**Emissions (tons)**	**3% Discount Rate**	**7% Discount Rate**	**Emissions (tons)**	**3% Discount Rate**	**7% Discount Rate**
2027	51	$0.38-0.79	$0.34-0.71	0.60	$0.19-0.40	$0.17-0.36	0.64	$0.32-0.67	$0.29-0.61
2028	110	$0.87-1.8	$0.78-1.6	1.3	$0.44-0.92	$0.39-0.83	1.3	$0.67-1.4	$0.6-1.3
2029	240	$1.8-3.8	$1.6-3.4	2.8	$0.94-2.0	$0.85-1.8	2.4	$1.2-2.6	$1.1-2.3
2030	500	$4.0-8.2	$3.6-7.3	6.3	$2.1-4.4	$1.9-4.0	4.5	$2.4-5.0	$2.2-4.5
2031	940	$7.7-16	$6.9-14	12	$4.2-8.7	$3.8-7.9	8.0	$4.4-9.0	$3.9-8.1
2032	1,600	$13-27	$12-24	21	$7.4-15	$6.7-14	13	$7.4-15	$6.6-14
2033	2,300	$19-39	$17-35	29	$11-22	$9.5-20	18	$10-21	$9.3-19
2034	3,100	$27-54	$24-49	36	$14-28	$12-25	22	$13-27	$12-24
2035	4,100	$37-74	$33-66	43	$17-34	$15-31	27	$17-33	$15-30
2036	5,500	$50-100	$45-91	50	$20-40	$18-36	32	$20-40	$18-36
2037	7,200	$67-130	$60-120	56	$23-46	$20-41	36	$23-47	$21-42
2038	9,100	$86-170	$77-150	61	$25-51	$23-46	41	$27-53	$24-48
2039	11,000	$100-210	$94-190	65	$28-55	$25-50	45	$30-60	$27-54
2040	12,000	$120-240	$110-220	69	$30-60	$27-54	49	$33-66	$30-59
2041	14,000	$140-270	$120-240	72	$32-63	$29-57	52	$36-71	$32-64
2042	15,000	$150-290	$130-260	74	$34-67	$30-60	55	$38-76	$35-68
2043	16,000	$160-310	$140-280	76	$35-69	$32-62	57	$41-80	$36-72
2044	17,000	$170-330	$150-300	78	$36-72	$33-64	58	$42-83	$38-75
2045	17,000	$180-340	$160-310	78	$37-73	$33-66	59	$44-86	$39-77
2046	17,000	$180-350	$160-320	79	$38-74	$34-67	59	$45-87	$40-78
2047	18,000	$180-360	$170-320	79	$38-75	$35-68	59	$45-88	$41-80
2048	18,000	$190-370	$170-330	78	$39-76	$35-68	59	$46-89	$41-80
2049	18,000	$190-370	$170-330	78	$39-76	$35-69	59	$46-90	$42-81
2050	18,000	$190-380	$170-340	78	$40-77	$36-69	59	$47-91	$42-82
2051	18,000	$200-380	$180-340	77	$40-78	$36-70	59	$47-91	$42-82
2052	18,000	$200-380	$180-340	77	$40-78	$36-70	58	$47-92	$43-83
2053	18,000	$200-380	$180-340	76	$41-79	$37-71	58	$48-92	$43-83
2054	18,000	$200-380	$180-350	76	$41-79	$37-71	57	$48-92	$43-83
2055	18,000	$200-380	$180-350	75	$41-79	$37-71	57	$48-92	$43-83
PV		$1,800-3,500	$780-1,500		$430-850	$200-400		$490-960	$220-440
AV		$94-180	$64-130		$22-44	$16-32		$25-50	$18-36

Notes: The range of benefits in this table reflect the range of premature mortality estimates derived from the Medicare study (Wu et al., 2020) and the NHIS study (Pope III et al., 2019). All benefits estimates are rounded to two significant figures. Annual benefit values presented here are not discounted. The present value of benefits is the total aggregated value of the series of discounted annual benefits that occur between 2027-2055 (in 2022 dollars) using either a 3% or 7% discount rate.

Table 7-13 Summary of the estimated tons of reduced NO_X, SO_2 and direct $PM_{2.5}$ per year from Heavy-Duty Gasoline Vehicles and the associated monetized $PM_{2.5}$-related health benefits (millions, 2022$) for the alternative program

	NOx Reduction Benefits			**SO_2 Reduction Benefits**			**Direct PM Reduction Benefits**		
	Emissions (tons)	**3% Discount Rate**	**7% Discount Rate**	**Emissions (tons)**	**3% Discount Rate**	**7% Discount Rate**	**Emissions (tons)**	**3% Discount Rate**	**7% Discount Rate**
2027	31	$0.23-0.48	$0.21-0.43	0.69	$0.12-0.25	$0.1-0.22	1.5	$0.98-2.1	$0.88-1.9
2028	63	$0.47-0.98	$0.42-0.88	1.3	$0.23-0.48	$0.21-0.43	3.0	$2.0-4.2	$1.8-3.7
2029	94	$0.72-1.5	$0.65-1.3	1.9	$0.34-0.71	$0.3-0.63	4.4	$3.0-6.3	$2.7-5.7
2030	130	$1.0-2.1	$0.90-1.8	2.5	$0.46-0.94	$0.41-0.85	5.9	$4.2-8.6	$3.7-7.7
2031	180	$1.5-3.0	$1.3-2.7	3.3	$0.62-1.3	$0.56-1.2	8.8	$6.4-13	$5.7-12
2032	250	$2.1-4.2	$1.9-3.8	4.4	$0.86-1.8	$0.77-1.6	12	$9.0-18	$8.1-17
2033	310	$2.6-5.3	$2.3-4.7	5.2	$1.0-2.1	$0.92-1.9	15	$11-23	$10-21
2034	350	$3.0-6.1	$2.7-5.5	5.7	$1.2-2.3	$1.0-2.1	17	$13-27	$12-24
2035	380	$3.4-6.7	$3.0-6.0	5.9	$1.2-2.5	$1.1-2.2	19	$15-30	$13-27
2036	410	$3.7-7.3	$3.3-6.6	5.9	$1.3-2.5	$1.1-2.3	20	$17-33	$15-30
2037	420	$3.9-7.8	$3.5-7.0	5.9	$1.3-2.6	$1.2-2.3	21	$18-36	$16-32
2038	430	$4.1-8.0	$3.6-7.2	5.8	$1.3-2.6	$1.2-2.3	22	$19-38	$17-34
2039	430	$4.1-8.1	$3.7-7.3	5.6	$1.3-2.5	$1.1-2.3	22	$19-38	$17-34
2040	420	$4.1-8.0	$3.7-7.2	5.3	$1.2-2.4	$1.1-2.2	21	$19-38	$17-34
2041	400	$3.9-7.7	$3.5-7.0	5.0	$1.2-2.3	$1.1-2.1	20	$19-37	$17-33
2042	380	$3.8-7.4	$3.4-6.6	4.6	$1.1-2.2	$0.99-2.0	20	$18-36	$16-32
2043	350	$3.5-6.9	$3.2-6.2	4.2	$1.0-2.0	$0.93-1.8	18	$17-34	$15-30
2044	330	$3.3-6.5	$3.0-5.8	3.9	$0.96-1.9	$0.86-1.7	17	$16-32	$15-29
2045	300	$3.1-6.0	$2.8-5.4	3.5	$0.89-1.7	$0.8-1.6	15	$15-29	$13-26
2046	280	$2.9-5.6	$2.6-5.0	3.2	$0.83-1.6	$0.74-1.5	14	$14-27	$12-24
2047	260	$2.7-5.2	$2.4-4.7	3.0	$0.77-1.5	$0.69-1.3	13	$13-25	$11-22
2048	240	$2.5-4.9	$2.2-4.4	2.7	$0.71-1.4	$0.64-1.2	12	$12-23	$11-21
2049	220	$2.3-4.6	$2.1-4.1	2.5	$0.67-1.3	$0.6-1.2	11	$11-21	$9.8-19
2050	210	$2.2-4.3	$2.0-3.9	2.4	$0.64-1.2	$0.57-1.1	10	$10-20	$9.0-18
2051	200	$2.1-4.1	$1.9-3.7	2.2	$0.61-1.2	$0.55-1.1	8.8	$9.3-18	$8.4-16
2052	190	$2.0-3.9	$1.8-3.5	2.1	$0.59-1.1	$0.53-1.0	8.2	$8.7-17	$7.8-15
2053	180	$2.0-3.8	$1.8-3.4	2.0	$0.57-1.1	$0.51-0.98	7.4	$8.1-16	$7.2-14
2054	170	$1.9-3.7	$1.7-3.3	1.9	$0.55-1.1	$0.49-0.95	6.7	$7.4-14	$6.6-13
2055	160	$1.8-3.5	$1.6-3.2	1.9	$0.53-1.0	$0.48-0.92	6.0	$6.7-13	$6.0-12
PV		$48-95	$26-51		$16-31	$8.7-18		$220-430	$120-230
AV		$2.5-4.9	$2.1-4.2		$0.8-1.6	$0.7-1.4		$11-23	$10-19

Notes: The range of benefits in this table reflect the range of premature mortality estimates derived from the Medicare study (Wu et al., 2020) and the NHIS study (Pope III et al., 2019). All benefits estimates are rounded to two significant figures. Annual benefit values presented here are not discounted. The present value of benefits is the total aggregated value of the series of discounted annual benefits that occur between 2027-2055 (in 2022 dollars) using either a 3% or 7% discount rate.

Table 7-14 Summary of the estimated tons of increased NO$_X$, SO2 and direct PM$_{2.5}$ per year from EGUs and the associated monetized PM$_{2.5}$-related health impacts (millions, 2022$) for the alternative program

	NO$_X$			SO$_2$			Direct PM		
	Emissions (tons)	**3% Discount Rate**	**7% Discount Rate**	**Emissions (tons)**	**3% Discount Rate**	**7% Discount Rate**	**Emissions (tons)**	**3% Discount Rate**	**7% Discount Rate**
2027	41	$(0.36)-(0.75)	$(0.33)-(0.68)	49	$(3.2)-(6.8)	$(2.9)-(6.1)	6.0	$(0.78)-(1.6)	$(0.70)-(1.5)
2028	92	$(0.83)-(1.7)	$(0.75)-(1.6)	110	$(7.5)-(16)	$(6.7)-(14)	13	$(1.8)-(3.8)	$(1.6)-(3.4)
2029	200	$(1.9)-(3.8)	$(1.7)-(3.4)	240	$(17)-(35)	$(15)-(31)	29	$(4.0)-(8.4)	$(3.6)-(7.5)
2030	510	$(4.8)-(9.9)	$(4.3)-(8.9)	620	$(43)-(90)	$(39)-(81)	74	$(11)-(22)	$(9.4)-(20)
2031	1,000	$(10)-(21)	$(9.1)-(19)	1,300	$(91)-(190)	$(82)-(170)	150	$(22)-(46)	$(20)-(41)
2032	1,900	$(18)-(37)	$(17)-(34)	2,200	$(170)-(340)	$(150)-(300)	270	$(40)-(83)	$(36)-(74)
2033	2,600	$(27)-(54)	$(24)-(49)	3,200	$(240)-(490)	$(220)-(440)	390	$(59)-(120)	$(53)-(110)
2034	3,400	$(35)-(71)	$(32)-(64)	4,100	$(320)-(640)	$(290)-(580)	500	$(78)-(160)	$(70)-(140)
2035	4,100	$(44)-(87)	$(39)-(79)	5,000	$(390)-(790)	$(350)-(720)	600	$(97)-(200)	$(87)-(180)
2036	4,000	$(43)-(85)	$(39)-(77)	4,700	$(380)-(770)	$(340)-(690)	590	$(97)-(190)	$(87)-(180)
2037	3,600	$(39)-(77)	$(35)-(70)	4,200	$(340)-(680)	$(310)-(610)	540	$(90)-(180)	$(81)-(160)
2038	2,900	$(32)-(64)	$(29)-(57)	3,300	$(270)-(540)	$(240)-(490)	450	$(78)-(160)	$(70)-(140)
2039	2,000	$(23)-(45)	$(20)-(40)	2,100	$(180)-(350)	$(160)-(320)	340	$(60)-(120)	$(54)-(110)
2040	950	$(11)-(22)	$(9.8)-(19)	700	$(61)-(120)	$(54)-(110)	200	$(36)-(72)	$(33)-(65)
2041	910	$(11)-(21)	$(9.4)-(19)	630	$(55)-(110)	$(49)-(98)	210	$(38)-(75)	$(34)-(68)
2042	850	$(9.8)-(19)	$(8.8)-(17)	550	$(48)-(95)	$(43)-(85)	220	$(39)-(77)	$(35)-(70)
2043	780	$(9.0)-(18)	$(8)-(16)	460	$(40)-(79)	$(36)-(71)	220	$(40)-(79)	$(36)-(71)
2044	690	$(8.0)-(16)	$(7.1)-(14)	350	$(31)-(61)	$(28)-(54)	220	$(40)-(79)	$(36)-(71)
2045	590	$(6.9)-(13)	$(6.1)-(12)	240	$(21)-(42)	$(19)-(37)	220	$(40)-(79)	$(36)-(71)
2046	590	$(6.8)-(13)	$(6)-(12)	200	$(17)-(34)	$(16)-(31)	220	$(39)-(77)	$(35)-(69)
2047	570	$(6.6)-(13)	$(5.9)-(12)	160	$(14)-(27)	$(12)-(24)	210	$(37)-(74)	$(33)-(66)
2048	560	$(6.5)-(13)	$(5.8)-(11)	110	$(9.7)-(19)	$(8.8)-(17)	200	$(35)-(70)	$(32)-(64)
2049	550	$(6.3)-(12)	$(5.7)-(11)	68	$(5.9)-(12)	$(5.3)-(11)	190	$(34)-(67)	$(30)-(61)
2050	530	$(6.2)-(12)	$(5.5)-(11)	24	$(2.1)-(4.2)	$(1.9)-(3.7)	180	$(32)-(64)	$(29)-(58)
2051	530	$(6.2)-(12)	$(5.5)-(11)	24	$(2.1)-(4.2)	$(1.9)-(3.7)	180	$(32)-(64)	$(29)-(58)
2052	530	$(6.1)-(12)	$(5.5)-(11)	24	$(2.1)-(4.1)	$(1.9)-(3.7)	180	$(32)-(64)	$(29)-(57)
2053	530	$(6.1)-(12)	$(5.5)-(11)	24	$(2.1)-(4.1)	$(1.9)-(3.7)	180	$(32)-(63)	$(29)-(57)
2054	520	$(6.0)-(12)	$(5.4)-(11)	24	$(2.0)-(4.1)	$(1.8)-(3.6)	180	$(32)-(63)	$(28)-(57)
2055	520	$(6.0)-(12)	$(5.4)-(11)	24	$(2.0)-(4.0)	$(1.8)-(3.6)	180	$(31)-(62)	$(28)-(56)
PV		$(280)-(550)	$(250)-(500)		$(2,100)-(4,200)	$(1,900)-(3,700)		$(790)-(1,600)	$(710)-(1,400)
AV		$(14)-(29)	$(13)-(26)		$(110)-(220)	$(97)-(190)		$(41)-(83)	$(37)-(75)

Notes: The range of benefits in this table reflect the range of premature mortality estimates derived from the Medicare study (Wu et al., 2020) and the NHIS study (Pope III et al., 2019). A negative benefit value (in parentheses) implies an increase in adverse health outcomes. All benefits estimates are rounded to two significant figures. Annual benefit values presented here are not discounted. The present value of benefits is the total aggregated value of the series of discounted annual benefits that occur between 2027-2055 (in 2022 dollars) using either a 3% or 7% discount rate.

Table 7-15 Summary of the estimated tons of reduced NO$_X$, SO$_2$ and direct PM$_{2.5}$ per year from Refineries and the associated monetized PM$_{2.5}$-related health benefits (millions, 2022$) for the alternative program

	NOx Reduction Benefits			SO$_2$ Reduction Benefits			Direct PM Reduction Benefits		
	Emissions (tons)	3% Discount Rate	7% Discount Rate	Emissions (tons)	3% Discount Rate	7% Discount Rate	Emissions (tons)	3% Discount Rate	7% Discount Rate
2027	2.7	$0.073-0.15	$0.065-0.14	0.8	$0.048-0.1	$0.043-0.092	0.7	$0.27-0.58	$0.25-0.53
2028	5.4	$0.15-0.31	$0.13-0.28	1.6	$0.097-0.2	$0.087-0.18	1.3	$0.55-1.2	$0.49-1.0
2029	8.4	$0.23-0.48	$0.21-0.44	2.6	$0.16-0.33	$0.14-0.29	2.0	$0.87-1.8	$0.78-1.7
2030	13	$0.36-0.75	$0.33-0.68	4.0	$0.25-0.51	$0.22-0.46	3.0	$1.4-2.8	$1.2-2.5
2031	20	$0.58-1.2	$0.52-1.1	6.2	$0.39-0.81	$0.35-0.74	4.7	$2.2-4.5	$1.9-4.0
2032	30	$0.90-1.8	$0.81-1.7	9.3	$0.61-1.3	$0.55-1.1	7.0	$3.3-6.9	$3.0-6.2
2033	39	$1.2-2.4	$1.1-2.2	12	$0.81-1.7	$0.73-1.5	9.0	$4.4-9.0	$3.9-8.1
2034	46	$1.5-2.9	$1.3-2.7	14	$0.99-2.0	$0.89-1.8	11	$5.3-11	$4.8-9.8
2035	52	$1.7-3.4	$1.5-3.1	16	$1.2-2.3	$1.0-2.1	12	$6.2-13	$5.6-11
2036	57	$1.9-3.8	$1.7-3.4	18	$1.3-2.6	$1.2-2.4	13	$6.9-14	$6.2-13
2037	62	$2.1-4.2	$1.9-3.8	19	$1.4-2.9	$1.3-2.6	14	$7.6-15	$6.9-14
2038	65	$2.2-4.5	$2.0-4.0	20	$1.5-3.1	$1.4-2.8	15	$8.2-17	$7.4-15
2039	68	$2.4-4.8	$2.1-4.3	21	$1.6-3.3	$1.5-3.0	16	$8.7-18	$7.9-16
2040	70	$2.5-5.0	$2.3-4.5	22	$1.7-3.4	$1.6-3.1	16	$9.2-18	$8.2-16
2041	71	$2.6-5.1	$2.3-4.5	22	$1.8-3.5	$1.6-3.2	16	$9.3-19	$8.4-17
2042	71	$2.6-5.1	$2.3-4.6	22	$1.8-3.5	$1.6-3.2	16	$9.4-19	$8.4-17
2043	71	$2.6-5.1	$2.3-4.6	22	$1.8-3.5	$1.6-3.2	16	$9.4-19	$8.4-17
2044	71	$2.6-5.1	$2.3-4.6	22	$1.8-3.5	$1.6-3.2	16	$9.3-19	$8.4-17
2045	70	$2.5-5.0	$2.3-4.5	22	$1.8-3.5	$1.6-3.2	16	$9.2-18	$8.3-17
2046	70	$2.5-5.0	$2.3-4.5	22	$1.7-3.5	$1.6-3.1	16	$9.1-18	$8.2-16
2047	69	$2.5-4.9	$2.2-4.4	22	$1.7-3.4	$1.5-3.1	16	$9.0-18	$8.1-16
2048	68	$2.5-4.9	$2.2-4.4	21	$1.7-3.4	$1.5-3.1	15	$8.9-18	$8.0-16
2049	68	$2.4-4.8	$2.2-4.3	21	$1.7-3.4	$1.5-3.0	15	$8.8-18	$7.9-16
2050	67	$2.4-4.8	$2.2-4.3	21	$1.7-3.3	$1.5-3.0	15	$8.7-18	$7.9-16
2051	66	$2.4-4.7	$2.2-4.3	21	$1.7-3.3	$1.5-3.0	15	$8.6-17	$7.8-16
2052	65	$2.4-4.7	$2.1-4.2	21	$1.6-3.3	$1.5-2.9	15	$8.5-17	$7.7-15
2053	64	$2.3-4.6	$2.1-4.1	20	$1.6-3.2	$1.4-2.9	15	$8.4-17	$7.5-15
2054	63	$2.3-4.5	$2.1-4.1	20	$1.6-3.2	$1.4-2.9	14	$8.3-17	$7.4-15
2055	63	$2.3-4.5	$2.0-4.0	20	$1.6-3.1	$1.4-2.8	14	$8.1-16	$7.3-15
PV		$33-65	$29-59		$22-45	$20-41		$120-240	$110-220
AV		$1.7-3.4	$1.5-3.1		$1.2-2.3	$1.1-2.1		$6.2-12	$5.6-11

Notes: The range of benefits in this table reflect the range of premature mortality estimates derived from the Medicare study (Wu et al., 2020) and the NHIS study (Pope III et al., 2019). All benefits estimates are rounded to two significant figures. Annual benefit values presented here are not discounted. The present value of benefits is the total aggregated value of the series of discounted annual benefits that occur between 2027-2055 (in 2022 dollars) using either a 3% or 7% discount rate.

Table 7-16 Year-over-year monetized $PM_{2.5}$-related health benefits (millions, 2022$) associated with Onroad Heavy-Duty Vehicle and upstream (EGU plus refinery) emissions from the alternative program

	Total Onroad Benefits		**Upstream Benefits**		**Net Benefits**	
	3% Discount Rate	**7% Discount Rate**	**3% Discount Rate**	**7% Discount Rate**	**3% Discount Rate**	**7% Discount Rate**
2027	$2.2-4.6	$2.0-4.2	$(4.0)-(8.4)	$(3.6)-(7.5)	$(1.8)-(3.7)	$(1.6)-(3.3)
2028	$4.7-9.8	$4.2-8.8	$(9.3)-(19)	$(8.4)-(17)	$(4.6)-(9.7)	$(4.2)-(8.7)
2029	$8.1-17	$7.3-15	$(21)-(44)	$(19)-(40)	$(13)-(27)	$(12)-(24)
2030	$14-29	$13-26	$(57)-(120)	$(51)-(110)	$(43)-(88)	$(38)-(79)
2031	$25-51	$22-46	$(120)-(250)	$(110)-(220)	$(96)-(200)	$(86)-(180)
2032	$40-82	$36-74	$(220)-(450)	$(200)-(400)	$(180)-(370)	$(160)-(330)
2033	$55-110	$50-100	$(320)-(650)	$(290)-(590)	$(260)-(540)	$(240)-(490)
2034	$71-140	$64-130	$(420)-(860)	$(380)-(770)	$(350)-(710)	$(320)-(640)
2035	$90-180	$81-160	$(530)-(1,100)	$(470)-(950)	$(440)-(880)	$(390)-(790)
2036	$110-220	$100-200	$(510)-(1,000)	$(460)-(920)	$(400)-(800)	$(360)-(720)
2037	$140-270	$120-240	$(460)-(920)	$(410)-(830)	$(320)-(650)	$(290)-(580)
2038	$160-320	$150-290	$(370)-(740)	$(330)-(660)	$(210)-(410)	$(190)-(370)
2039	$190-370	$170-330	$(250)-(490)	$(220)-(440)	$(61)-(120)	$(55)-(110)
2040	$210-410	$190-370	$(94)-(190)	$(85)-(170)	$110-230	$100-200
2041	$230-450	$200-400	$(89)-(180)	$(80)-(160)	$140-270	$120-240
2042	$240-480	$220-430	$(83)-(160)	$(74)-(150)	$160-320	$140-290
2043	$260-510	$230-450	$(74)-(150)	$(67)-(130)	$180-360	$160-320
2044	$270-530	$240-470	$(65)-(130)	$(58)-(120)	$200-400	$180-360
2045	$280-540	$250-490	$(54)-(110)	$(49)-(97)	$220-430	$200-390
2046	$280-550	$250-490	$(49)-(98)	$(44)-(88)	$230-450	$210-410
2047	$280-560	$260-500	$(44)-(87)	$(40)-(79)	$240-470	$220-420
2048	$290-560	$260-500	$(39)-(76)	$(35)-(69)	$250-480	$220-440
2049	$290-560	$260-510	$(33)-(66)	$(30)-(59)	$260-500	$230-450
2050	$290-570	$260-510	$(28)-(55)	$(25)-(49)	$260-510	$240-460
2051	$290-570	$260-510	$(28)-(55)	$(25)-(50)	$270-520	$240-460
2052	$300-570	$270-520	$(28)-(55)	$(25)-(50)	$270-520	$240-470
2053	$300-570	$270-520	$(28)-(55)	$(25)-(49)	$270-520	$240-470
2054	$300-570	$270-520	$(28)-(55)	$(25)-(49)	$270-520	$240-470
2055	$300-570	$270-510	$(27)-(54)	$(25)-(49)	$270-520	$240-470
PV	$3,000-5,900	$1,400-2,700	$(3,000)-(5,900)	$(1,800)-(3,600)	$40-(58)	$(440)-(950)
AV	$160-310	$110-220	$(150)-(310)	$(150)-(300)	$2.1-(3.0)	$(36)-(77)

Notes:

The range of benefits in this table reflect the range of premature mortality estimates derived from the Medicare study (Wu et al., 2020) and the NHIS study (Pope et al., 2019), respectively. All benefits estimates are rounded to two significant figures. Annual benefit values presented here are not discounted. Negative values in parentheses are health disbenefits related to increases in estimated emissions. The present value of benefits is the total aggregated value of the series of discounted annual benefits that occur between 2027-2055 (in 2022 dollars) using either a 3% or 7% discount rate. Depending on the discount rate used, the present and annualized value of the stream of $PM_{2.5}$ health benefits may either be positive or negative. The upstream impacts associated with the standards presented here include health benefits associated with reduced criteria pollutant emissions from refineries and health disbenefits associated with increased criteria pollutant emissions from EGUs. The benefits in this table also do not include the full complement of health and environmental benefits (such as health benefits related to reduced ozone exposure) that, if quantified and monetized, would increase the total monetized benefits.

We use a constant 3-percent and 7-pecent discount rate to calculate present and annualized values, consistent with current applicable OMB Circular A-4 guidance (2003). For the purposes of presenting total net benefits (see RIA Chapter 8), we also use a constant 2-percent discount rate to calculate present and annualized values. We note that we do not currently have BPT estimates that use a 2-percent discount rate to account for cessation lag. If we discount the stream of annual benefits of the final rule based on the 3-percent cessation lag BPT values using a constant 2-percent discount rate, the annualized value of total $PM_{2.5}$-related benefits would be $160 to $300 million and the present value of total $PM_{2.5}$-related benefits would be $3.5 to $6.5 billion.

7.2.5 Characterizing Uncertainty in the Estimated Benefits

There are likely to be sources of uncertainty in any complex analysis using estimated parameters and inputs from numerous models, including this analysis. The Benefits TSD details our approach to characterizing uncertainty in both quantitative and qualitative terms. That TSD describes the sources of uncertainty associated with key input parameters including emissions inventories, air quality data from models (with their associated parameters and inputs), population data, population estimates, health effect estimates from epidemiology studies, economic data for monetizing benefits, and assumptions regarding the future state of the country (i.e., regulations, technology, and human behavior). Each of these inputs is uncertain and affects the size and distribution of the estimated benefits.

The BPT approach is a simplified approach that relies on additional assumptions and has its own limitations, some of which are described in Section 7.2.6. We plan to consider a more complete assessment of benefits in future rulemakings. Additional uncertainties related to key assumptions underlying the estimates for $PM_{2.5}$-related premature mortality described in Section 7.2.2 of this chapter include the following:

- We assume that all fine particles, regardless of their chemical composition, are equally potent in causing premature mortality. This is an important assumption because $PM_{2.5}$ varies considerably in composition across sources, but the scientific evidence is not yet sufficient to allow differentiation of effect estimates by particle type. The PM ISA, which was reviewed by CASAC, concluded that "across exposure durations and health effects categories … the evidence does not indicate that any one source or component is consistently more strongly related with health effects than $PM_{2.5}$ mass."[1986]
- We assume that the health impact function for fine particles is log-linear down to the lowest air quality levels modeled in this analysis. Thus, the estimates include health benefits from reducing fine particles in areas with varied concentrations of $PM_{2.5,}$ including both regions that are in attainment with the fine particle standard and those that do not meet the standard down to the lowest modeled concentrations. The PM ISA concluded that "the majority of evidence continues to indicate a linear, no-threshold concentration-response relationship for long-term exposure to $PM_{2.5}$ and total (nonaccidental) mortality."[1987]
- We assume that there is a "cessation" lag between the change in PM exposures and the total realization of changes in mortality effects. Specifically, we assume that some of the incidences of premature mortality related to $PM_{2.5}$ exposures occur in a distributed fashion over the 20 years following exposure based on the advice of the SAB-HES, which affects the valuation of mortality benefits at different discount rates. The above assumptions are subject to uncertainty.[1988] Similarly, we assume there is a cessation lag between the change in PM exposures and both the development and diagnosis of lung cancer.

[1986] U.S. Environmental Protection Agency (U.S. EPA). 2019. Integrated Science Assessment (ISA) for Particulate Matter (Final Report, 2019). U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-19/188, 2019.
[1987] U.S. Environmental Protection Agency (U.S. EPA). 2019. Integrated Science Assessment (ISA) for Particulate Matter (Final Report, 2019). U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-19/188, 2019.
[1988] U.S. Environmental Protection Agency—Science Advisory Board (U.S. EPA-SAB). 2004. Advisory Council on Clean Air Compliance Analysis Response to Agency Request on Cessation Lag. EPA-COUNCIL-LTR-05-001. December. Available at: https://council.epa.gov/ords/sab/f?p=104:12:968651521971.

7.2.6 Benefit-per-Ton Estimate Limitations

All BPT estimates have inherent limitations. One limitation of using the $PM_{2.5}$-related BPT approach is an inability to provide estimates of the health and welfare benefits associated with exposure to ozone, welfare benefits and some unquantified health benefits associated with $PM_{2.5}$, as well as health and welfare benefits associated with ambient NO_2 and SO_2. Table 7-17 presents a selection of unquantified criteria pollutant health and welfare benefits categories. Another limitation is that the mobile sector-specific air quality modeling that underlies the $PM_{2.5}$ BPT value did not provide estimates of the $PM_{2.5}$-related benefits associated with reducing VOC emissions, but these unquantified benefits are generally small compared to benefits associated with other $PM_{2.5}$ precursors.

Table 7-17 Unquantified Criteria Pollutant Health and Welfare Benefits Categories

Category	Unquantified Effect	More Information
Improved Human Health		
Mortality from exposure to ozone	Premature respiratory mortality from short-term exposure (0-99)	Ozone ISA[a]
	Premature respiratory mortality from long-term exposure (age 30–99)	Ozone ISA[a]
Nonfatal morbidity from exposure to ozone	Hospital admissions—respiratory (ages 65-99)	Ozone ISA[a]
	Emergency department visits—respiratory (ages 0-99)	Ozone ISA[a]
	Asthma onset (0-17)	Ozone ISA[a]
	Asthma symptoms/exacerbation (asthmatics age 5-17)	Ozone ISA[a]
	Allergic rhinitis (hay fever) symptoms (ages 3-17)	Ozone ISA[a]
	Minor restricted-activity days (age 18–65)	Ozone ISA[a]
	School absence days (age 5–17)	Ozone ISA[a]
	Decreased outdoor worker productivity (age 18–65)	Ozone ISA[b]
	Metabolic effects (e.g., diabetes)	Ozone ISA[b]
	Other respiratory effects (e.g., premature aging of lungs)	Ozone ISA[b]
	Cardiovascular and nervous system effects	Ozone ISA[b]
	Reproductive and developmental effects	Ozone ISA[b]
Reduced incidence of morbidity from exposure to NO_2	Asthma hospital admissions	NO_2 ISA[1989,a]
	Chronic lung disease hospital admissions	NO_2 ISA[a]
	Respiratory emergency department visits	NO_2 ISA[a]
	Asthma exacerbation	NO_2 ISA[a]
	Acute respiratory symptoms	NO_2 ISA[a]
	Premature mortality	NO_2 ISA[a,b,c]
	Other respiratory effects (e.g., airway hyperresponsiveness and inflammation, lung function, other ages and populations)	NO_2 ISA[b,c]
Improved Environment		
Reduced visibility impairment	Visibility in Class 1 areas	PM ISA[a]
	Visibility in residential areas	PM ISA[a]
Reduced effects on materials	Household soiling	PM ISA[a,b]
	Materials damage (e.g., corrosion, increased wear)	PM ISA[b]
Reduced effects from PM deposition (metals and organics)	Effects on individual organisms and ecosystems	PM ISA[b]
Reduced vegetation and ecosystem effects from exposure to ozone	Visible foliar injury on vegetation	Ozone ISA[a]
	Reduced vegetation growth and reproduction	Ozone ISA[a]
	Yield and quality of commercial forest products and crops	Ozone ISA[a]
	Damage to urban ornamental plants	Ozone ISA[b]
	Carbon sequestration in terrestrial ecosystems	Ozone ISA[a]
	Recreational demand associated with forest aesthetics	Ozone ISA[b]
	Other non-use effects	Ozone ISA[b]
	Ecosystem functions (e.g., water cycling, biogeochemical cycles, net primary productivity, leaf-gas exchange, community composition)	Ozone ISA[b]

[1989] U.S. Environmental Protection Agency (U.S. EPA). 2016. Integrated Science Assessment for Oxides of Nitrogen - Health Criteria (Final Report). National Center for Environmental Assessment, Research Triangle Park, NC. July. Available at: < https://cfpub.epa.gov/ncea/isa/recordisplay.cfm?deid=310879>.

Category	**Unquantified Effect**	**More Information**
Reduced effects from acid deposition	Recreational fishing	NO_X SO_X ISA [1990,a]
	Tree mortality and decline	NO_X SO_XISA[b]
	Commercial fishing and forestry effects	NO_X SO_XISA[b]
	Recreational demand in terrestrial and aquatic ecosystems	NO_X SO_XISA[b]
	Other non-use effects	NO_X SO_XISA[b]
	Ecosystem functions (e.g., biogeochemical cycles)	NO_X SO_XISA[b]
Reduced effects from nutrient enrichment	Species composition and biodiversity in terrestrial and estuarine ecosystems	NO_X SO_XISA[b]
	Coastal eutrophication	NO_X SO_XISA[b]
	Recreational demand in terrestrial and estuarine ecosystems	NO_X SO_XISA[b]
	Other non-use effects	NO_X SO_XISA[b]
	Ecosystem functions (e.g., biogeochemical cycles, fire regulation)	NO_X SO_XISA[b]
Reduced vegetation effects from ambient exposure to SO_2 and NO_X	Injury to vegetation from SO_2 exposure	NO_X SO_XISA[b]
	Injury to vegetation from NO_X exposure	NO_X SO_XISA[b]

[a] We assess these benefits qualitatively due to data and resource limitations for this RIA.

[b] We assess these benefits qualitatively because we do not have sufficient confidence in available data or methods.

[c] We assess these benefits qualitatively because current evidence is only suggestive of causality or there are other significant concerns over the strength of the association.

There are also benefits associated with reductions in air toxic pollutant emissions that will result from the program (see RIA Chapter 5) but that the $PM_{2.5}$-related BPT approach also does not capture. While EPA continues to work to improve its benefits estimation tools, there remain critical limitations for estimating incidence and assessing benefits of reducing air toxics.

National-average BPT values reflect the geographic distribution of the underlying modeled emissions used in their calculation, which may not exactly match the geographic distribution of the emission reductions that will occur due to a specific rulemaking. Similarly, BPT estimates may not reflect local variability in population density, meteorology, exposure, baseline health incidence rates, or other local factors for any specific location. For instance, even though we assume that all fine particles have equivalent health effects, the BPT estimates vary across precursors depending on the location and magnitude of their impact on $PM_{2.5}$ levels, which drives population exposure. The photochemically-modeled emissions of the onroad mobile and upstream sector-attributable $PM_{2.5}$ concentrations used to derive the BPT values may not match the change in air quality resulting from the control strategies associated with the final standards. For this reason, the PM-related health benefits reported here may be larger, or smaller, than those that will be realized through this final rule.

Given the uncertainty that surrounds BPT analysis, EPA systematically compared benefits estimated using its BPT approach (and other reduced-form approaches) to benefits derived from full-form photochemical model representation. This work is referred to as the "Reduced Form Tool Evaluation Project" (Project), which began in 2017, and the initial results were available at the end of 2018.[1991] The Agency's goal was to better understand the suitability of alternative reduced-form air quality modeling techniques for estimating the health impacts of criteria pollutant emissions changes in EPA's benefit-cost analysis. The Project analyzed air quality policies that varied in the magnitude and composition of their emissions changes and in the

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[1990] U.S. Environmental Protection Agency (U.S. EPA). 2008. Integrated Science Assessment for Oxides of Nitrogen and Sulfur–Ecological Criteria National (Final Report). National Center for Environmental Assessment – RTP Division, Research Triangle Park, NC. EPA/600/R-08/139. December. Available at: <http://cfpub.epa.gov/ncea/cfm/recordisplay.cfm?deid=201485>.

[1991] U.S. EPA. 2019. Reduced Form Evaluation Project Report. Available at: https://www.epa.gov/benmap/reduced-form-evaluation-project-report emissions source affected (e.g., on-road mobile, industrial point, or electricity generating units). The policies also differed in terms of the spatial distribution of emissions and concentration changes, and in their impacts on directly-emitted $PM_{2.5}$ and secondary $PM_{2.5}$ precursor emissions (NO_X and SO_2).

For scenarios where the spatial distribution of emissions was similar to the inventories used to derive the BPT, the Project found that total $PM_{2.5}$ BPT-derived benefits were within approximately 10 percent to 30 percent of the health benefits calculated from full-form air quality modeling, though the discrepancies varied by regulated scenario and $PM_{2.5}$ species. The scenario-specific emission inputs developed for the Project, and a final project report, are available online.[1992] We note that while the BPT values used to monetize the benefits of the final program were not part of the Project, they reflect our best estimate of benefits absent air quality modeling, and we have confidence that the BPT approach provides a reasonable estimate of the monetized $PM_{2.5}$-related health benefits associated with this rulemaking. EPA continues to research and develop reduced-form approaches for estimating $PM_{2.5}$ benefits.

7.3 Energy Security

The final CO_2 emission standards are designed to require reductions in GHG emissions from HD vehicles in the MYs 2027–2032 and beyond timeframe and, thereby, are expected to reduce liquid fuel consumption. Our modeled potential compliance pathway projects a mix of ZEV technologies and ICE vehicle technologies in compliant fleets. Our analysis is based on this modeled potential compliance pathway but, as noted, many other potential pathways to compliance exist, and analytic results would differ from those presented here in such cases. Under our modeled compliance pathway, the standards will be met through a combination of zero-emission and ICE vehicle technologies, which will, in turn, reduce the demand for oil and enable the U.S. to reduce its petroleum imports. A reduction of U.S. petroleum imports reduces both financial and strategic risks caused by potential sudden disruptions in the supply of imported petroleum to the U.S., thus increasing U.S. energy security. In other words, reduced U.S. oil imports act as a “shock absorber” when there is a supply disruption in world oil markets.

This section summarizes the Agency’s estimates of U.S. oil import reductions and energy security benefits of the final HD GHG Phase 3 program for model years 2027–2032. Energy security is broadly defined as the uninterrupted availability of energy sources at affordable prices.[1993] Most discussions of U.S. energy security revolve around the topic of the economic costs of U.S. dependence on oil imports.[1994] Energy independence and energy security are distinct but related concepts, and an analysis of energy independence informs our analysis of energy security. The goal of U.S. energy independence is generally the elimination of all U.S.

[1992] U.S. EPA. 2019. Reduced Form Evaluation Project Report. Available at: https://www.epa.gov/benmap/reduced-form-evaluation-project-report

[1993] https://www.iea.org/topics/energy-security

[1994] The issue of cyberattacks is another energy security issue that could grow in significance over time. For example, in 2021, one of the U.S.’s largest pipeline operators, Colonial Pipeline, was forced to shut down after being hit by a ransomware attack. The pipeline carries refined gasoline and jet fuel from Texas to New York. Cyberattack Forces a Shutdown of a Top U.S. Pipeline. New York Times. May 8th, 2021.

imports of petroleum and other foreign sources of energy, or more broadly, reducing the sensitivity of the U.S.'s economy to energy imports and foreign energy markets.[1995]

The U.S.'s oil consumption had been gradually increasing in recent years (2015-2019) before the COVID-19 pandemic in 2020 dramatically decreased U.S. and global oil consumption.[1996] By July 2021, however, U.S. oil consumption had returned to pre-pandemic levels and has remained fairly stable since then.[1997] The U.S. has increased its production of oil, particularly "tight" (i.e., shale) oil, over the last decade.[1998] As a result of the recent increase in U.S. oil production, the U.S. became a net exporter of crude oil and refined petroleum products in 2020 and is now projected to be a net exporter of crude oil and refined petroleum products through 2027 to 2050.[1999] This is a significant reversal of the U.S.'s net export position since the U.S. has been a substantial net importer of crude oil and refined petroleum products starting in the early 1950s.[2000]

Oil is a commodity that is globally traded and, as a result, an oil price shock is transmitted globally. Given that the U.S. is projected to be a net exporter of crude oil and refined petroleum products in the 2027–2055 timeframe of this analysis, one could reason that the U.S. no longer has a significant energy security problem. However, U.S. refineries still rely on significant imports of heavy crude oil which could be subject to supply disruptions. Also, oil exporters with a large share of global production have the ability to raise or lower the price of oil by exerting the market power associated with a cartel, the Organization of Petroleum Exporting Countries (OPEC), to alter oil supply relative to demand. The degree of market power that OPEC has during the timeframe of this analysis is difficult to quantify. These factors contribute to the continued vulnerability of the U.S. economy to episodic oil supply shocks and price spikes, even when the U.S. is projected to be a net exporter of crude oil and refined petroleum products in the timeframe of this analysis, 2027–2055.

For this final HDV GHG Phase 3 rule, EPA distinguishes between energy security and mineral/metal security and security issues associated with the importation of critical minerals, EV batteries and component parts (i.e., EV supply chain issues). We address energy security issues involving U.S. oil consumption and oil imports associated with this final rule in this Chapter of the RIA and Section 22 of the RTC document. Comments associated with wider use of EV's impacts on the U.S. mineral/metal security and security issues associated with the importation of EV batteries and their component parts (i.e., EV supply chain issues) are addressed in Section II.D.1.ii of this final rule's preamble, Chapter 1 of the RIA and in Section 17 of the RTC document.

7.3.1 Review of Historical Energy Security Literature

Energy security discussions are typically based around the concept of the oil import premium. The oil import premium is the extra cost and impacts of importing oil beyond the price of the oil

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[1995] Greene, D. 2010. Measuring energy security: Can the United States achieve oil independence? *Energy Policy* 38, pp. 1614–1621.

[1996] EIA. 2022. Monthly Energy Review. Table 3.1. Petroleum Overview. December.

[1997] Ibid.

[1998] Ibid.

[1999] EIA. 2023. *Annual Energy Outlook* 2022. Reference Case. Table A11. Petroleum and Other Liquids Supply and Disposition.

[2000] EIA https://www.eia.gov/energyexplained/oil-and-petroleum-products/imports-and-exports.php itself as a result of: (1) potential macroeconomic disruption and increased oil import costs to the economy from oil price spikes or "shocks", and (2) monopsony impacts. Monopsony impacts stem from changes in the demand for imported oil, which changes the price of all imported oil.

The so called oil import premium gained attention as a guiding concept for energy policy in the aftermath of the oil price shocks of the 1970's (Bohi and Montgomery 1982, EMF 1981).[2001] Plummer et al. (1982) provided valuable discussion of many of the key issues related to the oil import premium as well as the analogous oil stockpiling premium.[2002] Bohi and Montgomery (1982) detailed the theoretical foundations of the oil import premium and established many of the critical analytic relationships.[2003] Hogan (1981) and Broadman and Hogan (1986, 1988) revised and extended the established analytical framework to estimate optimal oil import premia with a more detailed accounting of macroeconomic effects.[2004] Since the original work on energy security was undertaken in the 1980's, there have been several reviews on this topic by Leiby et al. (1997) and Parry and Darmstadter (2004).[2005,2006]

The economics literature on whether oil shocks are the same level of threat to economic stability as they once were, is mixed. Some of the literature asserts that the macroeconomic component of the energy security externality is small. For example, the National Research Council (2009) argued that the non-environmental externalities associated with dependence on foreign oil are small, and potentially trivial.[2007] Analyses by Nordhaus (2007) and Blanchard and Gali (2010) questioned the impact of oil price shocks on the economy in the early 2000 timeframe.[2008] They were motivated by attempts to explain why the economy actually expanded during the oil shock in the early 2000 timeframe, and why there was no evidence of higher energy prices being passed on through higher wage inflation. One reason, according to Nordhaus and Blanchard and Gali, is that monetary policy has become more accommodating to the price impacts of oil shocks. Another reason is that consumers have simply decided that such

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[2001] Bohi, D. and Montgomery, D. 1982. Social Cost of Imported and U.S. Import Policy, *Annual Review of Energy*, 7:37-60. Energy Modeling Forum, 1981. World Oil, EMF Report 6, Stanford University Press: Stanford 39 CA.

[2002] Plummer, J. et al. (Ed.). 1982. Energy Vulnerability, "Basic Concepts, Assumptions and Numerical Results," pp. 13-36, Cambridge MA: Ballinger Publishing Co.

[2003] Bohi, D. and Montgomery, D. 1982. Social Cost of Imported Oil and U.S. Import Policy, *Annual Review of Energy*, 7:37-60.

[2004] Hogan, W. 1981. "Import Management and Oil Emergencies," Chapter 9 in Deese, David and Joseph Nye, eds. Energy and Security. Cambridge, MA: Ballinger Publishing Co. Broadman, H. 1986. "The Social Cost of Imported Oil," *Energy Policy* 14(3):242-252. Broadman H. and Hogan, W. 1988. "Is an Oil Import Tariff Justified? An American Debate: The Numbers Say 'Yes'". *The Energy Journal* 9: 7-29.

[2005] Leiby, P., Jones, D., Curlee, R. and Lee, R. 1997. Oil Imports: An Assessment of Benefits and Costs, ORNL-6851, Oak Ridge National Laboratory, November.

[2006] Parry, I. and Darmstadter, J. 2004. "The Costs of U.S. Oil Dependency," Resources for the Future, November 17, 2004. Also published as NCEP Technical Appendix Chapter 1: Enhancing Oil Security, the National Commission on Energy Policy 2004 Ending the Energy Stalemate–A Bipartisan Strategy to Meet America's Energy Challenges.

[2007] National Research Council. 2009. Hidden Costs of Energy: Unpriced Consequences of Energy Production and Use. National Academy of Science, Washington, DC.

[2008] Nordhaus, W. 2007. "Who's Afraid of a Big Bad Oil Shock?". Brookings Papers on Economic Activity, Economic Studies Program, The Brookings Institution, Volume 38(2), pp. 219-240. Blanchard, O. and Gali, J. 2010. The macroeconomic effects of oil price shocks: why are the 2000's so different from the 1970s. International Dimensions of Monetary Policy. University of Chicago Press.

movements are temporary and have noted that price impacts are not passed on as inflation in other parts of the economy.

Hamilton (2012) reviewed the empirical literature on oil shocks and suggests that the results are mixed. Hamilton notes that some work by Blanchard and Gali (2010) and Rasmussen and Roitman (2011) finds less evidence for economic effects of oil shocks or declining effects of shocks, while other work continues to find evidence regarding the economic importance of oil shocks.[2009] For example, Baumeister and Peersman (2012) find that an "oil price increase of a given size seems to have a decreasing effect over time, but noted that the declining price-elasticity of demand means that a given physical disruption had a bigger effect on price and turned out to have a similar effect on output as in the earlier data."[2010] Hamilton observed that "a negative effect of oil prices on real output has also been reported for a number of other countries, particularly when nonlinear functional forms have been employed", citing as examples Kim (2012) and Engemann, Kliesen, and Owyang (2011).[2011,2012] Alternatively, rather than a declining effect, Ramey and Vine (2010) find "remarkable stability in the response of aggregate real variables to oil shocks once we account for the extra costs imposed on the economy in the 1970s by price controls and a complex system of entitlements that led to some energy rationing and shortages."[2013]

Some of the literature on oil price shocks emphasizes that economic impacts depend on the nature of the oil shock, with differences between price increases caused by a sudden supply loss and those caused by rapidly growing demand. Recent analyses of oil price shocks have confirmed that "demand-driven" oil price shocks have greater effects on oil prices and tend to have positive effects on the economy while "supply-driven" oil shocks still have negative economic impacts, see Baumeister, Peersman and Robays (2010).[2014] A paper by Kilian and Vigfusson (2014), for example, assigned a more prominent role to the effects of price increases that are unusual, in the sense of being beyond the range of recent experience.[2015] Kilian and Vigfussen also concluded that the difference in response to oil shocks may well stem from the different effects of demand- and supply-based price increases: "One explanation is that oil price shocks are associated with a range of oil demand and oil supply shocks, some of which stimulate

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[2009] Hamilton, J. 2012. Oil Prices, Exhaustible Resources, and Economic Growth. In Handbook of Energy and Climate Change. Retrieved from *http://econweb.ucsd.edu/~jhamilto/handbook_climate.pdf.* Blanchard, O. and Gali, J. 2010. The macroeconomic effects of oil price shocks: why are the 2000's so different from the 1970s. International Dimensions of Monetary Policy. University of Chicago Press. Rasmussen, T. and Roitman, A. 2011. Oil Shocks in a Global Perspective: Are They Really That Bad. IMF Working Paper Series.

[2010] Baumeister, C. and Peersman, G. 2012. The Role of Time-Varying Price Elasticities in Accounting for Volatility Changes in the Crude Oil Market. *Journal of Applied Economics*.

[2011] Kim, D. 2012. What is an oil shock? Panel data evidence. *Empirical Economics*, Volume 43, pp. 121-143.

[2012] Engemann, K., Kliesen. K. and Owyang, M. 2011. Do Oil Shocks Drive Business Cycles, Some U.S. and International Evidence. Federal Reserve Bank of St. Louis, Working Paper Series. No. 2010-007D.

[2013] Ramey, V. and Vine, D. 2010. "Oil, Automobiles, and the U.S. Economy: How Much have Things Really Changed?". National Bureau of Economic Research Working Papers. WP 16067. June.

[2014] Baumeister C., Peersman, G. and Van Robays, I. 2010. "The Economic Consequences of Oil Shocks: Differences across Countries and Time". RBA Annual Conference Volume in: Renée Fry & Callum Jones & Christopher Kent (ed.), Inflation in an Era of Relative Price Shocks, Reserve Bank of Australia.

[2015] Kilian, L. and Vigfusson, R. 2014. "The role of oil price shocks in causing U.S. recessions". CFS Working Paper Series 460, Center for Financial Studies.

the U.S. economy in the short-run and some of which slow down U.S. economic growth (see Kilian (2009))".[2016]

The general conclusion that oil supply-driven shocks reduce economic output is also reached in a paper by Cashin et al. (2014) which focused on 38 countries from 1979–2011.[2017] They stated: "The results indicate that the economic consequences of a supply-driven oil-price shock are very different from those of an oil-demand shock driven by global economic activity, and vary for oil-importing countries compared to energy exporters". Cashin et al. continues "oil importers (including the U.S.) typically face a long-lived fall in economic activity in response to a supply-driven surge in oil prices". But almost all countries see an increase in real output for an oil-demand disturbance.

EPA's assessment of the energy security literature finds that there are benefits to the U.S. from reductions in U.S. oil imports. But there is some debate in the economics literature as to the magnitude of energy security benefits from U.S. oil import reductions. Over the last decade, differences in economic impacts from oil demand and oil supply shocks have been distinguished. The oil security premium calculations in this analysis are based on price shocks from potential future supply events only. Oil supply shocks, which reduce economic activity, have been the predominant focus of oil security issues since the oil price shocks/oil embargoes of the 1970's.

7.3.2 Review of Recent Energy Security Literature

There have also been a handful of recent studies that are relevant for the issue of energy security: one by Resources for the Future (RFF), a study by Brown, two studies by Oak Ridge National Laboratory (ORNL), and three studies by Newell and Prest, Bjørnland et al. and Walls and Zheng, on the responsiveness of U.S. tight oil (i.e., shale oil) to world oil price changes. [2018,2019,2020,2021,2022,2023,2024] We provide a review and high-level summary of each of these studies below.

7.3.2.1 Recent Oil Security Studies

The first studies on the energy security impacts of oil that we review are by Resources for the Future (RFF), a study by Brown, and two studies by Oak Ridge National Laboratory (ORNL).

[2016] Kilian, L. 2009. "Not All Oil Price Shocks Are Alike: Disentangling Demand and Supply Shocks in the Crude Oil Market." *American Economic Review*. 99 (3): pp. 1053-69.

[2017] Cashin, P., Mohaddes, K., and Raissi, M. 2014. The Differential Effects of Oil Demand and Supply Shocks on the Global Economy, *Energy Economics*. 12 (253).

[2018] Krupnick, A., Morgenstern, R., Balke, N., Brown, S., Herrara, M. and Mohan, S. 2017. "Oil Supply Shocks, U.S. Gross Domestic Product, and the Oil Security Problem," Resources for the Future Report.

[2019] Brown, S. 2018. New estimates of the security costs of U.S. oil consumption". *Energy Policy*, 113 pp. 171-192.

[2020] Uría-Martínez, R., Leiby, P., Oladosu, G., Bowman, D., Johnson, M. 2018. Using Meta-Analysis to Estimate World Oil Demand Elasticity, ORNL Working Paper.

[2021] Oladosu, G., Leiby, P., Bowman, D., Uría-Martínez, R., Johnson, M. 2018. Impacts of oil price shocks on the U.S. economy: a meta-analysis of oil price elasticity of GDP for net oil-importing economies, *Energy Policy* 115.

[2022] Newell, R. and Prest, B. 2019. The Unconventional Oil Supply Boom: Aggregate Price Response from Microdata. *The Energy Journal*. Volume 40, Issue Number 3.

[2023] Bjørnland, H., Nordvik, F. and Rohrer, M. 2021. "Supply flexibility in the shale patch: Evidence from North Dakota". *Journal of Applied Econometrics.* February.

[2024] Walls, W. D., & Zheng, X. 2022. Fracking and Structural Shifts in Oil Supply. *The Energy Journal*, *43*(3).

The RFF study (2017) attempts to develop updated estimates of the relationship among gross domestic product (GDP), oil supply and oil price shocks, and world oil demand and supply elasticities. In a follow-on study, Brown summarized the RFF study results as well. The RFF study argues that there have been major changes that have occurred in recent years that have reduced the impacts of oil shocks on the U.S. economy. First, the U.S. is less dependent on imported oil than in the early 2000s due in part to the "fracking revolution" (i.e., tight/shale oil), and to a lesser extent, increased U.S. production of renewable fuels such as ethanol and biodiesel. In addition, RFF argues that the U.S. economy is more resilient to oil shocks than in the earlier 2000s timeframe. Some of the factors that make the U.S. more resilient to oil shocks include increased global financial integration and greater flexibility of the U.S. economy (especially labor and financial markets), many of the same factors that Nordhaus and Blanchard and Gali pointed to as discussed above.

In the RFF effort, a number of comparative modeling scenarios are conducted by several economic modeling teams using three different types of energy-economic models to examine the impacts of oil shocks on U.S. GDP. The first is a dynamic stochastic general equilibrium model developed by Balke and Brown.[2025] The second set of modeling frameworks use alternative structural vector autoregressive models of the global crude oil market.[2026] The last of the models utilized is the U.S. Energy Information Administration's (EIA) National Energy Modeling System (NEMS).

Two key parameters are focused upon to estimate the impacts of oil shock simulations on U.S. GDP: oil price responsiveness (i.e., the short-run price elasticity of demand for oil) and GDP sensitivity (i.e., the elasticity of GDP to an oil price shock). The more inelastic (i.e., the less responsive) short-run oil demand is to changes in the price of oil, the higher will be the price impacts of a future oil shock. Higher price impacts from an oil shock result in higher GDP losses. The more inelastic (i.e., less sensitive) GDP is to an oil price change, the less the loss of U.S. GDP with future oil price shocks.

For oil price responsiveness, RFF reports three different values: a short-run price elasticity of oil demand from their assessment of the "new literature," –0.17; a "blended" elasticity estimate; –0.05, and short-run oil price elasticities from the "new models" RFF uses, ranging from –0.20 to –0.35. The "blended" elasticity is characterized by RFF in the following way: "Recognizing that these two sets of literature [old and new] represent an *evolution* in thinking and modeling, but that the older literature has not been wholly overtaken by the new, Benchmark-E [the blended elasticity] allows for a range of estimates to better capture the uncertainty involved in calculating the oil security premiums."

The second parameter that RFF examines is the GDP sensitivity. For this parameter, RFF's assessment of the "new literature" finds a value of –0.018, a "blended elasticity" estimate of –

[2025] Balke, N. and Brown, S. 2018. "Oil Supply Shocks and the U.S. Economy: An Estimated DSGE Model." *Energy Policy*, 116.

[2026] These models include Kilian, L. 2009. "Not All Oil Price Shocks are Alike: Disentangling Demand and Supply Shocks in the Crude Oil Market", *American Economic Review*, 99:3, pp., 1053-1069; Kilian, L. and Murphy, D. 2013. "The Role of Inventories and Speculative Trading in the Global Market for Crude Oil," *Journal of Applied Econometric*s 29(3); and Baumeister, C. and Hamilton, J. 2019. "Structural Interpretation of Vector Autoregressions with Incomplete Identification: Revisiting the Role of Oil Supply and Demand Shocks," *American Economic Review*, 109(5).

0.028, and a range of GDP elasticities from the "new models" that RFF uses that range from –0.007 to –0.027. One of the limitations of the RFF study is that the large variations in oil price over the last fifteen years are believed to be predominantly "demand shocks;" for example, a rapid growth in global oil demand followed by the Great Recession and then the post-recession recovery.

There have only been two recent situations where events have led to a potential significant supply-side oil shock in the last several years. The first event was the attack on the Saudi Aramco Abqaiq oil processing facility and the Khurais oil field. On September 14th, 2019, a drone and cruise missile attack damaged the Saudi Aramco Abqaiq oil processing facility and the Khurais oil field in eastern Saudi Arabia. The Abqaiq oil processing facility is the largest crude oil processing and stabilization plant in the world, with a capacity of roughly 7 million barrels of oil per day (MMBD) or about 7 percent of global crude oil production capacity.[2027] On September 16th, the first full day of commodity trading after the attack, both Brent and West Texas Intermediate (WTI) crude oil prices surged by $7.17/barrel and $8.34/barrel, respectively, in response to the attack, the largest price increase in roughly a decade.

However, by September 17th, Saudi Aramco reported that the Abqaiq plant was producing 2 MMBD, and they expected its entire output capacity to be fully restored by the end of September.[2028] Tanker loading estimates from third-party data sources indicated that loadings at two Saudi Arabian export facilities were restored to the pre-attack levels.[2029] As a result, both Brent and WTI crude oil prices fell on September 17th, but not back to their original levels. The oil price spike from the attack on the Abqaiq plant and Khurais oil field was prominent and unusual, as Kilian and Vigfusson (2014) describe. While pointing to possible risks to world oil supply, the oil shock was short-lived, and generally viewed by market participants as being transitory, so it did not influence oil markets over a sustained time period.

The second situation is the set of events leading to the recent world oil price spike experienced in 2022. World oil prices rose fairly rapidly in the beginning of 2022. For example, as of January 3rd, 2022, the WTI crude oil price was roughly $76 per barrel. The WTI oil price increased to roughly $123 per barrel on March 8th, 2022, a 62 percent increase.[2030] High and volatile oil prices in the first half of 2022 were a result of supply concerns with Russia's invasion of Ukraine on February 24th contributing to crude oil price increases.[2031] Russia's invasion of Ukraine came during eight consecutive quarters (from the third quarter of 2020 to the second quarter of 2022) of global crude oil inventory decreases. The lower inventory of crude oil stocks was the result of rising economic activity after COVID-19 pandemic restrictions were eased. Oil prices drifted downwards throughout the second half of 2022 and early 2023. Since both significant demand and supply factors influenced world oil prices in 2022, it is not clear how to evaluate these oil market price trends from an energy security standpoint. Thus, the attack of the Abqaiq oil processing facility in Saudi Arabia and the unfolding events in the world oil market in

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[2027] EIA. September 23, 2019. "Saudi Arabia crude oil production outage affects global crude oil and gasoline prices." Today in Energy.

[2028] Ibid.

[2029] Ibid.

[2030] EIA. 2022. *Petroleum and Other Liquids Spot Prices*. https://www.eia.gov/dnav/pet/pet_pri_spt_s1_d.htm

[2031] U.S. Energy Information Administration. Today in Energy. Crude oil prices increased in the first half of 2022 and declined in the second half of 2022. January.

2022 do not currently offer enough empirical evidence to provide an updated estimate of the response of the U.S. economy to an oil supply shock of a significant magnitude.[2032]

More recently, in its November 2023 *Short-term Energy Outlook*, EIA is forecasting global oil production will increase by 1.0 million barrels per day in 2024.[2033] Ongoing OPEC+ production cuts will offset production growth from non-OPEC countries and help maintain a relatively balanced global oil market next year. The surprise attack by Hamas on Israel on October 7th, 2023, leading to the Hamas-Israel War, is leaving oil markets on edge, increasing fears that fighting between Israel and Hamas may affect oil production in the Middle East.[2034] Although the conflict between Israel and Hamas has not affected physical oil supply at this point, uncertainties surrounding the conflict and other global oil supply conditions could put upward pressure on crude oil prices in the coming months. EIA is forecasting the Brent crude oil price will average $93/barrel in 2024.

A second set of recent studies related to energy security are from ORNL. In the first study, ORNL (2018) undertakes a quantitative meta-analysis of world oil demand elasticities based upon the recent economics literature. The ORNL study estimates oil demand elasticities for two sectors (transportation and non-transportation) and by world regions (OECD and Non-OECD) by meta-regression. To establish the dataset for the meta-analysis, ORNL undertakes a literature search of peer reviewed journal articles and working papers between 2000 and 2015 that contain estimates of oil demand elasticities. The dataset consisted of 1,983 elasticity estimates from 75 published studies. The study finds a short-run price elasticity of world oil demand of –0.07 and a long-run price elasticity of world oil demand of –0.26. The second relevant ORNL (2018) study from the standpoint of energy security is a meta-analysis that examines the impacts of oil price shocks on the U.S. economy as well as many other net oil-importing economies. Nineteen studies after 2000 were identified that contain quantitative/accessible estimates of the economic impacts of oil price shocks. Almost all studies included in the review were published since 2008. The key result that the study finds is a short-run oil price elasticity of U.S. GDP, roughly one year after an oil shock, of –0.021, with a 68 percent confidence interval of –0.006 to –0.036.

7.3.2.2 Recent Tight (i.e., Shale) Oil Studies

The discovery and development of U.S. tight (i.e., shale) oil reserves that started in the mid-2000s could affect U.S. energy security in at least a couple of ways.[2035] First, the increased availability of domestic supplies has resulted in a reduction of U.S. oil imports and an increasing role of the U.S. as an exporter of crude oil and petroleum-based products. In December 2015, the 40-year ban on the export of domestically produced crude oil was lifted as part of the Consolidated Appropriations Act, 2016. Pub. L. 114-113 (Dec. 18, 2015).[2036] According to the

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[2032] The Hurricanes Katrina/Rita in 2005 primarily caused a disruption in U.S. oil refinery production, with a more limited disruption of some crude supply in the U.S. Gulf Coast area. Thus, the loss of refined petroleum products exceeded the loss of crude oil, and the regional impact varied even within the U.S. The Katrina/Rita Hurricanes were a different type of oil disruption event than is quantified in the Stanford EMF risk analysis framework, which provides the oil disruption probabilities than ORNL is using.

[2033] U.S. EIA, *Short-term Energy Outlook,* November 7th, 2023.

[2034] IEA, Oil Market Report, October 2023. https://www.iea.org/reports/oil-market-report-october-2023

[2035] Union of Concerned Scientist. “What is Tight Oil?”. 2015. “Tight oil is a type of oil found in impermeable shale and limestone rock deposits. Also known as “shale oil”, tight oil is processed into gasoline, diesel, and jet fuels–just like conventional oil–but is extracted using hydraulic fracturing, or “fracking”.

[2036] https://uscode.house.gov/statutes/pl/114/113.pdf (see 129 stat. 2987).

GAO, the ban was lifted in part due to increases in tight (i.e., shale) oil.[2037,2038] Second, due to differences in development cycle characteristics and average well productivity, tight oil producers could be more price responsive than most other oil producers. However, the oil price level that triggers a substantial increase in tight oil production appears to be higher in 2021-2022 relative to the 2010s as tight oil producers seek higher profit margins per barrel in order to reduce the debt burden accumulated in previous cycles of production growth.[2039]

U.S. crude oil production increased from 5.0 MMBD in 2008 to an all-time peak of 12.7 MMBD in 2023 (January through July) and tight oil wells have been responsible for most of the increase.[2040] Figure 7-1 below shows tight oil (i.e., shale oil) production changes from various tight oil producing regions (i.e., Eagle Ford, Bakken etc.) in the U.S. and the West Texas Intermediate (WTI) crude oil spot price. Viewing Figure 7-1, one can see that the annual average U.S. tight oil production grew from 0.6 MMBD in 2008 to 7.8 MMBD in 2019.[2041] Growth in U.S. tight oil production during this period was only interrupted in 2015-2016 following the world oil price downturn which began in mid-2014. The second growth phase started in late 2016 and continued until 2020. The sharp decrease in demand that followed the onset of the COVID-19 pandemic resulted in a 25 percent decrease in tight oil production in the period from December 2019 to May 2020. U.S. tight oil production in 2020 and 2021 averaged 7.4 MMBD and 7.2 MMBD, respectively. More recently, in March 2023, tight oil production surpassed the previous historical maximum (8.37 MMBD in November 2019) with 8.43 MMBD. Growth has continued in the following months and July 2023 production reached 8.57 MMBD. Most of the 2023 growth has come from two Permian producing regions: Spraberry and Bonespring. U.S. tight oil production represents a relatively modest share (less than 10 percent in 2019) of global liquid fuel supply.[2042]

Importantly, U.S. tight oil is considered the most price-elastic component of non-OPEC supply due to differences between its development and production cycle and that of conventional oil wells. Unlike conventional wells where oil starts flowing naturally after drilling, shale oil wells require the additional step of fracking to complete the well and release the oil.[2043] Shale oil producers keep a stock of drilled but uncompleted wells and can optimize the timing of the completion operation depending on price expectations. Combining this decoupling between

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[2037] According to the GAO, “Between 1975 and the end of 2015, the Energy Policy and Conservation Act directed a ban on nearly all exports of U.S. crude oil. This ban was not considered a significant policy issue when U.S. oil production was declining and import volumes were increasing. However, U.S. crude oil production roughly doubled from 2009 to 2015, due in part to a boom in shale oil production made possible by advancements in drilling technologies. In December 2015, Congress effectively repealed the ban, allowing the free export of U.S. crude oil worldwide”.

[2038] GAO, 2020. Crude Oil Markets: Effects of the Repeal of the Crude Oil Export Ban. GAO-21-118.

[2039] Kemp, J. 2021. U.S. shale restraint pushes oil prices to multi-year high. Reuters. June 4th, 2021.

[2040] EIA. 2021. *Crude Oil Production*. Accessed on 12/20/2021: https://www.eia.gov/dnav/pet/pet_crd_crpdn_adc_mbbl_m.htm

[2041] EIA. 2021. *Tight oil production estimates by play*. Accessed on 12/20/2021: https://www.eia.gov/petroleum/data.php#prices

[2042] The 2019 global crude oil production value used to compute the U.S. tight oil share is from EIA International Energy Statistics, https://www.eia.gov/international/data/world/petroleum-and-other-liquids/annual-petroleum-and-other-liquids-production.

[2043] Hydraulic fracturing (“fracking”) involves injecting water, chemicals, and sand at high pressure to open fractures in low-permeability rock formations and release the oil that is trapped in them.

drilling and production with the "front-loaded" production profile of tight oil–the fraction of total output from a well that is extracted in the first year of production is higher for tight oil wells than conventional oil wells–tight oil producers have a clear incentive to be responsive to prices in order to maximize their revenues.[2044]

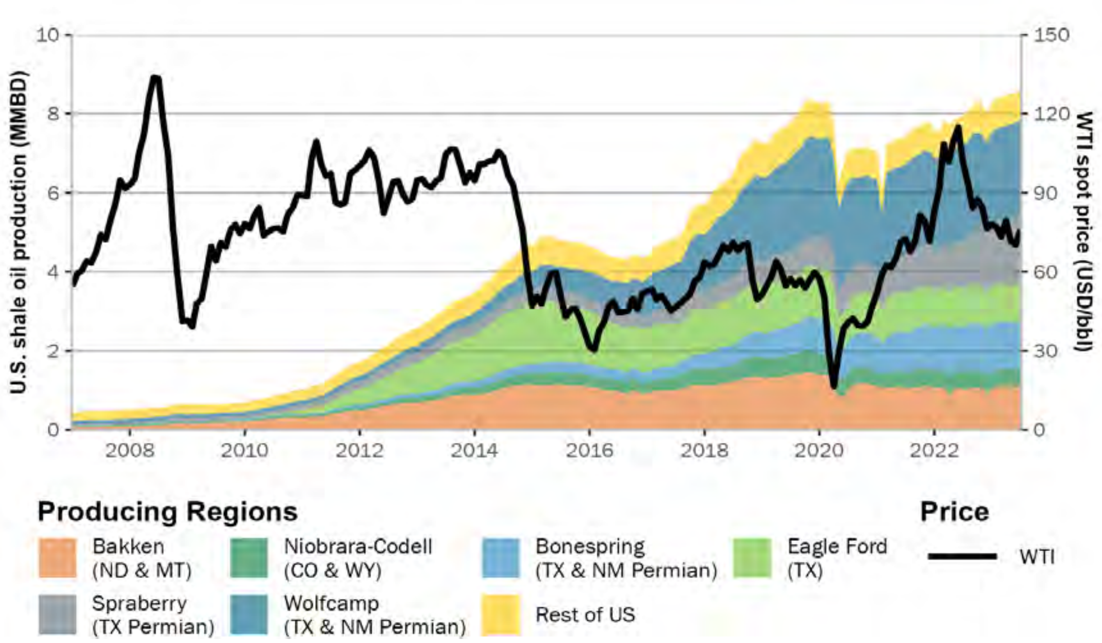

Figure 7-1 U.S. Tight Oil Production by Producing Regions (in MMBD) and West Texas Intermediate (WTI) Crude Oil Spot Price (in U.S. Dollars per Barrel), Source: EIA[2045,2046]

Only in recent years have the implications of the "tight/shale oil revolution" been felt in the international market where U.S. production of oil is rising to be roughly on par with Saudi Arabia and Russia. Recent economics literature of the tight (i.e., shale/unconventional) oil expansion in the U.S. has a bearing on the issue of energy security as well. It could be that the large expansion in tight oil has eroded the ability of OPEC to set world oil prices to some degree, since OPEC cannot directly influence tight oil production decisions. Also, by effecting the percentage of global oil supply controlled by OPEC, the growth in U.S. oil production may be influencing OPEC's degree of market power. But given that the tight oil expansion is a relatively recent trend, it is difficult to know how much of an impact the increase in tight oil is having, or will have, on OPEC behavior.

Three recent studies have examined the characteristics of tight oil supply that have relevance for the topic of energy security. In the context of energy security, the question that arises is: Can tight oil respond to an oil price shock more quickly and substantially than conventional oil? If so,

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[2044] Bjørnland, H., Nordvik, F. and Rohrer, M. 2021. "Supply flexibility in the shale patch: Evidence from North Dakota," *Journal of Applied Econometrics*, February.
[2045] EIA. 202. *Tight oil production estimates by play*. https://www.eia.gov/petroleum/data.php#prices
[2046] EIA. 2023. *Petroleum and Other Liquids Spot Prices*. https://www.eia.gov/dnav/pet/pet_pri_spt_s1_d.htm

then tight oil could potentially lessen the impacts of future oil shocks on the U.S. economy by moderating the price increases from a future oil supply shock.

Newell and Prest (2019) look at differences in the price responsiveness of conventional versus shale oil wells, using a detailed dataset of 150,000 oil wells, during the timeframe of 2005–2017 in five major oil-producing states: Texas, North Dakota, California, Oklahoma, and Colorado. For both conventional oil wells and shale oil wells (i.e., unconventional oil wells), Newell and Prest estimate the elasticities of drilling operations and well completion operations with respect to expected revenues and the elasticity of supply from wells already in operation with respect to spot prices. Combining the three elasticities and accounting for the increased share of tight oil in total U.S. oil production during the period of analysis, they conclude that U.S. oil supply responsiveness to prices increased more than tenfold from 2006 to 2017. They find that tight/shale oil wells are more price responsive than conventional oil wells, mostly due to their much higher productivity, but the estimated oil supply elasticity is still relatively small. Newell and Prest note that the tight oil supply response still takes more time to arise than is typically considered for a "swing producer," referring to a supplier able to increase production quickly, within 30–90 days. In the past, only Saudi Arabia and possibly one or two other oil producers in the Middle East have been able to ramp up oil production in such a short period of time.

Another study, by Bjørnland et al. (2021), uses a well-level monthly production data set covering more than 16,000 crude oil wells in North Dakota from February 1990 to June 2017 to examine differences in supply responses between conventional and tight oil/shale oil. They find a short-run (i.e., one-month) supply elasticity with respect to oil price for tight oil wells of 0.71, whereas the one-month response of conventional oil supply is not statistically different from zero. It should be noted that the elasticity value estimated by Bjørnland et al. combines the supply response to changes in the spot price of oil as well as changes in the spread between the spot price and the 3-month futures price.

Walls and Zheng (2022) explore the change in U.S. oil supply elasticity that resulted from the tight oil revolution using monthly, state-level data on oil production and crude oil prices from January 1986 to February 2019 for North Dakota, Texas, New Mexico, and Colorado. They conduct statistical tests that reveal an increase in the supply price elasticities starting between 2008 and 2011 coinciding with the times in which tight oil production increased sharply in each of these states. Walls and Zheng also find that supply responsiveness in the tight oil era is greater with respect to price increases than price decreases. The short-run (one-month) supply elasticity with respect to price increases during the tight oil era ranges from zero in Colorado to 0.076 in New Mexico; pre-tight oil, it ranged from zero to 0.021.

The results from Newell and Prest, Bjørnland et al., and Walls and Zheng all suggest that tight oil may have a larger supply response to oil prices in the short-run than conventional oil, although the estimated short-run elasticity is still relatively small. The three studies use datasets that end in 2019 or earlier. The responsiveness of U.S. tight oil production to recent price increases does not appear to be consistent with that observed during the episodes of crude oil price increases in the 2010s captured in these three studies. Despite an 80 percent increase in the WTI crude oil spot price from October 2020 to the end of 2021, Figure 7-1 shows that U.S. tight oil production has increased by only 8 percent in the same period. It is a somewhat challenging period in which to examine the supply response of tight oil to its price to some degree, given that the 2020–2021 time period coincided with the COVID-19 pandemic. Previous shale oil production growth cycles were financed predominantly with debt, at very low interest rates.[2047] Most U.S. tight oil producers did not generate positive cashflow.[2048] As of 2021, U.S. shale oil producers have pledged to repay their debt and reward shareholders through dividends and stock buybacks.[2049] These pledges translate into higher prices that need to be reached (or sustained for a longer period) than in the past decade to trigger larger increases in drilling activity.

In its first quarter 2022 energy survey, the Dallas Fed (i.e., the Federal Reserve Bank of Dallas) asked oil exploration and production firms about the WTI price levels needed to cover operating expenses for existing wells or to profitably drill a new well. The average breakeven price to continue operating existing wells in the shale oil regions ranged from $23/barrel (bbl) to $35/bbl. To profitably drill new wells, the required average WTI prices ranged from $48/bbl to $69/bbl. For both types of breakeven prices, there was substantial variation across companies, even within the same region.

The actual WTI price level observed in the first quarter of 2022 has been roughly $95/bbl, substantially larger than the breakeven price to drill new wells. However, the median production growth expected by the respondents to the Dallas Fed Energy Survey from the fourth quarter of 2021 to the fourth quarter of 2022 is modest (6 percent among large firms and 15 percent among small firms). Investor pressure to maintain capital discipline was cited by 59 percent of respondents as the primary reason why publicly traded oil producers are restraining growth despite high oil prices. The other reasons cited included supply chain constraints, difficulty in hiring workers, environmental, social, and governance concerns, lack of access to financing, and government regulations.[2050]

Given the recent behavior of tight oil producers, we do not believe that tight oil will provide additional significant energy security benefits in the timeframe of analysis of this final rule, 2027–2055, due to its muted price responsiveness. The ORNL model still accounts for the effect of U.S. tight oil production increases on U.S. oil imports and, in turn, the U.S.’s energy security position.

Finally, despite continuing uncertainty about oil market behavior and outcomes and the sensitivity of the U.S. economy to oil shocks, it is generally agreed that it is beneficial to reduce petroleum fuel consumption from an energy security standpoint. The relative significance of petroleum consumption and import levels for the macroeconomic disturbances that follow from oil price shocks is not fully understood. Recognizing that changing petroleum consumption will change U.S. imports, our quantitative assessment of oil energy security costs of this rule focuses on those incremental social costs that follow from the resulting changes in net imports, employing the usual oil import premium measure.

7.3.3 Cost of Existing U.S. Energy Security Policies

An additional often-identified component of the full economic costs of U.S. oil imports is the costs to the U.S. taxpayers of existing U.S. energy security policies. The two primary examples

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[2047] McLean, B. *The Next Financial Crisis Lurks Underground*. New York Times, September 1st, 2018.

[2048] Ibid.

[2049] https://www.bloomberg.com/news/articles/2021-08-02/shale-heavyweights-shower-investors-with-dividends-on-oil-rally

[2050] https://www.dallasfed.org/research/surveys/des/2022/2201.aspx#tab-questions are maintaining the Strategic Petroleum Reserve (SPR) and maintaining a military presence to help secure a stable oil supply from potentially vulnerable regions of the world.

The SPR is the largest stockpile of government-owned emergency crude oil in the world. Established in the aftermath of the 1973/1974 oil embargo, the SPR provides the U.S. with a response option should a disruption in commercial oil supplies threaten the U.S. economy.[2051] Emergency SPR drawdowns have taken place in 1991 (Operation Desert Storm), 2005 (Hurricane Katrina), 2011 (Libyan Civil War), and 2022. All of these releases have been in coordination with releases of strategic stocks from other International Energy Agency (IEA) member countries.

In the first four months of 2022, using the statutory authority under Section 161 of the Energy Policy and Conservation Act, President Biden directed the U.S. DOE to conduct two emergency SPR drawdowns in response to ongoing oil supply disruptions.[2052] The first drawdown resulted in a sale of 30 million barrels in March 2022. The second drawdown, announced in April, authorized a total release of approximately one MMBD from May to October 2022.[2053] In 2023, the DOE sold 26 million barrels of oil between April and June.[2054] A total of 246.6 million barrels were released from the SPR from January 2022 to July 2023. By the end of July 2023, the SPR stock level was 346.8 million barrels (the lowest level since August 1983). To start replenishing the stock, the SPR office purchased 10.23 million barrels through competitive solicitations conducted between May and November of 2023, for deliveries from August 2023 to February 2024. While the costs for building and maintaining the SPR are more clearly related to U.S. oil use and imports, these costs have not varied historically in response to changes in U.S. oil import levels. Thus, while the effect of the SPR in moderating price shocks is factored into the analysis that EPA is using to estimate the macroeconomic oil security premiums, the cost of maintaining the SPR is excluded.

We have also considered the possibility of quantifying the military benefits components of energy security but have not done so here for several reasons. The literature on the military components of energy security has described four broad categories of oil-related military and national security costs, all of which are hard to quantify. These include possible costs of U.S. military programs to secure oil supplies from unstable regions of the world, the energy security costs associated with the U.S. military's reliance on petroleum to fuel its operations, possible national security costs associated with expanded oil revenues to "rogue states" and, relatedly, the foreign policy costs of oil insecurity.

Of these categories listed above, the one that is most clearly connected to petroleum use and is, in principle, quantifiable is the first: the cost of military programs to secure oil supplies and stabilize oil supplying regions. There is an ongoing literature on the measurement of this component of energy security, but methodological and measurement issues – attribution and incremental analysis – pose two significant challenges to providing a robust estimate of this

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[2051] Energy Policy and Conservation Act, 42 U.S. Code § 6241(d) (1975).

[2052] https://www.energy.gov/fecm/articles/doe-announces-emergency-notice-sale-crude-oil-strategic-petroleum-reserve-address-oil

[2053] https://www.energy.gov/articles/doe-announces-second-emergency-notice-sale-crude-oil-strategic-petroleum-reserve-address

[2054] https://www.energy.gov/ceser/articles/doe-issues-notice-congressionally-mandated-sale-purchase-crude-oil-strategic component of energy security. The attribution challenge is to determine which military programs and expenditures can properly be attributed to oil supply protection, rather than some other objective. The incremental analysis challenge is to estimate how much the petroleum supply protection costs might vary if U.S. oil use were to be reduced or eliminated. Methods to address both of these challenges are necessary for estimating the effect on military costs arising from a modest reduction (not elimination) in oil use attributable to this final rule.

Since "military forces are, to a great extent, multipurpose and fungible" across theaters and missions (Crane et al. (2009)), and because the military budget is presented along regional accounts rather than by mission, the allocation to particular missions is not always clear.[2055] Approaches taken usually either allocate "partial" military costs directly associated with operations in a particular region, or allocate a share of total military costs (including some that are indirect in the sense of supporting military activities overall) (Koplow and Martin (1998)).[2056]

The challenges of attribution and incremental analysis have led some to conclude that the mission of oil supply protection cannot be clearly separated from others, and the military cost component of oil security should be taken as near zero (Moore et al. (1997)).[2057] Stern (2010), on the other hand, argues that many of the other policy concerns in the Persian Gulf follow from oil, and the reaction to U.S. policies taken to protect oil.[2058] Stern presents an estimate of military cost for Persian Gulf force projection, addressing the challenge of cost allocation with an activity-based cost method. He uses information on actual naval force deployments rather than budgets, focusing on the costs of carrier deployment. As a result of this different data set and assumptions regarding allocation, the estimated costs are much higher, roughly 4 to 10 times, than other estimates. Stern also provides some insight on the analysis of incremental effects, by estimating that Persian Gulf force projection costs are relatively strongly correlated to Persian Gulf petroleum export values and volumes. Still, the issue remains of the marginality of these costs with respect to Persian Gulf oil supply levels, the level of U.S. oil imports, or U.S. oil consumption levels.

Delucchi and Murphy (2008) seek to deduct from the cost of Persian Gulf military programs the costs associated with defending U.S. interests other than the objective of providing a more stable oil supply and price to the U.S. economy.[2059] Excluding an estimate of cost for missions unrelated to oil, and for the protection of oil in the interest of other countries, Delucchi and Murphy estimated military costs for all U.S. domestic oil interests of between $24 and $74 billion annually. Delucchi and Murphy assume that military costs from oil import reductions can be scaled proportionally, attempting to address the incremental issue.

[2055] Crane, K., Goldthau, A., Toman, M., Light, T., Johnson, S., Nader, A., Rabasa, A. and Dogo, H. 2009. Imported oil and US national security. RAND. 2009.

[2056] Koplow, D. and Martin, A. 1998. Fueling Global Warming: Federal Subsidies to Oil in the United States. Greenpeace, Washington, D.C.

[2057] Moore, J., Behrens, C. and Blodgett, J. 1997. "Oil Imports: An Overview and Update of Economic and Security Effects". CRS Environment and Natural Resources Policy Division Report 98, no. 1: pp. 1-14.

[2058] Stern, R. 2010. "United States cost of military force projection in the Persian Gulf, 1976–2007". *Energy Policy* 38, no. 6. June: 2816-2825.

[2059] Delucchi, M. and Murphy, J. 2008. "US military expenditures to protect the use of Persian Gulf oil for motor vehicles". *Energy Policy* 36, No. 6. June.

Crane et al. considers force reductions and cost savings that could be achieved if oil security were no longer a consideration. Taking two approaches and guided by post-Cold War force draw downs and by a top-down look at the current U.S. allocation of defense resources, they concluded that $75–$91 billion, or 12–15 percent of the current U.S. defense budget, could be reduced. Finally, an Issue Brief by Securing America's Future Energy (SAFE) (2018) found a conservative estimate of approximately $81 billion per year spent by the U.S. military protecting global oil supplies.[2060] This is approximately 16 percent of the recent U.S. Department of Defense's budget. Spread out over the 19.8 million barrels of oil consumed daily in the U.S. in 2017, SAFE concludes that the implicit subsidy for all petroleum consumers is approximately $11.25 per barrel of crude oil, or $0.28 per gallon. According to SAFE, a more comprehensive estimate suggests the costs could be greater than $30 per barrel, or over $0.70 per gallon.[2061]

As in the examples above, an incremental analysis can estimate how military costs would vary if the oil security mission is no longer needed, and many studies stop at this point. It is substantially more difficult to estimate how military costs would vary if U.S. oil use or imports are partially reduced, as is projected to be a consequence of this final rule. Partial reduction of U.S. oil use likely diminishes the magnitude of the energy security problem, but there is uncertainty that supply protection forces and their costs could be scaled down in proportion, and there remains the associated goal of protecting supply and transit for U.S. allies and other importing countries, if they do not decrease their petroleum use as well.[2062] We are unaware of a robust methodology for assessing the effect on military costs of a partial reduction in U.S. oil use. Therefore, we are unable to quantify this effect resulting from the projected reduction in U.S. oil use attributable to this final rule.

7.3.4 U.S. Oil Import Reductions Expected from the Final Rule

In this section, we compare oil import reductions from this final rule with an assessment of overall U.S. oil market trends. The U.S. Department of Energy's (DOE) Energy Information Administration's (EIA) Annual Energy Outlook (AEO) 2023 (Reference Case) projects oil market trends to 2050, which are reported below in Table 7-20.[2063] The AEO 2023 (Reference Case) projects that the U.S. will be both an exporter and an importer of crude oil through 2050.[2064] The U.S. produces more light crude oil than its refineries can refine. Thus, the U.S. exports lighter crude oil and imports heavier crude oils to satisfy the needs of U.S. refineries, which are configured to efficiently refine heavy crude oil. U.S. crude oil exports are projected to remain relatively stable, ranging between 2.9 and 3.4 MMBD between 2027 and 2050. U.S. crude oil imports, meanwhile, are projected to range between 6.6 and 7.2 MMBD over the 2027–2050 timeframe.

The AEO 2023 projects that U.S. net refined petroleum product exports will grow from 5.8 MMBD in 2027 to 6.7 MMBD in 2045 before dropping off somewhat to 6.2 MMBD in 2050.

[2060] Securing America's Future Energy. 2018. Issue Brief. The Military Cost of Defending the Global Oil Supply.
[2061] Ibid.
[2062] Crane, K., Goldthau, A., Toman, M., Light, T., Johnson, S., Nader, A., Rabasa, A. and Dogo, H. 2009. Imported oil and US national security. 2009. RAND.
[2063] The AEO 2023 oil market trends are projected out to 2050. Thus, we report U.S. oil market trends through 2050 based upon the AEO 2023. However, EPA's analysis of this final rule is from 2027–2055. Therefore, EPA provides estimate of U.S. oil reductions from this final rule through 2055.
[2064] EIA. 2023. *Annual Energy Outlook* 2023. Reference Case. Table A11. Petroleum and Other Liquids Supply and Disposition.

Given the pattern of U.S. crude oil exports/imports, and U.S. net refined petroleum product exports, the U.S. is projected to be a net petroleum (crude oil and refined petroleum products) exporter from 2027 through 2050, with net exports ranging between 2.3 and 2.9 MMBD during that time period. Since the U.S. is projected to continue importing significant quantities of crude oil through 2050, EPA's assessment is that the U.S. is not expected to achieve an overall goal of U.S. energy independence during the analytical timeframe of this rule. However, the U.S. is projected to be a net exporter of crude oil and refined petroleum products through 2050.

U.S. oil consumption is projected to be fairly steady for the time period from 2027 to 2050, ranging between 18.2 and 18.9 MMBD. Thus, during the 2027–2050 timeframe, the AEO 2023 projects that the U.S. will continue to consume significant quantities of oil and will likewise continue to rely on significant quantities of crude oil imports.

Estimated petroleum consumption changes from this final rule are presented in Chapter 6.5 of the RIA. EPA uses an oil import reduction factor to estimate how changes in U.S. refined product demand from this rule (i.e., changes in U.S. oil consumption) influence U.S. net oil imports (i.e., changes in U.S. oil imports). For the proposed rule, EPA used an oil import reduction factor of 86.4 percent. After carefully reviewing comments on refinery throughput and in consultation with DOE and NHTSA, EPA is updating its assessment of the impact of this final rule on U.S. refinery throughput and, in turn, the air quality impacts from refinery emissions. Instead of estimating that U.S. refineries would largely reduce their production in response to reduced refined product demand from this rule, we are now estimating that U.S. refinery output will decline by half (50 percent) of the reduced demand, while increases in refined product exports (i.e., equivalently a decline in net refined product imports) will account for the other half (50 percent) of that reduced demand. We also look at an additional case in a sensitivity analysis where U.S. refinery throughput would be maintained by 80 percent as a result by increases in refined product exports, while 20 percent of the refinery throughput would be reduced. See Chapter 4 of the RIA and Section 13 of the Response to Comment document for more discussion of how EPA is updating its refinery throughput assumptions and, in turn, air quality impacts from refinery emissions, as a result of this rule. See Section 22 of the Response to Comment document for EPA's response to comments on EPA's updated estimate of the oil import reduction factor.

Since EPA's refinery throughput assumptions are being updated for this final rule, this will influence EPA's estimate of the oil import reductions and, in turn, the energy security benefits estimated in this analysis. For the DRIA, a summary table was docketed that contained the estimates of the oil import reduction factor. Table 7-18 shows that for a reduction in refined product estimated by AEO's 2022 Low Economic Growth Case relative to the Reference Case, 88.9 percent of the reduced product demand is attributed to reduced imported crude oil, while 2.6 percent is attributed to increased net imported products – resulting in the 86.4 percent oil import reduction factor. Global (i.e., rest of the world) oil demand is not changed in the Low Economic Growth Case compared to the Reference Case, so the comparison between the AEO Reference Case and the Low Economic Growth Case is only in the overall pattern of U.S. oil demand changes.

Table 7-18 Oil Import Reduction Factor based on AEO 2022

Average over the years 2027 to 2050	
88.9	Percent reduction of imported crude oil
13.3	Percent reduction in domestic crude oil
-2.6	Percent reduction in net imported product
100.0	
86.4	Total percentage of imported petroleum

For the final rule, the same methodology based on the AEO 2023 results in an 89.6 percent oil import reduction factor – 84.8 percent of which would be due to reduced imported crude oil and 4.8 percent would be due to reduced net U.S. imported products.[2065]

Table 7-19 Oil Import Reduction Factor based on AEO 2023

Average over the years 2027 to 2050	
84.8	Percent of imported crude oil
10.3	Percent reduction in domestic crude oil
4.8	Percent reduction in net imported product
100.0	
89.6	Total percentage of imported petroleum

Use of the two AEO cases cited above estimates a large reduction in U.S. refinery throughput – AEO 2022 estimates that 102.2 percent (89.9+13.3) of the reduced product demand would be attributed to reduced throughput at U.S. refineries – this is rounded down to 100 percent. Based on AEO 2023, the reduction in U.S. refinery throughput would be 95.1 percent (84.8+10.3).

However, for the final rulemaking, as noted above, we are estimating that U.S. refineries will not reduce their throughput to the same extent. Instead, for a given reduction in a volume of gasoline and diesel fuel demand, 50 percent of that reduced demand will be due to reduced production by U.S. refineries, while for the other 50 percent, refineries will continue to operate, and the U.S. will increase its refined product exports (i.e., reduce its net refined product imports). Thus, we needed a way to estimate the energy security impacts assuming that U.S. refiners would continue producing domestic fuels at a much higher level associated with the 50/50 assumption.

Since we are now estimating that in response to reduced refined product demand, half of that reduced demand will be reduced production from U.S. refineries and the other half will be increases in the exports of refined products (i.e., a decline in net refined product imports), two different methods for estimating the oil import reduction factor are being used. The portion of reduced refinery demand projected to result in reduced refinery throughput can be represented by the oil import reduction factor estimated by the two 2023 AEO cases. However, since reduced refinery throughput is estimated to comprise all of the reduced demand, we instead assumed that the percent reduction in net U.S. imported product would also be reduced imported crude oil –

[2065] Memo to Docket. Oil Import Reduction Factor Using AEO 2023. March 2024. Docket EPA-HQ-OAR-2022-0985.

thus, all of the 89.6 percent reduced imported petroleum would be imported crude oil. Conversely, the balance of reduced refinery demand which U.S. refineries keep operating can be represented by the oil import reduction factor which, by definition, would be 100 percent, since U.S. refined product exports increase at the same rate that refinery demand decreases. Thus, the oil import reduction factor is estimated by the following equation:

Oil Import Reduction Factor = 89.6% x 0.5 + 100% x 0.5 = 94.8%

If the sensitivity analysis 80/20 percent refinery throughput assumption is utilized, the oil import reduction factor is estimated by the following equation:

Oil Import Reduction Factor = 89.6% x 0.2 + 100% x 0.8 = 97.9%

Based upon the changes in oil consumption estimated in Chapter 6.5 and the revised 94.8 percent oil import reduction factor, the reduction in U.S. oil imports as a result of the final CO_2 emission standards for selected years are estimated below for the 2027–2055 timeframe. Once U.S. oil import reductions are calculated, EPA multiplies the oil import reductions from the final rule by the oil security premiums to calculate total energy security benefits over the timeframe of the analysis of the final rule.

For comparison purposes, based upon the AEO 2023 (Reference Case), Table 7-20 also shows the U.S.'s projected crude oil exports and imports, net refined petroleum product exports, net crude oil/refined petroleum product exports and U.S. oil consumption for the same years in the 2027–2050 timeframe.[2066]

Table 7-20 Projected Trends in U.S. Oil Exports/Imports, Net Refined Petroleum Product Exports, Net Crude Oil/Refined Petroleum Product Exports, Oil Consumption and U.S. Oil Import Reductions Resulting from the Final Rule for Selected Years from 2027 to 2055 (MMBD)

	2027	2030	2032	2035	2040	2045	2050	2055
U.S. Crude Oil Exports	3.3	3.4	3.4	3.4	3.2	3.2	2.9	-
U.S. Crude Oil Imports	6.9	7.0	7.1	7.1	7.2	7.1	6.6	-
U.S. Net Refined Petroleum Product Exports [a]	5.8	6.0	6.1	6.4	6.7	6.7	6.2	-
U.S. Net Crude Oil and Petroleum Product Exports	2.3	2.4	2.5	2.8	2.8	2.9	2.7	-
U.S. Oil Consumption [b]	18.6	18.4	18.3	18.2	18.2	18.5	18.9	-
Reduction in U.S. Oil Imports from the Final Standards [c]	0.00	0.02	0.08	0.20	0.33	0.40	0.42	0.42

[a] Calculated from AEO 2023 Table A11 as Net Product Exports minus Ethanol, Biodiesel, Renewable Diesel, and Other Biomass-derived Liquid Net Exports

[b] Calculated from AEO 2023 Table A11 as "Total Primary Supply" minus "Biofuels"

[c] U.S. oil import reductions (in MMBD) are derived from Table 6-2 Estimated U.S. Oil Import Reductions and Electricity and Hydrogen Consumption Increases due to the Final Rule in Chapter 6.5 of the RIA. Estimated U.S. oil imports are rounded off from the estimates in Table 6-2

[2066] EIA. 2023. *Annual Energy Outlook* 2023. Reference Case. Table A11. Petroleum and Other Liquids Supply and Disposition.

7.3.5 Oil Security Premiums Used in the Final Rule

The total energy security benefits of this final HDV GHG Phase 3 rule are calculated based upon U.S. net oil import reductions multiplied by the oil security premiums estimated for this rule. In the proceeding section (Chapter 7.3.4), we present estimates of the U.S. oil import reductions from this rule. In the section below, we present estimates of the oil security premiums used for this rule.

In order to understand the energy security implications of reducing U.S. oil imports, EPA has worked with Oak Ridge National Laboratory (ORNL), which has developed approaches for evaluating the social costs and energy security implications of oil use. The energy security estimates provided below are based upon a methodology developed in a peer-reviewed study entitled, "*The Energy Security Benefits of Reduced Oil Use, 2006-2015,*" completed in 2008.[2067] This ORNL study is an updated version of the approach used for estimating the energy security benefits of U.S. oil import reductions developed in a 1997 ORNL report.[2068] This same approach was first used in EPA GHG rules to estimate energy security benefits for the March 2010 RFS2 final rule.[2069] ORNL has updated this methodology regularly for EPA to account for updated projections of future energy market and economic trends reported in the U.S. EIA's AEO.

The ORNL methodology is used to compute the oil import premium (concept defined above in Chapter 7.3.1) per barrel of imported oil. The values of U.S. oil import premium components (macroeconomic disruption/adjustment costs and monopsony components) are numerically estimated with a compact model of the oil market by performing simulations of market outcomes using probabilistic distributions for the occurrence of oil supply shocks, calculating marginal changes in economic welfare with respect to changes in U.S. oil import levels in each of the simulations, and summarizing the results from the individual simulations into a mean and 90 percent confidence intervals for the import premium estimates. The macroeconomic disruption/adjustment import cost component is the sum of two parts: the marginal change in expected import costs during disruption events and the marginal change in gross domestic product due to the disruption. The monopsony component is the long-run change in U.S. oil import costs as the level of oil import changes.

For this final rule, EPA is using oil import premiums that incorporate the oil price projections and energy market and economic trends, particularly global regional oil supplies and demands (i.e., the U.S./OPEC/rest of the world), from the AEO 2023 into its model.[2070] EPA only

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[2067] Leiby, P. 2008. *Estimating the Energy Security Benefits of Reduced U.S. Oil Imports*. Final Report. ORNL/TM-2007/028. Oak Ridge National Laboratory. March.

[2068] Leiby, P., Jones, D., Curlee, R. and Lee, R. 1997. Oil Imports: An Assessment of Benefits and Costs, ORNL-6851. Oak Ridge National Laboratory. November.

[2069] See 40 CFR Part 80, Regulation of Fuels and Fuels Additives: Changes to the Renewable Fuel Standard Program; Final Rule, March 26, 2010.

[2070] The oil market projection data used for the calculation of the oil import premiums came from AEO 2023, supplemented by the latest EIA international projections from the *International Energy Outlook (IEO) 2021*. Global oil prices and all variables describing U.S. supply and disposition of petroleum liquids (domestic supply, tight oil supply fraction, imports, demands) as well as U.S. non-petroleum liquids supply and demand are from AEO 2023. Global and OECD Europe supply/demand projections as well as OPEC oil production share are from IEO 2021. The need to combine AEO 2023 and IEO 2021 data arises due to two reasons: (a) EIA stopped including Table 21 "International Petroleum and Other Liquids Supply, Disposition, and Prices" in the U.S. focused *Annual Energy Outlook* after 2019, (b) EIA does not publish complete updates of the IEO every year.

considers the avoided macroeconomic disruption/adjustment oil import premiums (i.e., labeled macroeconomic oil security premiums below) as costs, since we consider the monopsony impacts stemming from changes in U.S. oil imports transfer payments. In previous EPA rules when the U.S. was projected by EIA to be a net importer of crude oil and petroleum-based refined products, monopsony impacts represented reduced payments by U.S. consumers to oil producers outside of the U.S. There was some debate among economists as to whether the U.S. exercise of its monopsony power in oil markets, for example from the implementation of EPA's rules, was a "transfer payment" or a "benefit". Given the redistributive nature of this monopsony impact from a global perspective, and since there are no changes in resource costs when the U.S. exercises its monopsony power, some economists argued that it is a transfer payment. Other economists argued that monopsony impacts were a benefit since they partially address, and partially offset, the market power of OPEC. In previous EPA rules, after weighing both countervailing arguments, EPA concluded that the U.S.'s exercise of its monopsony power was a transfer payment, and not a benefit.[2071]

In the timeframe covered by this final HD vehicle rule, the U.S.'s oil trade balance is projected to be quite a bit different than during the time periods covered in many previous EPA rules. Starting in 2020, the U.S. became a net exporter of crude oil and refined oil products and the U.S. is projected to continue to be a net exporter of oil and refined petroleum products in the timeframe covered by the analysis of the final GHG emission standards, 2027-2055. As a result, reductions in U.S. oil consumption and, in turn, U.S. oil imports, still are expected to lower the world oil price modestly. But the net effect of the lower world oil price in the 2027-2055 period of this final rule is expected to be a decrease in revenue for U.S. exporters of crude oil and refined petroleum products, instead of a decrease in payments to foreign oil producers. The argument that monopsony impacts address the market power of OPEC is no longer appropriate. Thus, we continue to consider the U.S. exercise of monopsony power to be transfer payments. We also do not consider the effect of this final rule on the costs associated with existing energy security policies (e.g., maintaining the Strategic Petroleum Reserve or strategic military deployments), which are discussed above.

In addition, EPA and ORNL have worked together to revise the oil import premiums based upon recent energy security literature. Based upon EPA and ORNL's review of the recent energy security literature, EPA is assessing its macroeconomic oil security premiums for this final rule. The recent economics literature (discussed in Chapter 7.3.2) focuses on three factors that can influence the macroeconomic oil security premiums: the price elasticity of oil demand, the GDP elasticity in response to oil price shocks, and the impacts of the U.S. tight (i.e., shale) oil boom. We discuss each factor below and provide a rationale for how we are developing estimates for the first two factors for the macroeconomic oil security premiums being used in this final rule. We are not accounting for how U.S. tight oil is influencing the macroeconomic oil security premiums in this final rule, other than how it significantly reduces the need for U.S. oil imports.

First, we assess the price elasticity of demand for oil. In previous EPA Vehicle rulemakings, EPA used a short-run elasticity of demand for oil of –0.045.[2072] In the most recent EPA rule

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[2071] See the previous EPA GHG vehicle assessment, Proposed Determination on the Appropriateness of the Model Year 2022-2025 Light-Duty Greenhouse Gas Standards under the Mid-Term Evaluation. July 2016. Technical Support Document. EPA-420-D-16-900.

[2072] Ibid.

setting GHG emissions standards for passenger cars and light trucks through model year 2026, we used a short-run elasticity of demand for oil of –0.07, an update of previously used elasticities based on the below considerations.[2073] For this rule, we continue to use the elasticity value of –0.07.

From the RFF study, the "blended" price elasticity of demand for oil is –0.05. The ORNL meta-analysis estimate of this parameter is –0.07. We find the elasticity estimates from what RFF characterizes as the "new literature," –0.175, and from the "new models" that RFF uses, –0.20 to –0.33, somewhat high. We believe it would be surprising if short-run oil demand responsiveness has changed in a dramatic fashion.

The ORNL meta-analysis estimate encompasses the full range of the economics literature on this topic and develops a meta-analysis estimate from the results of many different studies in a structured way, while the RFF study's "new models" results represent only a small subset of the economics literature's estimates. Thus, we believe using a short-run price elasticity of demand for oil of –0.07 is more appropriate. This increase has the effect of lowering the macroeconomic oil security premium estimates undertaken by ORNL for EPA.

Second, we consider the elasticity of GDP to an oil price shock. In previous EPA Vehicle rulemakings, EPA used an elasticity of GDP to an oil shock of –0.032.[2074] In the most recent EPA rule setting GHG emissions standards for passenger cars and light trucks through model year 2026, we used an elasticity of GDP of –0.021, an update of previously used elasticities based on the below considerations.[2075] For this rule, we continue to use the elasticity value of –0.021.

The RFF "blended" GDP elasticity is –0.028, the RFF's "new literature" GDP elasticity is –0.018, while the RFF "new models" GDP elasticities range from –0.007 to –0.027. The ORNL meta-analysis GDP elasticity is –0.021. We believe that the ORNL meta-analysis value is representative of the recent literature on this topic since it considers a wider range of recent studies and does so in a structured way. Also, the ORNL meta-analysis estimate is within the range of GDP elasticities of RFF's "blended" and "new literature" elasticities. For this final rule, EPA is using a GDP elasticity of –0.021, a 34 percent reduction from the GDP elasticity used previously (i.e., the –0.032 value). This GDP elasticity is within the range of RFF's "new literature" elasticity, –0.018, and the elasticity EPA has used in previous rulemakings, –0.032, but lower than RFF's "blended" GDP elasticity, –0.028. This decrease has the effect of lowering the macroeconomic oil security premium estimates. For U.S. tight oil, EPA has not made any adjustments to the ORNL model, given the limited tight oil production response to rising world oil prices in the recent 2020–2023 timeframe.[2076] Increased tight oil production still results in

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[2073] Regulatory Impact Analysis: Revised 2023 and Later Model Year Light Duty Vehicle GHG Emissions Standards. EPA-420-R-21-028, December 2021.

[2074] See the previous EPA GHG vehicle assessment, Proposed Determination on the Appropriateness of the Model Year 2022-2025 Light-Duty Greenhouse Gas Standards under the Mid-Term Evaluation. Technical Support Document. EPA-420-R-16-021. November. 2016.

[2075] Regulatory Impact Analysis: Revised 2023 and Later Model Year Light Duty Vehicle GHG Emissions Standards. EPA-420-R-21-028, December 2021.

[2076] The short-run oil supply elasticity assumed in the ORNL model is 0.06 and is applied to production from both conventional and tight (i.e., shale) oil wells.

energy security benefits though, through its impact of reducing U.S. oil imports in the ORNL model.

Table 7-21 provides estimates of EPA's macroeconomic oil security premium estimates in the 2027–2055 timeframe. The macroeconomic oil security premiums are relatively steady over the time period of this final rule at $3.73/barrel (9 cents/gallon) in 2027, $3.65/barrel in 2030 (9 cents/gallon), $4.61/barrel (11 cents per gallon) in 2040 and $5.22/barrel (12 cents/gallon) in 2050 and 2055 (in 2022 U.S. dollars).

Table 7-21 Macroeconomic Oil Security Premiums for Final Rule from 2027–2055 (2022$/Barrel)*

Calendar Year	Macroeconomic Oil Security Premiums (Mid-point/range)
2027	$3.73 ($0.51 - $7.02)
2028	$3.78 ($0.51 - $7.15)
2029	$3.87 ($0.54 - $7.31)
2030	$3.92 ($0.51 - $7.46)
2031	$4.00 ($0.55 - $7.62)
2032	$4.05 ($0.53 - $7.77)
2033	$4.11 ($0.47 - $7.93)
2034	$4.16 ($0.44 - $8.07)
2035	$4.22 ($0.45 - $8.20)
2036	$4.28 ($0.44 - $8.29)
2037	$4.35 ($0.47 - $8.40)
2038	$4.44 ($0.52 - $8.55)
2039	$4.50 ($0.53 - $8.66)
2040	$4.62 ($0.65 - $8.85)
2041	$4.73 ($0.70 - $9.04)
2042	$4.77 ($0.69 - $9.15)
2043	$4.82 ($0.67 - $9.27)
2044	$4.85 ($0.66 - $9.35)
2045	$4.91 ($0.68 - $9.43)
2046	$4.98 ($0.71 - $9.52)
2047	$5.09 ($0.82 - $9.68)
2048	$5.14 ($0.85 - $9.79)
2049	$5.16 ($0.82 - $9.85)
2050	$5.22 ($0.91 - $9.89)
2051[†]	$5.22 ($0.91 - $9.89)
2052[†]	$5.22 ($0.91 - $9.89)
2053[†]	$5.22 ($0.91 - $9.89)
2054[†]	$5.22($0.91 - $9.89)
2055[†]	$5.22 ($0.91 - $9.89)

[*] Top-values in each cell are mean values. Values in parentheses are 90 percent confidence intervals.

[†] The ORNL oil security premium estimation methodology does not provide estimates for years after 2050 (the final year in the AEO projections which are used in the ORNL energy security premium model). We extend the estimated 2050 premium to the years 2051 through 2055, which can be considered a conservative assumption given the steadily increasing premium estimates produced through time by the ORNL model.

7.3.6 Energy Security Benefits of the Final Rule

Estimates of the total annual energy security benefits for the revised CO_2 emission standards for model year 2027 HD vehicles and new CO_2 emission standards for HD vehicles in model years 2028 through 2032 are based upon the ORNL oil import premium methodology with updated oil import premium estimates reflecting the recent energy security literature and using the AEO 2023. Annual per-gallon benefits are applied to the reductions in U.S. crude oil and refined petroleum product imports. We do not consider military cost impacts or the monopsony effect of U.S. crude oil and refined petroleum product import changes on the energy security benefits of this final rule. The energy security benefits of this final rule are presented below in Table 7-22, Energy Security Benefits from the Final Rule (in millions of 2022 dollars).

Table 7-22 Energy Security Benefits from the Final Rule (millions of 2022 dollars)

Calendar Year	Energy Security Benefits
2027	$4
2028	$10
2029	$18
2030	$32
2031	$65
2032	$120
2033	$180
2034	$240
2035	$300
2036	$360
2037	$410
2038	$460
2039	$510
2040	$560
2041	$600
2042	$640
2043	$670
2044	$690
2045	$720
2046	$740
2047	$760
2048	$770
2049	$780
2050	$790
2051	$800
2052	$800
2053	$800
2054	$800
2055	$800
PV, 2%	$9,800
PV, 3%	$8,200
PV, 7%	$4,200
AV, 2%	$450
AV, 3%	$430
AV, 7%	$340

Chapter 8 Comparison of Benefits and Costs

This chapter compares the estimated range of benefits associated with reductions of GHGs, monetized health benefits from reductions in $PM_{2.5}$, energy security benefits, fuel savings, and vehicle-related operating savings to total costs associated with the modeled potential compliance pathway for the final rule and for the alternative. Estimated costs are detailed and presented in Chapter 3 of this RIA. Those costs include costs for both the new technology in our modeled potential compliance pathways' technology packages and the operating costs associated with that new technology. Importantly, as detailed in Section IV of the preamble and Chapter 3 of this RIA, the vehicle costs presented here exclude the IRA battery tax credit, the vehicle tax credit, and the EVSE tax credit, while the fuel savings exclude fuel taxes. As such, as presented in this section, these costs, along with other operating costs, represent the social costs and/or savings associated with the final standards. Benefits from the reduction of GHG emissions and criteria pollutant emissions and energy security benefits associated with reductions of imported oil are presented in Chapter 7.

8.1 Methods

EPA presents three different benefit-cost comparisons for the final rule and the for the alternative:

1. A future-year snapshot comparison of annual benefits and costs in the year 2055, chosen to approximate the annual costs and benefits that will occur in a year when most of the regulated fleet will consist of HD vehicles subject to the HD GHG Phase 3 standards due to fleet turnover. Benefits, costs, and net benefits are presented in year 2022 dollars and are not discounted.
2. The present value (PV) of the stream of benefits, costs, and net benefits calculated for the analytical time horizon of 2027–2055, discounted back to the first year of implementation of the final rule (2027) using 2-percent, 3-percent, and 7-percent discount rates, and presented in year 2022 dollars.[2077] Note that year-over-year costs are presented in RIA Chapter 3 and year-over-year benefits can be found in RIA Chapter 7.
3. The equivalent annualized value (AV) of benefits, costs and net benefits representing a flow of constant annual values that, had they occurred in each year from 2027 through 2055, will yield an equivalent present value to those estimated in method 2 (using a 2-percent, 3-percent, and 7-percent discount rate). Each AV represents a typical benefit, cost, or net benefit for each year of the analysis and is presented in year 2022 dollars.

[2077] We use a constant 3-percent and 7-pecent discount rate to calculate present and annualized values, consistent with current applicable OMB Circular A-4 guidance (2003). While we were conducting the analysis for this rule, OMB finalized an update to Circular A-4 (2023), in which it recommended the general application of a 2-percent discount rate to costs and benefits (see https://www.whitehouse.gov/wp-content/uploads/2023/11/CircularA-4.pdf). Although the effective date of the updated Circular A-4 does not apply to this rulemaking, we have also included 2 percent discount rates in our analysis. Climate benefits, however, are based on reductions in GHG emissions and are calculated using three different social cost estimates that assume either a 1.5-percent, 2.0-percent, or 2.5-percent near-term Ramsey discount rate. For presentational purposes, we also use a constant 2-percent discount rate to calculate present and annualized values to be approximately consistent with the SC-GHG values estimated using the 2-percent near-term Ramsey discount rate.

8.2 Results

Table 8-1 shows the undiscounted annual monetized vehicle-related projected technology package RPE costs of the final rule and the alternative in calendar year 2055. The table also shows the PV and AV of those costs for the calendar years 2027–2055 using 2-percent, 3-percent and 7-percent discount rates. The table includes an estimate of the projected vehicle technology packages RPE costs and corresponding costs associated with EVSE.

Note that all costs, savings, and benefits estimates presented in the tables that follow are rounded to two significant figures; numbers may not sum due to independent rounding.

Table 8-1 Vehicle-Related Technology Costs Associated with the Final Rule and Alternative, Millions of 2022 dollars

	Final Rule			Alternative		
	Vehicle Technology Package RPE	EVSE RPE	Sum	Vehicle Technology Package RPE	EVSE RPE	Sum
2055	-$590	$1,100	$550	$55	$79	$130
PV, 2%	-$4,200	$28,000	$24,000	$3,000	$5,000	$8,000
PV, 3%	-$3,200	$25,000	$22,000	$2,600	$4,600	$7,200
PV, 7%	-$1,000	$15,000	$14,000	$1,700	$3,400	$5,000
AV, 2%	-$190	$1,300	$1,100	$140	$230	$370
AV, 3%	-$170	$1,300	$1,100	$140	$240	$380
AV, 7%	-$83	$1,300	$1,200	$140	$270	$410

Table 8-2 and Table 8-3 show the undiscounted annual monetized vehicle-related operating savings of the final rule and alternative, respectively, in calendar year 2055. The tables also show the PV and AV of those savings for the calendar years 2027–2055 using 2-percent, 3-percent and 7-percent discount rates. The savings in DEF consumption arise in the modeled potential compliance pathway's technology packages from the decrease in diesel engine-equipped vehicles which require DEF to maintain compliance with NO_X emission standards. The maintenance and repair savings are due again to the HD vehicle technologies utilized in the modeled potential compliance pathway; BEVs are projected to ultimately require 71 percent of the maintenance and repair and HD FCEVs are projected to ultimately require 75 percent of the maintenance and repair required of HD ICE vehicles (see RIA Chapter 3.4.5).

Table 8-2 Vehicle-Related Operating Savings Associated with the Final Rule, Millions of 2022 dollars *

	Pre-tax Fuel Savings	DEF Savings	Maintenance & Repair Savings	Insurance Savings	Vehicle Replacement Savings	EVSE Replacement Savings	Sum of Savings
2055	-$350	$1,800	$6,900	$250	$140	-$1,300	$7,400
PV, 2%	-$9,500	$21,000	$73,000	$1,300	$1,900	-$11,000	$76,000
PV, 3%	-$7,900	$17,000	$60,000	$1,000	$1,500	-$8,700	$63,000
PV, 7%	-$3,900	$8,700	$30,000	$460	$720	-$3,700	$32,000
AV, 2%	-$430	$950	$3,300	$60	$86	-$500	$3,500
AV, 3%	-$410	$900	$3,100	$55	$80	-$450	$3,300
AV, 7%	-$310	$710	$2,400	$38	$58	-$300	$2,600

*Fuel savings are net of savings in diesel, gasoline, and CNG consumption with increased electricity and hydrogen consumption; DEF savings accrue only to diesel vehicles; maintenance and repair savings include impacts associated with all fuels; replacement savings are net of costs associated with replacement/rebuild of liquid-fueled engines and replacement of batteries on electric vehicles.

Table 8-3 Vehicle-Related Operating Savings Associated with the Alternative, Millions of 2022 dollars *

	Pre-tax Fuel Savings	DEF Savings	Maintenance & Repair Savings	Insurance Savings	Vehicle Replacement Savings	EVSE Replacement Savings	Sum of Savings
2055	-$1,300	$580	$2,000	-$78	$44	-$130	$1,100
PV, 2%	-$16,000	$7,500	$25,000	-$830	$710	-$2,700	$13,000
PV, 3%	-$13,000	$6,200	$21,000	-$680	$590	-$2,200	$11,000
PV, 7%	-$6,500	$3,200	$10,000	-$310	$280	-$1,000	$6,100
AV, 2%	-$750	$340	$1,100	-$38	$33	-$120	$600
AV, 3%	-$700	$330	$1,100	-$35	$31	-$110	$580
AV, 7%	-$530	$260	$850	-$25	$23	-$81	$490

*Fuel savings are net of savings in diesel, gasoline, and CNG consumption with increased electricity and hydrogen consumption; DEF savings accrue only to diesel vehicles; maintenance and repair savings include impacts associated with all fuels; replacement savings are net of costs associated with replacement/rebuild of liquid-fueled engines and replacement of batteries on electric vehicles.

Table 8-4 shows the undiscounted annual monetized energy security benefits of the final rule and the alternative in calendar year 2055. The table also shows the PV and AV of those benefits for the calendar years 2027–2055 using 2-percent, 3-percent and 7-percent discount rates.

Table 8-4 Energy Security Benefits Associated with the Final Rule and Alternative, Millions of 2022 dollars

	Final Rule	Alternative
2055	$800	$240
PV, 2%	$9,800	$3,400
PV, 3%	$8,200	$2,800
PV, 7%	$4,200	$1,500
AV, 2%	$450	$150
AV, 3%	$430	$150
AV, 7%	$340	$120

Table 8-5 shows the benefits of reduced GHG emissions, and consequently the annual quantified benefits (i.e., total GHG benefits), for each of the three social cost of GHG (SC-GHG) values estimated by the *EPA Report on the Social Cost of Greenhouse Gases: Estimates Incorporating Recent Scientific Advances* (EPA 2023).[2078] As discussed in RIA Chapter 7, there are some limitations to the SC-GHG analysis, including the incomplete way in which the integrated assessment models capture catastrophic and non-catastrophic impacts, their incomplete treatment of adaptation and technological change, uncertainty in the extrapolation of damages to high temperatures, and assumptions regarding risk aversion. These climate benefits include benefits associated with changes to HD vehicle GHGs and both refinery and EGU GHG emissions, but do not include any impacts associated with the extraction or transportation of fuels for either EGUs or refineries.

Table 8-6 shows the undiscounted annual monetized $PM_{2.5}$-related health benefits of the final rule and the alternative in calendar year 2055. The table also shows the PV and AV of those benefits for the calendar years 2027 through 2055 using a 2-percent, 3-percent and 7-percent discount rate. The benefits in Table 8-6 reflect the two premature mortality estimates derived from the Medicare study (Wu et al., 2020) and the NHIS study (Pope et al., 2019).[2079,2080] The monetized criteria pollutant health benefits include reductions in $PM_{2.5}$-related emissions from HD vehicles. Monetized upstream health impacts associated with the standards also include benefits associated with reduced $PM_{2.5}$-related emissions from refineries and health disbenefits associated with increased $PM_{2.5}$-related emissions from EGUs. Negative monetized values are associated with health disbenefits related to increases in estimated emissions from EGUs. Depending on the discount rate used, the present and annualized value of the stream of $PM_{2.5}$-related benefits may either be positive or negative.

Table 8-5 Climate Benefits from Reduction in GHG Emissions Associated with the Final Rule and Alternative, Millions of 2022 dollars

	Final Rule			**Alternative**		
	1.5% Average	**2% Average**	**2.5% Average**	**1.5% Average**	**2% Average**	**2.5% Average**
2055	$15,000	$22,000	$34,000	$4,300	$6,400	$9,800
PV	$130,000	$220,000	$390,000	$42,000	$71,000	$120,000
AV	$6,600	$10,000	$17,000	$2,100	$3,200	$5,300

Notes:
Climate benefits are based on changes (reductions) in CO_2, CH_4, and N_2O emissions and are calculated using three different estimates of the social cost of carbon (SC-CO_2), the social cost of methane (SC-CH_4), and the social cost of nitrous oxide (SC-N_2O) (model average at 1.5-percent, 2-percent, and 2.5-percent Ramsey discount rates). See RIA Chapter 7.1 for more information. Annual benefits shown are undiscounted values.

[2078] For more information about the development of these estimates, see *www.epa.gov/environmental-economics/scghg*.

[2079] Wu, X, Braun, D, Schwartz, J, Kioumourtzoglou, M and Dominici, F (2020). Evaluating the impact of long-term exposure to fine particulate matter on mortality among the elderly. Science advances 6(29): eaba5692.

[2080] Pope III, CA, Lefler, JS, Ezzati, M, Higbee, JD, Marshall, JD, Kim, S-Y, Bechle, M, Gilliat, KS, Vernon, SE and Robinson, AL (2019). Mortality risk and fine particulate air pollution in a large, representative cohort of US adults. Environmental health perspectives 127(7): 077007.

Table 8-6 Monetized $PM_{2.5}$-related Emission Benefits Associated with the Final Rule and Alternative, Millions of 2022 dollars

	Final Rule			**Alternative**		
	2%	**3%**	**7%**	**2%**	**3%**	**7%**
2055	$1,000-1,900	$1,000-1,900	$900-1,700	$270-520	$270-520	$240-470
PV	$3,500-6,500	$2,300-4,200	$(110)-(400)	$320-480	$40-(58)	$(440)-(950)
AV	$160-300	$120-220	$(9.1)-(32)	$15-22	$2.1-(3.0)	$(36)-(77)

Notes:

Monetized $PM_{2.5}$-related health impacts are based on benefit-per-ton (BPT) values. The benefits in this table reflect two premature mortality estimates derived from the Medicare study (Wu et al., 2020) and the NHIS study (Pope III et al., 2019), respectively. Annual $PM_{2.5}$ BPT estimates use 3-percent and 7-percent discount rates to account for avoided health outcomes that are expected to accrue over more than a single year (the "cessation lag" between the change in PM exposures and the total realization of changes in health effects). We do not currently have BPT estimates that use a 2-percent discount rate to account for cessation lag; for this reason, annual benefits in 2055 are the same in the 2% and 3% columns.

All benefits estimates are rounded to two significant figures. The present value of benefits is the total aggregated value of the series of discounted annual benefits that occur between 2027-2055 (in 2022 dollars) using either a 2-percent, 3-percent, or 7-percent discount rate.

Monetized criteria pollutant health benefits include reductions in $PM_{2.5}$-related emissions from HD vehicles. Monetized upstream health impacts associated with the standards also include benefits associated with reduced $PM_{2.5}$-related emissions from refineries and health disbenefits associated with increased $PM_{2.5}$-related emissions from EGUs. Negative monetized values in parentheses are associated with health disbenefits related to increases in estimated emissions from EGUs. Depending on the discount rate used, the present and annualized value of the stream of $PM_{2.5}$ benefits may either be positive or negative.

The benefits in this table also do not include the full complement of health and environmental benefits (such as health benefits related to reduced ozone exposure) that, if quantified and monetized, would increase the total monetized benefits.

Table 8-7 shows the undiscounted annual total benefits of the final standards and alternative in calendar year 2055, as well as the PV and AV of the total benefits for the calendar years 2027 through 2055. Total benefits are the sum of climate benefits, non-GHG benefits and energy security benefits. The present and annualized values of energy security benefits and $PM_{2.5}$ health impacts are discounted using either a 2-percent, 3-percent, or 7-percent constant discount rate (see Table 8-4 and Table 8-6, respectively). Climate benefits are based on reductions in GHG emissions and are calculated using three different social cost estimates that assume either a 1.5-percent, 2.0-percent, or 2.5-percent near-term Ramsey discount rate (see Table 8-5). For presentational purposes in Table 8-7, we use the climate benefits associated with the SC-GHG under the 2-percent near-term Ramsey discount rate for the total benefits calculation. The benefits include those associated with changes to HD vehicle GHGs and both EGU and refinery GHG emissions, but do not include any impacts associated with the extraction or transportation of fuels for either EGUs or refineries. This likely underestimates the refinery-related emission reductions projected in the rule but likely also underestimates EGU-related emission increases in the rule.

Table 8-7 Total Benefits Associated with the Final Rule and Alternative, Millions of 2022 dollars

	Final Rule	Alternative
2055	$25,000	$7,100
PV, 2%	$240,000	$75,000
PV, 3%	$240,000	$73,000
PV, 7%	$230,000	$71,000
AV, 2%	$11,000	$3,400
AV, 3%	$11,000	$3,400
AV, 7%	$11,000	$3,300

Notes:
Total benefits are the sum of climate benefits, $PM_{2.5}$-related benefits and energy security benefits.
Climate benefits are based on reductions in GHG emissions and are calculated using three different SC-GHG estimates that assume either a 1.5-percent, 2.0-percent, or 2.5-percent near-term Ramsey discount rate (see Table 8-5). For presentational purposes in this table, we use the climate benefits associated with the SC-GHG under the 2-percent near-term Ramsey discount rate for the total benefits calculation.
The present and annualized values of energy security benefits and $PM_{2.5}$ health impacts are discounted using either a 2-percent, 3-percent, or 7-percent constant discount rate (see Table 8-4 and Table 8-6, respectively). For presentational clarity, we use the monetized suite of total avoided $PM_{2.5}$-related health effects that includes avoided deaths based on the Pope III et al., 2019 study, which is the larger of the two $PM_{2.5}$ health benefits estimates presented in RIA Chapter 7.2. All benefits estimates are rounded to two significant figures.

We summarize the vehicle costs, operational savings, and benefits of the final rule, as shown in Table 8-8. Table 8-8 reproduces the final rule’s costs from Table 8-1, operating savings from Table 8-2, benefits from Table 8-7 (comprised of benefits presented in Table 8-4 through Table 8-6), in a single table. We summarize the vehicle costs, operational savings, and benefits of the alternative in Table 8-9. We remind readers that, in the NPRM, we used the interim SC-GHG values, while in this final rule we are using the updated SC-GHG values (see RIA Chapter 7.1). We include the 2 percent discount rate here for consistency with the 2 percent near-term Ramsey discount rate used in the updated SC-GHG values.

Table 8-8 Summary of Vehicle Costs, Operating Savings, and Benefits of the Final Rule, Billions of 2022 Dollars

	CY 2055	PV, 2%	PV, 3%	PV, 7%	AV, 2%	AV, 3%	AV, 7%
Vehicle Technology Package RPE	-$0.59	-$4.2	-$3.2	-$1	-$0.19	-$0.17	-$0.083
EVSE RPE	$1.1	$28	$25	$15	$1.3	$1.3	$1.3
Sum of Vehicle Costs	$0.55	$24	$22	$14	$1.1	$1.1	$1.2
Pre-tax Fuel Savings	-$0.35	-$9.5	-$7.9	-$3.9	-$0.43	-$0.41	-$0.31
Diesel Exhaust Fluid Savings	$1.8	$21	$17	$8.7	$0.95	$0.9	$0.71
Repair & Maintenance Savings	$6.9	$73	$60	$30	$3.3	$3.1	$2.4
Insurance Savings	$0.25	$1.3	$1	$0.46	$0.06	$0.055	$0.038
Vehicle Replacement Savings	$0.14	$1.9	$1.5	$0.72	$0.086	$0.08	$0.058
EVSE Replacement Savings	-$1.3	-$11	-$8.7	-$3.7	-$0.5	-$0.45	-$0.3
Sum of Operating Savings	$7.4	$76	$63	$32	$3.5	$3.3	$2.6
Energy Security Benefits	$0.8	$9.8	$8.2	$4.2	$0.45	$0.43	$0.34
Climate Benefits – 2% Average Ramsey[a]	$22	$220	$220	$220	$10	$10	$10
$PM_{2.5}$ Health Benefits[b,c,d]	$1.9	$6.5	$4.2	-$0.4	$0.3	$0.22	-$0.032
Sum of Benefits	$25	$240	$240	$230	$11	$11	$11
Net Benefits	$32	$290	$280	$250	$13	$13	$12

[a] Climate benefits are based on reductions in GHG emissions and are calculated using three different SC-GHG estimates that assume either a 1.5-percent, 2.0-percent, or 2.5-percent near-term Ramsey discount rate. For presentational purposes in this table, we use the climate benefits associated with the SC-GHG under the 2-percent near-term Ramsey discount rate. See Table 8-5 for the full range of monetized climate benefit estimates. All other costs and benefits are discounted using either a 2-percent, 3-percent, or 7-percent constant discount rate. For further discussion of the SC-GHGs and how EPA accounted for these estimates, please refer to Chapter 7 of the RIA.

[b] Monetized non-GHG health benefits are based on $PM_{2.5}$-related benefit-per-ton (BPT) values. To calculate net benefits, we use the monetized suite of total avoided $PM_{2.5}$-related health effects that includes avoided deaths based on the Pope III et al., 2019 study, which is the larger of the two $PM_{2.5}$ health benefits estimates presented in RIA Chapter 7.2.

[c] The annual $PM_{2.5}$ health benefits estimate presented in the CY 2055 column reflects the value of certain avoided health outcomes, such as avoided deaths, that are expected to accrue over more than a single year discounted using a 3-percent discount rate.

[d] We do not currently have year-over-year estimates of $PM_{2.5}$ benefits that discount such annual health outcomes using a 2-percent discount rate. We have therefore discounted the annual stream of health benefits that reflect a 3-percent discount rate lag adjustment using a 2-percent discount rate to populate the PV, 2% and AV, 2% columns. The annual stream of $PM_{2.5}$-related health benefits that reflect a 3-percent and 7-percent discount rate lag adjustment were used to populate the PV/AV 3% and PV/AV 7% columns, respectively. See RIA Chapter 7.2 for more details on the annual stream of $PM_{2.5}$-related benefits associated with this rule.

Table 8-9 Summary of Vehicle Costs, Operating Savings, and Benefits of the Alternative, Billions of 2022 Dollars

	CY 2055	PV, 2%	PV, 3%	PV, 7%	AV, 2%	AV, 3%	AV, 7%
Vehicle Technology Package RPE	$0.055	$3	$2.6	$1.7	$0.14	$0.14	$0.14
EVSE RPE	$0.079	$5	$4.6	$3.4	$0.23	$0.24	$0.27
Sum of Vehicle Costs	$0.13	$8	$7.2	$5	$0.37	$0.38	$0.41
Pre-tax Fuel Savings	-$1.3	-$16	-$13	-$6.5	-$0.75	-$0.7	-$0.53
Diesel Exhaust Fluid Savings	$0.58	$7.5	$6.2	$3.2	$0.34	$0.33	$0.26
Repair & Maintenance Savings	$2	$25	$21	$10	$1.1	$1.1	$0.85
Insurance Savings	-$0.078	-$0.83	-$0.68	-$0.31	-$0.038	-$0.035	-$0.025
Vehicle Replacement Savings	$0.044	$0.71	$0.59	$0.28	$0.033	$0.031	$0.023
EVSE Replacement Savings	-$0.13	-$2.7	-$2.2	-$1	-$0.12	-$0.11	-$0.081
Sum of Operating Savings	$1.1	$13	$11	$6.1	$0.6	$0.58	$0.49
Energy Security Benefits	$0.24	$3.4	$2.8	$1.5	$0.15	$0.15	$0.12
Climate Benefits – 2% Average Ramsey[a]	$0.64	$71	$71	$71	$3.2	$3.2	$3.2
$PM_{2.5}$ Health Benefits[b,c,d]	$0.52	$0.48	-$0.058	-$0.95	$0.022	-$0.003	-$0.077
Sum of Benefits	$7.1	$75	$73	$71	$3.4	$3.4	$3.3
Net Benefits[e]	$8.1	$80	$77	$72	$3.6	$3.6	$3.4

[a] Climate benefits are based on reductions in GHG emissions and are calculated using three different SC-GHG estimates that assume either a 1.5 percent, 2.0 percent, or 2.5 percent near-term Ramsey discount rate. For presentational purposes in this table, we use the climate benefits associated with the SC-GHG under the 2-percent near-term Ramsey discount rate. See Table 8-5 for the full range of monetized climate benefit estimates. All other costs and benefits are discounted using either a 2-percent, 3-percent, or 7-percent constant discount rate. For further discussion of the SC-GHGs and how EPA accounted for these estimates, please refer to Chapter 7 of the RIA.

[b] Monetized non-GHG health benefits are based on $PM_{2.5}$-related benefit-per-ton (BPT) values. To calculate net benefits, we use the monetized suite of total avoided $PM_{2.5}$-related health effects that includes avoided deaths based on the Pope III et al., 2019 study, which is the larger of the two $PM_{2.5}$ health benefits estimates presented in RIA Chapter 7.2.

[c] The annual $PM_{2.5}$ health benefits estimate presented in the CY 2055 column reflects the value of certain avoided health outcomes, such as avoided deaths, that are expected to accrue over more than a single year discounted using a 3-percent discount rate.

[d] We do not currently have year-over-year estimates of $PM_{2.5}$ benefits that discount such annual health outcomes using a 2-percent discount rate. We have therefore discounted the annual stream of health benefits that reflect a 3-percent discount rate lag adjustment using a 2-percent discount rate to populate the PV, 2% and AV, 2% columns. The annual stream of $PM_{2.5}$-related health benefits that reflect a 3-percent and 7-percent discount rate lag adjustment were used to populate the PV/AV 3% and PV/AV 7% columns, respectively. See RIA Chapter 7.2 for more details on the annual stream of $PM_{2.5}$-related benefits associated with this rule.[e] Net benefits are the sum of benefits and operating savings minus vehicle costs.

We have also estimated the total transfers, or taxes, associated with the final standards, as shown in Table 8-10 and the alternative, as shown in Table 8-11. The transfers consist of the IRA battery tax credit, vehicle tax credit, EVSE tax credits, fuel, federal excise and state sales taxes, and annual vehicle registration fees on all ZEVs. None of these are included in the prior tables in this comparison of benefits and costs. Note that the transfers are presented from the perspective of purchasers, so positive values represent transfers to purchasers.

Table 8-10 Transfers Associated with the Final Rule, Millions of 2022 Dollars

	Battery Tax Credits	**Vehicle Tax Credits**	**EVSE Tax Credits**	**Fuel Taxes**	**Federal Excise Taxes**	**State Sales Taxes**	**State Registration Fees on ZEVs**	**Sum**
2055	$0	$0	$0	$3,400	-$11	$30	-$230	$3,200
PV, 2%	$1,400	$1,500	$950	$46,000	-$990	$280	-$2,500	$46,000
PV, 3%	$1,300	$1,400	$910	$38,000	-$890	$230	-$2,100	$39,000
PV, 7%	$1,100	$1,100	$770	$20,000	-$580	$110	-$1,000	$22,000
AV, 2%	$63	$67	$43	$2,100	-$45	$13	-$110	$2,100
AV, 3%	$69	$73	$47	$2,000	-$46	$12	-$110	$2,100
AV, 7%	$92	$93	$63	$1,600	-$47	$8.8	-$85	$1,800

Table 8-11 Transfers Associated with the Alternative, Millions of 2022 Dollars

	Battery Tax Credits	**Vehicle Tax Credits**	**EVSE Tax Credits**	**Fuel Taxes**	**Federal Excise Taxes**	**State Sales Taxes**	**State Registration Fees on ZEVs**	**Sum**
2055	$0	$0	$0	$990	-$9.8	-$2.8	-$46	$930
PV, 2%	$670	$700	$400	$16,000	-$510	-$120	-$660	$16,000
PV, 3%	$650	$670	$380	$13,000	-$450	-$99	-$560	$14,000
PV, 7%	$550	$550	$330	$7,100	-$290	-$56	-$300	$7,800
AV, 2%	$31	$32	$18	$710	-$23	-$5.3	-$30	$740
AV, 3%	$34	$35	$20	$680	-$24	-$5.2	-$29	$720
AV, 7%	$45	$45	$27	$570	-$24	-$4.6	-$25	$640

Chapter 9 Small Business Analysis

The Regulatory Flexibility Act, as amended by the Small Business Regulatory Enforcement Fairness Act of 1996 (SBREFA), generally requires an agency to prepare a regulatory flexibility analysis for any rule subject to notice-and-comment rulemaking requirements under the Administrative Procedure Act or any other statute. This requirement does not apply if the agency certifies that the rule will not have a significant economic impact on a substantial number of small entities. This chapter contains an overview of small entities in the heavy-duty vehicle and engine market and our assessment that the rule will not have a significant impact on a substantial number of small entities.

9.1 Definition of Small Businesses

Under the Regulatory Flexibility Act (5 USC 601 et seq.), a small entity is defined as: (1) a business that meets the definition for small business based on the Small Business Administration's (SBA) size standards; (2) a small governmental jurisdiction that is a government of a city, county, town, school district or special district with a population of less than 50,000; or (3) a small organization that is any not-for-profit enterprise which is independently owned and operated and is not dominant in its field.

This analysis considers only small business entities that are potentially affected by the final GHG emission standards. Small governmental jurisdictions and small not-for-profit organizations are not subject to the rule as they have no certification or compliance requirements. Note that while the proposed rule included changes to the locomotive preemption provision, that portion of the proposed rule was finalized in a separate action and is therefore not part of this RFA analysis.

9.2 Categories of Small Businesses Potentially Affected by the Rule

There are four broad categories of highway heavy-duty engine and vehicle entities that are potentially affected by the rule:

- Heavy-duty engine manufacturers
- Heavy-duty conventional vehicle manufacturers, including:
  - Manufacturers that make both the engine and the vehicle
  - Manufacturers that make a vehicle of its own design using an engine certified by another company
  - Manufacturers that finish an incomplete vehicle produced and certified by another company
- Heavy-duty electric vehicle manufacturers
- Alternative fuel engine converters

Table 9-1 provides an overview of the primary SBA small business categories for the industry sectors potentially affected by this rule, by NAICS category.

Table 9-1 Primary Small Business NAICS Categories Affected by this Rule[2081]

	NAICS Codes (2022)[2082]	**Defined by SBA (3/17/2023) as a small business if less than or equal to:**[2083]
Other Engine Equipment Manufacturing	333618	1,500 employees
Automobile and Light Duty Motor Vehicle Manufacturing	336110	1,500 employees
Heavy-Duty Truck Manufacturer, Conventional or Electric	336120	1,500 employees
Secondary manufacturer: Motor Vehicle Body Manufacturing	336211	1,000 employees
Secondary manufacturer: Motor home manufacturing	336213	1,250 employees
All Other Automotive Repair and Maintenance (alternative fuel engine converters)	811198	$10.0 million annual receipts

This regulatory flexibility analysis was performed using data on small entities assembled for EPA's Final Rule: Control of Air Pollution from New Motor Vehicles: Heavy-Duty Engine and Vehicle Standards, finalized in December 2022. Chapter 11 of the Regulatory Impact Assessment for that rule describes how EPA identified the small entities in each of the relevant NAICS categories and the results of applying that methodology.[2084] The following small entities were identified: 14 small entity heavy-duty vehicle manufacturers (one conventional vehicle manufacturer and 13 electric vehicle manufacturers; this was reduced to 9 in the following analysis because three did not meet the definition of small entity and one has not filed a production report with EPA and is therefore assumed to not be producing vehicles), 249 small entity secondary vehicle manufacturers, and 2 small entity alternative fuel engine converters.

[2081] According to SBA's regulations (13 CFR Part 121), businesses with no more than the listed number of employees or dollars in annual receipts are considered "small entities" for RFA purposes.

[2082] North American Industry Classification System, United States, 2022. Executive Office of the President, Office of Management and Budget. Downloaded 2/10/23. The official OMB publication is available at https://www.census.gov/naics/reference_files_tools/2022_NAICS_Manual.pdf.

[2083] U.S. Small Business Administration. Table of Small Business Size Standards Matched to North American Industry Classification System Codes. Effective March 17, 2023. Downloaded 12/12/23. The official SBA publication is available at https://www.sba.gov/document/support-table-size-standards; .pdf version at https://www.sba.gov/sites/default/files/2023-06/Table%20of%20Size%20Standards_Effective%20March%2017%2C%202023%20%282%29.pdf

[2084] See Chapter 11, Small Business Analysis, in Control of Air Pollution from New Motor Vehicles: Heavy-Duty Engine and Vehicle Standards Draft Regulatory Impact Analysis, EPA-420-D-22-001, March 2022, finalized December 2022, EPA-420-R-22-035.

9.3 Description of Small Businesses Potentially Affected by the Rule

This section provides a brief description of each of the four categories of manufacturers and the number of small entities potentially affected by the rule. The information about these companies presented below is consistent with the Regulatory Flexibility Analysis developed for our recently finalized HD 2027 rulemaking.[2085]

9.3.1 Heavy-Duty Engine Manufacturers

Heavy-duty engine manufacturers have been developing, testing, and certifying engines for many years in compliance with EPA rulemakings adopted under the CAA. The heavy-duty engine manufacturers that certify engines to EPA's program include no small entities based on the SBA definition for this category. This rule does not include new heavy-duty engine standards.

9.3.2 Heavy-Duty Conventional Vehicle Manufacturers

There are three types of companies that manufacture heavy-duty vehicles and that may be affected by the rule.

The first type of company manufactures both the engine and the associated vehicle. None of these companies are small entities based on the SBA definition for this category.

The second type of vehicle manufacturer produces a vehicle of its own design using a certified engine produced and certified by a different company. We identified one small entity engaged in the manufacture of conventional vehicles based on the SBA definition for this category and employment data from Hoovers D&B. This company is not subject to the new standards; instead, the company will continue to be subject to the previously promulgated standards. We assessed the regulatory burden of the program for this company by comparing its expected burden (a one-time cost of about $4,855 to review the regulations and make any needed changes to their general certification processes) to annual revenue obtained from Experian. According to this analysis, the small entity is expected to experience an impact of less than 1 percent of annual revenue.

The third type of vehicle manufacturer finishes an incomplete vehicle produced and certified by a different company; these so-called "secondary manufacturers" complete the vehicle by adding the truck body and other equipment. We identified 249 alternative fuel converters that are small businesses based on the SBA definition for this category and employment data from Hoovers D&B. Because the incomplete vehicle is already certified, these secondary vehicle manufacturers are not subject to the standards. Notes that any cost increases incurred by the primary manufacturer that are passed on to the secondary manufacturer through their delegated assembly agreement are included under the compliance costs of the main program, and are not part of this regulatory flexibility analysis.

[2085] See Chapter 11, Control of Air Pollution from New Motor Vehicles: Heavy-Duty Engine and Vehicle Standards Regulatory Impact Analysis (EPA-420-R-22-035 December 2022). https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P1016A9N.pdf.

9.3.3 Heavy-Duty Electric Vehicle Manufacturers

Heavy-duty electric vehicle manufacturers make both the engine and the associated vehicle. In 2021, 25 companies that make electric heavy-duty vehicles certified with EPA. We identified 9 small entities based on the SBA definition for this category and employment data from Hoovers D&B.

Qualifying small EV manufacturers are not subject to the new standards; instead, the company will continue to be subject to the previously promulgated standards (see Section II of the Preamble). However, small EV manufacturers will have to comply with a new regulation to provide a battery health monitor and make associated changes to vehicle owners manuals. We estimate compliance will impose a one-time cost of about $20,000 for each EV manufacturer, including small manufacturers[2086]. In addition, EV manufacturers will be subject to the warranty requirement at 40 CFR 1037.120. Because EV manufacturers already provide vehicle warranties and thus have the systems in place to implement the warranty requirements in their pricing, compliance costs will be limited to reporting their warranty periods on their certification application and updating owners manuals. We estimate compliance will impose a one-time cost of about $991 for each EV manufacturer, including small manufacturers.[2087] Finally, we estimate a one-time cost of about $4,855 for each manufacturer, including small EV manufacturers, to review the regulations and make any needed changes to their general certification processes.

We assessed the regulatory burden of the program for each of the 9 small EV manufacturers by comparing estimated compliance costs with annual revenue obtained from Hoovers or Experian for that company or its parent company if the affected company is a subsidiary of another company. According to this analysis, no small entity is expected to experience an impact greater than 3 percent of annual revenue. Eight of the 9 companies are expected to experience an impact of less than one percent and 1 is expected to experience an impact of 1 to 3 percent.

9.3.4 Alternative Fuel Engine Converters

Alternative fuel engine converters are also subject to heavy-duty highway engine standards. We identified two alternative fuel converters that are small businesses based on the SBA definition for this category and employment data from Hoovers D&B. We are not adopting new engine standards for this sector in this rule and there is no new burden for alternative fuel engine converters, including small entities, as a result of this rule.

9.4 Potential Impacts on Small Entities

EPA is certifying that the rule will not have a significant economic impact on a substantial number of small entities. Small entities are exempt from the revisions to EPA's HD Phase 2 GHG requirements for MY 2027 and the HD Phase 3 GHG program requirements for model years 2028 through 2032. While small entities will be required to comply with the new regulations regarding battery health monitors and make associated changes to their owners

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[2086] We estimate $15,100 in Operations and Maintenance costs and $4,378 in Labor costs. See the Supporting Statement for the draft Information Collection Request for this rule, in Docket EPA-HQ-OAR-2022-0985.

[2087] See the Supporting Statement for the draft Information Collection Request for this rule, in Docket EPA-HQ-OAR-2022-0985.

manuals, we estimate that these costs will exceed 3 percent of annual revenue for no small companies within the regulated industries. Given the results of this analysis, we have therefore concluded that this action will not have a significant economic impact on a substantial number of small entities. Table 9-2 summarizes the results.

Table 9-2 Summary of Small Entity Impacts

NAICS Category	**Sector description**	**SBA Threshold**	**Number of small companies subject to the rule**	**Impact as percent of annual revenue, number of small companies**		
				≥3%	1-3%	<1%
336120	Heavy-duty conventional vehicle manufacturer	1,500 employees	1			1
336120	Heavy-duty electric vehicle manufacturers	1,500 employees	9	0	1	8
Total			*10*	*0*	*1*	*9*

Appendix A – VMT for HD TRUCS

This Appendix A presents the VMT used in the final version of HD TRUCS for each of the first ten years of operation. The 10-year schedule for VMT in Table A-1, combined with the M&R cost per mile (by vehicle age), the cost of diesel and DEF per gallon (by calendar year), and the cost of insurance can be used to calculate the operating costs for each year of a 10-year schedule (see RIA Chapter 2).

Table A-1 VMT by Vehicle Age

Vehicle ID	Vehicle Age (years)									
	0	1	2	3	4	5	6	7	8	9
01V_Amb_Cl4-5_MP	8,480	8,444	8,448	8,508	8,091	7,612	7,072	6,579	6,158	5,863
02V_Amb_Cl2b-3_MP	12,353	12,300	12,305	12,392	11,786	11,088	10,301	9,583	8,969	8,540
03V_Amb_Cl4-5_U	9,769	9,728	9,731	9,801	9,321	8,769	8,147	7,579	7,094	6,754
04V_Amb_Cl2b-3_U	9,941	9,899	9,902	9,973	9,485	8,923	8,290	7,712	7,218	6,873
05T_Box_Cl8_MP	16,500	16,430	16,436	16,553	15,743	14,810	13,759	12,800	11,981	11,407
06T_Box_Cl8_R	16,500	16,430	16,436	16,553	15,610	14,543	13,360	12,267	11,305	10,565
07T_Box_Cl6-7_MP	9,961	9,918	9,922	9,993	9,504	8,941	8,306	7,727	7,233	6,886
08T_Box_Cl6-7_R	9,961	9,918	9,922	9,993	9,423	8,779	8,065	7,405	6,824	6,378
09T_Box_Cl8_U	16,500	16,430	16,436	16,553	15,743	14,810	13,759	12,800	11,981	11,407
10T_Box_Cl6-7_U	9,718	9,676	9,680	9,749	9,272	8,722	8,104	7,539	7,056	6,718
11T_Box_Cl2b-3_U	14,836	14,773	14,778	14,883	14,155	13,316	12,371	11,509	10,772	10,256
12T_Box_Cl2b-3_R	14,836	14,773	14,778	14,883	14,155	13,316	12,371	11,509	10,772	10,256
13T_Box_Cl2b-3_MP	14,836	14,773	14,778	14,883	14,155	13,316	12,371	11,509	10,772	10,256
14T_Box_Cl4-5_U	9,526	9,485	9,489	9,556	9,089	8,550	7,944	7,390	6,917	6,585
15T_Box_Cl4-5_R	9,526	9,485	9,489	9,556	9,089	8,550	7,944	7,390	6,917	6,585
16T_Box_Cl4-5_MP	9,526	9,485	9,489	9,556	9,089	8,550	7,944	7,390	6,917	6,585
17B_Coach_Cl8_R	39,506	38,247	37,040	35,834	34,679	33,578	32,528	31,479	30,482	29,485
18B_Coach_Cl8_MP	39,506	38,247	37,040	35,834	34,679	33,578	32,528	31,479	30,482	29,485
19C_Mix_Cl8_MP	22,339	22,244	22,252	22,410	21,314	20,051	18,628	17,329	16,220	15,443
20T_Dump_Cl8_U	10,000	9,958	9,961	10,032	9,541	8,976	8,339	7,758	7,261	6,913
21T_Dump_Cl8_MP	10,000	9,958	9,961	10,032	9,541	8,976	8,339	7,758	7,261	6,913
22T_Dump_Cl6-7_MP	14,044	13,984	13,989	14,089	13,399	12,606	11,711	10,895	10,197	9,709
23T_Dump_Cl8_U	10,000	9,958	9,961	10,032	9,541	8,976	8,339	7,758	7,261	6,913
24T_Dump_Cl6-7_U	14,044	13,984	13,989	14,089	13,399	12,606	11,711	10,895	10,197	9,709
25T_Fire_Cl8_MP	10,000	9,958	9,961	10,032	9,541	8,976	8,339	7,758	7,261	6,913
26T_Fire_Cl8_U	10,000	9,958	9,961	10,032	9,541	8,976	8,339	7,758	7,261	6,913
27T_Flat_Cl6-7_MP	9,961	9,918	9,922	9,993	9,504	8,941	8,306	7,727	7,233	6,886
28T_Flat_Cl6-7_R	9,961	9,918	9,922	9,993	9,504	8,941	8,306	7,727	7,233	6,886
29T_Flat_Cl6-7_U	9,961	9,918	9,922	9,993	9,504	8,941	8,306	7,727	7,233	6,886
30Tractor_DC_Cl8	24,250	24,250	24,250	24,250	22,630	21,010	19,389	17,769	16,149	14,528
31Tractor_DC_Cl7	24,256	24,256	24,256	24,256	22,635	21,014	19,394	17,773	16,152	14,532
32Tractor_SC_Cl8	105,000	105,000	105,000	105,000	99,463	93,926	88,389	82,853	77,316	71,779
33Tractor_DC_Cl8	53,925	53,925	53,925	53,925	50,322	46,719	43,116	39,513	35,910	32,307
34T_Ref_Cl8_MP	12,995	12,995	12,995	12,995	12,414	11,834	11,253	10,672	10,091	9,510
35T_Ref_Cl6-7_MP	23,400	23,400	23,400	23,400	22,354	21,308	20,262	19,216	18,170	17,124
36T_Ref_Cl8_U	12,995	12,995	12,995	12,995	12,414	11,834	11,253	10,672	10,091	9,510
37T_Ref_Cl6-7_U	23,400	23,400	23,400	23,400	22,354	21,308	20,262	19,216	18,170	17,124
38RV_Cl8_R	2,680	2,673	2,676	2,693	2,678	2,649	2,595	2,557	2,541	2,499
39RV_Cl6-7_R	2,680	2,673	2,676	2,693	2,678	2,649	2,595	2,557	2,541	2,499

Vehicle ID	Vehicle Age (years)									
	0	1	2	3	4	5	6	7	8	9
40RV_Cl4-5_R	2,680	2,673	2,676	2,693	2,678	2,649	2,595	2,557	2,541	2,499
41Tractor_DC_Cl7	53,914	53,914	53,914	53,914	50,312	46,710	43,107	39,505	35,902	32,300
42RV_Cl8_MP	2,680	2,673	2,676	2,693	2,678	2,649	2,595	2,557	2,541	2,499
43RV_Cl6-7_MP	2,680	2,673	2,676	2,693	2,678	2,649	2,595	2,557	2,541	2,499
44RV_Cl4-5_MP	2,680	2,673	2,676	2,693	2,678	2,649	2,595	2,557	2,541	2,499
45Tractor_DC_Cl8	53,914	53,914	53,914	53,914	50,312	46,710	43,107	39,505	35,902	32,300
46B_School_Cl8_MP	12,000	11,617	11,251	10,884	10,534	10,199	9,880	9,562	9,259	8,956
47B_School_Cl6-7_MP	12,777	12,369	11,979	11,589	11,216	10,859	10,520	10,181	9,858	9,536
48B_School_Cl4-5_MP	12,000	11,617	11,251	10,884	10,534	10,199	9,880	9,562	9,259	8,956
49B_School_Cl2b-3_MP	12,000	11,617	11,251	10,884	10,534	10,199	9,880	9,562	9,259	8,956
50B_School_Cl8_U	12,000	11,617	11,251	10,884	10,534	10,199	9,880	9,562	9,259	8,956
51B_School_Cl6-7_U	12,777	12,369	11,979	11,589	11,216	10,859	10,520	10,181	9,858	9,536
52B_School_Cl4-5_U	12,000	11,617	11,251	10,884	10,534	10,199	9,880	9,562	9,259	8,956
53B_School_Cl2b-3_U	12,000	11,617	11,251	10,884	10,534	10,199	9,880	9,562	9,259	8,956
54Tractor_SC_Cl8	105,000	105,000	105,000	105,000	99,463	93,926	88,389	82,853	77,316	71,779
55B_Shuttle_Cl2b-3_MP	29,429	28,491	27,592	26,693	25,833	25,013	24,231	23,449	22,707	21,964
56B_Shuttle_Cl4-5_U	29,429	28,491	27,592	26,693	25,833	25,013	24,231	23,449	22,707	21,964
57B_Shuttle_Cl2b-3_U	29,429	28,491	27,592	26,693	25,833	25,013	24,231	23,449	22,707	21,964
58B_Shuttle_Cl6-7_MP	29,429	28,491	27,592	26,693	25,833	25,013	24,231	23,449	22,707	21,964
59B_Shuttle_Cl6-7_U	29,429	28,491	27,592	26,693	25,833	25,013	24,231	23,449	22,707	21,964
60S_Plow_Cl6-7_MP	9,963	9,921	9,924	9,995	9,506	8,943	8,308	7,729	7,234	6,888
61S_Plow_Cl8_MP	11,060	11,013	11,017	11,096	10,553	9,928	9,223	8,580	8,031	7,646
62S_Plow_Cl6-7_U	9,963	9,921	9,924	9,995	9,506	8,943	8,308	7,729	7,234	6,888
63S_Plow_Cl8_U	11,060	11,013	11,017	11,096	10,553	9,928	9,223	8,580	8,031	7,646
64V_Step_Cl6-7_MP	15,224	15,159	15,165	15,273	14,525	13,665	12,695	11,810	11,054	10,525
65V_Step_Cl4-5_MP	9,526	9,485	9,489	9,556	9,089	8,550	7,944	7,390	6,917	6,585
66V_Step_Cl2b-3_MP	14,836	14,773	14,778	14,883	14,035	13,076	12,012	11,029	10,164	9,499
67V_Step_Cl6-7_U	15,224	15,159	15,165	15,273	14,525	13,665	12,695	11,810	11,054	10,525
68V_Step_Cl4-5_U	9,526	9,485	9,489	9,556	9,089	8,550	7,944	7,390	6,917	6,585
69V_Step_Cl2b-3_U	14,836	14,773	14,778	14,883	14,035	13,076	12,012	11,029	10,164	9,499
70S_Sweep_Cl6-7_U	12,600	12,547	12,551	12,640	12,022	11,310	10,507	9,775	9,149	8,711
71T_Tanker_Cl8_R	12,900	12,845	12,850	12,941	12,308	11,579	10,757	10,007	9,367	8,918
72T_Tanker_Cl8_MP	12,900	12,845	12,850	12,941	12,308	11,579	10,757	10,007	9,367	8,918
73T_Tanker_Cl8_U	12,900	12,845	12,850	12,941	12,308	11,579	10,757	10,007	9,367	8,918
74T_Tow_Cl8_R	16,100	16,032	16,038	16,152	15,361	14,451	13,426	12,490	11,690	11,131
75T_Tow_Cl6-7_R	14,020	13,960	13,966	14,065	13,377	12,584	11,691	10,876	10,180	9,692
76T_Tow_Cl8_U	16,100	16,032	16,038	16,152	15,361	14,451	13,426	12,490	11,690	11,131
77T_Tow_Cl6-7_U	14,020	13,960	13,966	14,065	13,377	12,584	11,691	10,876	10,180	9,692
78Tractor_SC_Cl8	75,000	75,000	75,000	75,000	71,045	67,090	63,135	59,181	55,226	51,271
79Tractor_SC_Cl8	105,000	105,000	105,000	105,000	99,463	93,926	88,389	82,853	77,316	71,779
80Tractor_DC_Cl8	26,500	26,388	26,397	26,585	25,284	23,786	22,098	20,558	19,242	18,320
81Tractor_DC_Cl7	53,914	53,914	53,914	53,914	50,312	46,710	43,107	39,505	35,902	32,300
82Tractor_DC_Cl8	53,914	53,914	53,914	53,914	50,312	46,710	43,107	39,505	35,902	32,300
83Tractor_DC_Cl7	30,080	30,080	30,080	30,080	28,070	26,060	24,050	22,041	20,031	18,021
84Tractor_DC_Cl8	30,000	30,000	30,000	30,000	27,996	25,991	23,987	21,982	19,978	17,973
85B_Transit_Cl8_MP	33,928	32,847	31,810	30,774	29,783	28,837	27,935	27,034	26,178	25,322
86B_Transit_Cl6-7_MP	20,022	19,384	18,773	18,161	17,576	17,018	16,486	15,954	15,449	14,944
87B_Transit_Cl8_U	33,928	32,847	31,810	30,774	29,783	28,837	27,935	27,034	26,178	25,322
88B_Transit_Cl6-7_U	20,022	19,384	18,773	18,161	17,576	17,018	16,486	15,954	15,449	14,944
89T_Utility_Cl8_MP	6,673	6,644	6,647	6,694	6,366	5,989	5,564	5,176	4,845	4,613
90T_Utility_Cl8_R	6,673	6,644	6,647	6,694	6,366	5,989	5,564	5,176	4,845	4,613

Vehicle ID	**Vehicle Age (years)**									
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
91T_Utility_Cl6-7_MP	12,300	12,248	12,252	12,340	11,736	11,040	10,257	9,542	8,931	8,503
92T_Utility_Cl6-7_R	12,300	12,248	12,252	12,340	11,736	11,040	10,257	9,542	8,931	8,503
93T_Utility_Cl4-5_MP	12,300	12,248	12,252	12,340	11,736	11,040	10,257	9,542	8,931	8,503
94T_Utility_Cl2b-3_MP	5,629	5,605	5,607	5,647	5,370	5,052	4,694	4,366	4,087	3,891
95T_Utility_Cl4-5_R	12,300	12,248	12,252	12,340	11,636	10,841	9,959	9,144	8,427	7,875
96T_Utility_Cl2b-3_R	12,300	12,248	12,252	12,340	11,636	10,841	9,959	9,144	8,427	7,875
97T_Utility_Cl8_U	6,673	6,644	6,647	6,694	6,366	5,989	5,564	5,176	4,845	4,613
98T_Utility_Cl6-7_U	12,300	12,248	12,252	12,340	11,736	11,040	10,257	9,542	8,931	8,503
99T_Utility_Cl4-5_U	12,300	12,248	12,252	12,340	11,736	11,040	10,257	9,542	8,931	8,503
100T_Utility_Cl2b-3_U	5,629	5,605	5,607	5,647	5,370	5,052	4,694	4,366	4,087	3,891
101Tractor_DC_Cl8	15,095	15,096	15,095	15,095	14,087	13,078	12,070	11,061	10,052	9,044

Appendix B – Additional MOVES Adoption Rates

This Appendix B contains tables showing HD BEV and FCEV adoption rates in the reference case, final standards case (reflecting the technology package for the modeled compliance pathway), and alternative case (reflecting a different technology package). The ZEV adoption rates shown elsewhere in this RIA chapter and in preamble Sections V and IX are the sum of the BEV and FCEV adoption rates. We calculated the BEV and FCEV adoption rates based on our technology assessment using HD TRUCS as described in RIA Chapter 2 and preamble Section II.

All ZEVs are modeled as BEVs except for some day cab tractors (MOVES source type 61), sleeper cab tractors (MOVES source type 62), and coach buses (MOVES source type 41 and regulatory class 47) which have a mix of BEV and FCEV adoption. All ZEVs are modeled as BEVs for MY 2029 and earlier. For the tractors in the reference case, we calculated ZEV adoption rates as described in Chapter 4.3.1 and apportioned them to BEVs and FCEVs in MY 2030 and beyond using the mix of BEV and FCEV technology by MOVES source type and regulatory class from HD TRUCS for MY 2032 as shown in RIA Chapter 2. These are shown in Table B-1 below. For coach buses, any increase to the ZEV adoption rate above the MY 2029 level is apportioned to FCEVs, with the MY 2029 BEV adoption rate held constant in MY 2029 and beyond. We note that ZEV adoption rates for coach buses are constant across the reference and control cases.

Table B-1 Proportion of tractor ZEVs that are BEVs and FCEVs for MY 2030 and beyond

Source type	**Regulatory class**	**Proportion of ZEVs that are BEVs for MY 2030 and beyond**	**Proportion of ZEVs that are FCEVs for MY 2030 and beyond**
61	46	0.748	0.252
61	47	0.962	0.038
62	46,[a] 47	0.632	0.368

[a] MOVES regulatory class 46 corresponds to Class 6-7. Sleeper cab tractors (source type 62) in this regulatory class are not modeled in HD TRUCS, but they do exist in MOVES, so we based all ZEV adoption rates for regulatory class 46 sleeper cab tractors on regulatory class 47 sleeper cab tractors.

The rest of the appendix presents the adoption tables of BEVs and FCEVs used in our modeling for the reference case, final standards, and alternative by MOVES source type, regulatory class, and model year. Appendix B.1 shows adoption rates in ACT states, Appendix B.2 shows the adoption rates in non-ACT states, Appendix B.3 shows national adoption rates, which are based on a sales-weighting of state-specific adoption rates, and Appendix B.4 shows the results of the HD ZEV adoption sensitivity analysis.

B.1 ZEV Sales Percentages in ACT States

Table B-2 ZEV sales percentages for Class 4-5 (regClassID 42) other buses (sourceTypeID 41) in ACT states

Model Year	BEV Sales Percentage			FCEV Sales Percentage		
	Reference	Final Standards	Alternative	Reference	Final Standards	Alternative
2027	25.6%	25.6%	25.6%	0%	0%	0%
2028	38.5%	38.5%	38.5%	0%	0%	0%
2029	51.2%	51.2%	51.2%	0%	0%	0%
2030	63.7%	63.7%	63.7%	0%	0%	0%
2031	69.8%	69.8%	69.8%	0%	0%	0%
2032	76.1%	76.1%	76.1%	0%	0%	0%
2033	82.4%	82.4%	82.4%	0%	0%	0%
2034	88.6%	88.6%	88.6%	0%	0%	0%
2035	94.8%	94.8%	94.8%	0%	0%	0%
2036	94.7%	94.7%	94.7%	0%	0%	0%
2037	94.6%	94.6%	94.6%	0%	0%	0%
2038	94.4%	94.4%	94.4%	0%	0%	0%
2039	94.2%	94.2%	94.2%	0%	0%	0%
2040	94.1%	94.1%	94.1%	0%	0%	0%
2041	94.0%	94.0%	94.0%	0%	0%	0%
2042	93.9%	93.9%	93.9%	0%	0%	0%
2043	93.8%	93.8%	93.8%	0%	0%	0%
2044	93.7%	93.7%	93.7%	0%	0%	0%
2045	93.4%	93.4%	93.4%	0%	0%	0%
2046	93.1%	93.1%	93.1%	0%	0%	0%
2047	93.0%	93.0%	93.0%	0%	0%	0%
2048	92.9%	92.9%	92.9%	0%	0%	0%
2049	92.7%	92.7%	92.7%	0%	0%	0%
2050	92.6%	92.6%	92.6%	0%	0%	0%
2051	92.4%	92.4%	92.4%	0%	0%	0%
2052	92.3%	92.3%	92.3%	0%	0%	0%
2053	92.2%	92.2%	92.2%	0%	0%	0%
2054	92.1%	92.1%	92.1%	0%	0%	0%
2055	91.9%	91.9%	91.9%	0%	0%	0%

Table B-3 ZEV sales percentages for Class 6-7 (regClassID 46) other buses (sourceTypeID 41) in ACT states

Model Year	BEV Sales Percentage			FCEV Sales Percentage		
	Reference	Final Standards	Alternative	Reference	Final Standards	Alternative
2027	19.2%	19.2%	19.2%	0%	0%	0%
2028	28.9%	28.9%	28.9%	0%	0%	0%
2029	38.4%	38.4%	38.4%	0%	0%	0%
2030	47.8%	47.8%	47.8%	0%	0%	0%
2031	52.4%	52.4%	52.4%	0%	0%	0%
2032	57.1%	57.1%	57.1%	0%	0%	0%
2033	61.8%	61.8%	61.8%	0%	0%	0%
2034	66.5%	66.5%	66.5%	0%	0%	0%
2035	71.1%	71.1%	71.1%	0%	0%	0%
2036	71.0%	71.0%	71.0%	0%	0%	0%
2037	70.9%	70.9%	70.9%	0%	0%	0%
2038	70.8%	70.8%	70.8%	0%	0%	0%
2039	70.7%	70.7%	70.7%	0%	0%	0%
2040	70.6%	70.6%	70.6%	0%	0%	0%
2041	70.5%	70.5%	70.5%	0%	0%	0%
2042	70.4%	70.4%	70.4%	0%	0%	0%
2043	70.4%	70.4%	70.4%	0%	0%	0%
2044	70.2%	70.2%	70.2%	0%	0%	0%
2045	70.0%	70.0%	70.0%	0%	0%	0%
2046	69.8%	69.8%	69.8%	0%	0%	0%
2047	69.7%	69.7%	69.7%	0%	0%	0%
2048	69.7%	69.7%	69.7%	0%	0%	0%
2049	69.6%	69.6%	69.6%	0%	0%	0%
2050	69.5%	69.5%	69.5%	0%	0%	0%
2051	69.3%	69.3%	69.3%	0%	0%	0%
2052	69.2%	69.2%	69.2%	0%	0%	0%
2053	69.1%	69.1%	69.1%	0%	0%	0%
2054	69.0%	69.0%	69.0%	0%	0%	0%
2055	69.0%	69.0%	69.0%	0%	0%	0%

Table B-4 ZEV sales percentages for Class 8 (regClassID 47) other buses (sourceTypeID 41) in ACT states

Model Year	BEV Sales Percentage			FCEV Sales Percentage		
	Reference	Final Standards	Alternative	Reference	Final Standards	Alternative
2027	12.8%	12.8%	12.8%	0.0%	0.0%	0.0%
2028	19.2%	19.2%	19.2%	0.0%	0.0%	0.0%
2029	25.6%	25.6%	25.6%	0.0%	0.0%	0.0%
2030	25.6%	25.6%	25.6%	6.3%	6.3%	6.3%
2031	25.6%	25.6%	25.6%	9.3%	9.3%	9.3%
2032	25.6%	25.6%	25.6%	12.5%	12.5%	12.5%
2033	25.6%	25.6%	25.6%	15.6%	15.6%	15.6%
2034	25.6%	25.6%	25.6%	18.7%	18.7%	18.7%
2035	25.6%	25.6%	25.6%	21.8%	21.8%	21.8%
2036	25.6%	25.6%	25.6%	21.8%	21.8%	21.8%
2037	25.6%	25.6%	25.6%	21.7%	21.7%	21.7%
2038	25.6%	25.6%	25.6%	21.6%	21.6%	21.6%
2039	25.6%	25.6%	25.6%	21.5%	21.5%	21.5%
2040	25.6%	25.6%	25.6%	21.5%	21.5%	21.5%
2041	25.6%	25.6%	25.6%	21.4%	21.4%	21.4%
2042	25.6%	25.6%	25.6%	21.4%	21.4%	21.4%
2043	25.6%	25.6%	25.6%	21.3%	21.3%	21.3%
2044	25.6%	25.6%	25.6%	21.2%	21.2%	21.2%
2045	25.6%	25.6%	25.6%	21.1%	21.1%	21.1%
2046	25.6%	25.6%	25.6%	21.0%	21.0%	21.0%
2047	25.6%	25.6%	25.6%	20.9%	20.9%	20.9%
2048	25.6%	25.6%	25.6%	20.9%	20.9%	20.9%
2049	25.6%	25.6%	25.6%	20.8%	20.8%	20.8%
2050	25.6%	25.6%	25.6%	20.7%	20.7%	20.7%
2051	25.6%	25.6%	25.6%	20.6%	20.6%	20.6%
2052	25.6%	25.6%	25.6%	20.6%	20.6%	20.6%
2053	25.6%	25.6%	25.6%	20.5%	20.5%	20.5%
2054	25.6%	25.6%	25.6%	20.4%	20.4%	20.4%
2055	25.6%	25.6%	25.6%	20.4%	20.4%	20.4%

Table B-5 ZEV sales percentages for Class 4-5 (regClassID 42) transit buses (sourceTypeID 42) in ACT states

Model Year	BEV Sales Percentage			FCEV Sales Percentage		
	Reference	Final Standards	Alternative	Reference	Final Standards	Alternative
2027	25.6%	25.6%	25.6%	0%	0%	0%
2028	38.5%	38.5%	38.5%	0%	0%	0%
2029	51.2%	51.2%	51.2%	0%	0%	0%
2030	63.7%	63.7%	63.7%	0%	0%	0%
2031	69.8%	69.8%	69.8%	0%	0%	0%
2032	76.1%	76.1%	76.1%	0%	0%	0%
2033	82.4%	82.4%	82.4%	0%	0%	0%
2034	88.6%	88.6%	88.6%	0%	0%	0%
2035	94.8%	94.8%	94.8%	0%	0%	0%
2036	94.7%	94.7%	94.7%	0%	0%	0%
2037	94.6%	94.6%	94.6%	0%	0%	0%
2038	94.4%	94.4%	94.4%	0%	0%	0%
2039	94.2%	94.2%	94.2%	0%	0%	0%
2040	94.1%	94.1%	94.1%	0%	0%	0%
2041	94.0%	94.0%	94.0%	0%	0%	0%
2042	93.9%	93.9%	93.9%	0%	0%	0%
2043	93.8%	93.8%	93.8%	0%	0%	0%
2044	93.7%	93.7%	93.7%	0%	0%	0%
2045	93.4%	93.4%	93.4%	0%	0%	0%
2046	93.1%	93.1%	93.1%	0%	0%	0%
2047	93.0%	93.0%	93.0%	0%	0%	0%
2048	92.9%	92.9%	92.9%	0%	0%	0%
2049	92.7%	92.7%	92.7%	0%	0%	0%
2050	92.6%	92.6%	92.6%	0%	0%	0%
2051	92.4%	92.4%	92.4%	0%	0%	0%
2052	92.3%	92.3%	92.3%	0%	0%	0%
2053	92.2%	92.2%	92.2%	0%	0%	0%
2054	92.1%	92.1%	92.1%	0%	0%	0%
2055	91.9%	91.9%	91.9%	0%	0%	0%

Table B-6 ZEV sales percentages for Class 6-7 (regClassID 46) transit buses (sourceTypeID 42) in ACT states

Model Year	BEV Sales Percentage			FCEV Sales Percentage		
	Reference	Final Standards	Alternative	Reference	Final Standards	Alternative
2027	19.2%	19.2%	19.2%	0%	0%	0%
2028	28.9%	28.9%	28.9%	0%	0%	0%
2029	38.4%	38.4%	38.4%	0%	0%	0%
2030	47.8%	47.8%	47.8%	0%	0%	0%
2031	52.4%	52.4%	52.4%	0%	0%	0%
2032	57.1%	57.1%	57.1%	0%	0%	0%
2033	61.8%	61.8%	61.8%	0%	0%	0%
2034	66.5%	66.5%	66.5%	0%	0%	0%
2035	71.1%	71.1%	71.1%	0%	0%	0%
2036	71.0%	71.0%	71.0%	0%	0%	0%
2037	70.9%	70.9%	70.9%	0%	0%	0%
2038	70.8%	70.8%	70.8%	0%	0%	0%
2039	70.7%	70.7%	70.7%	0%	0%	0%
2040	70.6%	70.6%	70.6%	0%	0%	0%
2041	70.5%	70.5%	70.5%	0%	0%	0%
2042	70.4%	70.4%	70.4%	0%	0%	0%
2043	70.4%	70.4%	70.4%	0%	0%	0%
2044	70.2%	70.2%	70.2%	0%	0%	0%
2045	70.0%	70.0%	70.0%	0%	0%	0%
2046	69.8%	69.8%	69.8%	0%	0%	0%
2047	69.7%	69.7%	69.7%	0%	0%	0%
2048	69.7%	69.7%	69.7%	0%	0%	0%
2049	69.6%	69.6%	69.6%	0%	0%	0%
2050	69.5%	69.5%	69.5%	0%	0%	0%
2051	69.3%	69.3%	69.3%	0%	0%	0%
2052	69.2%	69.2%	69.2%	0%	0%	0%
2053	69.1%	69.1%	69.1%	0%	0%	0%
2054	69.0%	69.0%	69.0%	0%	0%	0%
2055	69.0%	69.0%	69.0%	0%	0%	0%

Table B-7 ZEV sales percentages for urban buses (regClassID 48 and sourceTypeID 42) in ACT states

Model Year	BEV Sales Percentage			FCEV Sales Percentage		
	Reference	Final Standards	Alternative	Reference	Final Standards	Alternative
2027	12.8%	12.8%	12.8%	0%	0%	0%
2028	19.2%	19.2%	19.2%	0%	0%	0%
2029	25.6%	25.6%	25.6%	0%	0%	0%
2030	31.8%	31.8%	31.8%	0%	0%	0%
2031	34.9%	34.9%	34.9%	0%	0%	0%
2032	38.0%	39.0%	38.0%	0%	0%	0%
2033	41.2%	41.2%	41.2%	0%	0%	0%
2034	44.3%	44.3%	44.3%	0%	0%	0%
2035	47.4%	47.4%	47.4%	0%	0%	0%
2036	47.3%	47.3%	47.3%	0%	0%	0%
2037	47.3%	47.3%	47.3%	0%	0%	0%
2038	47.2%	47.2%	47.2%	0%	0%	0%
2039	47.1%	47.1%	47.1%	0%	0%	0%
2040	47.0%	47.0%	47.0%	0%	0%	0%
2041	47.0%	47.0%	47.0%	0%	0%	0%
2042	46.9%	46.9%	46.9%	0%	0%	0%
2043	46.9%	46.9%	46.9%	0%	0%	0%
2044	46.8%	46.8%	46.8%	0%	0%	0%
2045	46.7%	46.7%	46.7%	0%	0%	0%
2046	46.6%	46.6%	46.6%	0%	0%	0%
2047	46.5%	46.5%	46.5%	0%	0%	0%
2048	46.4%	46.4%	46.4%	0%	0%	0%
2049	46.4%	46.4%	46.4%	0%	0%	0%
2050	46.3%	46.3%	46.3%	0%	0%	0%
2051	46.2%	46.2%	46.2%	0%	0%	0%
2052	46.1%	46.1%	46.1%	0%	0%	0%
2053	46.1%	46.1%	46.1%	0%	0%	0%
2054	46.0%	46.0%	46.0%	0%	0%	0%
2055	46.0%	46.0%	46.0%	0%	0%	0%

Table B-8 ZEV sales percentages for Class 4-5 (regClassID 42) school buses (sourceTypeID 43) in ACT states

Model Year	BEV Sales Percentage			FCEV Sales Percentage		
	Reference	Final Standards	Alternative	Reference	Final Standards	Alternative
2027	25.6%	25.6%	25.6%	0%	0%	0%
2028	38.5%	38.5%	38.5%	0%	0%	0%
2029	51.2%	51.2%	51.2%	0%	0%	0%
2030	63.7%	63.7%	63.7%	0%	0%	0%
2031	69.8%	69.8%	69.8%	0%	0%	0%
2032	76.1%	76.1%	76.1%	0%	0%	0%
2033	82.4%	82.4%	82.4%	0%	0%	0%
2034	88.6%	88.6%	88.6%	0%	0%	0%
2035	94.8%	94.8%	94.8%	0%	0%	0%
2036	94.7%	94.7%	94.7%	0%	0%	0%
2037	94.6%	94.6%	94.6%	0%	0%	0%
2038	94.4%	94.4%	94.4%	0%	0%	0%
2039	94.2%	94.2%	94.2%	0%	0%	0%
2040	94.1%	94.1%	94.1%	0%	0%	0%
2041	94.0%	94.0%	94.0%	0%	0%	0%
2042	93.9%	93.9%	93.9%	0%	0%	0%
2043	93.8%	93.8%	93.8%	0%	0%	0%
2044	93.7%	93.7%	93.7%	0%	0%	0%
2045	93.4%	93.4%	93.4%	0%	0%	0%
2046	93.1%	93.1%	93.1%	0%	0%	0%
2047	93.0%	93.0%	93.0%	0%	0%	0%
2048	92.9%	92.9%	92.9%	0%	0%	0%
2049	92.7%	92.7%	92.7%	0%	0%	0%
2050	92.6%	92.6%	92.6%	0%	0%	0%
2051	92.4%	92.4%	92.4%	0%	0%	0%
2052	92.3%	92.3%	92.3%	0%	0%	0%
2053	92.2%	92.2%	92.2%	0%	0%	0%
2054	92.1%	92.1%	92.1%	0%	0%	0%
2055	91.9%	91.9%	91.9%	0%	0%	0%

Table B-9 ZEV sales percentages for Class 6-7 (regClassID 46) school buses (sourceTypeID 43) in ACT states

Model Year	BEV Sales Percentage			FCEV Sales Percentage		
	Reference	Final Standards	Alternative	Reference	Final Standards	Alternative
2027	19.2%	20.0%	19.2%	0%	0%	0%
2028	28.9%	28.9%	28.9%	0%	0%	0%
2029	38.4%	38.4%	38.4%	0%	0%	0%
2030	47.8%	47.8%	47.8%	0%	0%	0%
2031	52.4%	53.3%	52.4%	0%	0%	0%
2032	57.1%	70.0%	57.1%	0%	0%	0%
2033	61.8%	70.0%	61.8%	0%	0%	0%
2034	66.5%	70.0%	66.5%	0%	0%	0%
2035	71.1%	71.1%	71.1%	0%	0%	0%
2036	71.0%	71.0%	71.0%	0%	0%	0%
2037	70.9%	70.9%	70.9%	0%	0%	0%
2038	70.8%	70.8%	70.8%	0%	0%	0%
2039	70.7%	70.7%	70.7%	0%	0%	0%
2040	70.6%	70.6%	70.6%	0%	0%	0%
2041	70.5%	70.5%	70.5%	0%	0%	0%
2042	70.4%	70.4%	70.4%	0%	0%	0%
2043	70.4%	70.4%	70.4%	0%	0%	0%
2044	70.2%	70.2%	70.2%	0%	0%	0%
2045	70.0%	70.0%	70.0%	0%	0%	0%
2046	69.8%	70.0%	69.8%	0%	0%	0%
2047	69.7%	70.0%	69.7%	0%	0%	0%
2048	69.7%	70.0%	69.7%	0%	0%	0%
2049	69.6%	70.0%	69.6%	0%	0%	0%
2050	69.5%	70.0%	69.5%	0%	0%	0%
2051	69.3%	70.0%	69.3%	0%	0%	0%
2052	69.2%	70.0%	69.2%	0%	0%	0%
2053	69.1%	70.0%	69.1%	0%	0%	0%
2054	69.0%	70.0%	69.0%	0%	0%	0%
2055	69.0%	70.0%	69.0%	0%	0%	0%

Table B-10 ZEV sales percentages for Class 8 (regClassID 47) school buses (sourceTypeID 43) in ACT states

Model Year	BEV Sales Percentage			FCEV Sales Percentage		
	Reference	Final Standards	Alternative	Reference	Final Standards	Alternative
2027	12.8%	12.8%	12.8%	0%	0%	0%
2028	19.2%	19.2%	19.2%	0%	0%	0%
2029	25.6%	25.6%	25.6%	0%	0%	0%
2030	31.8%	31.8%	31.8%	0%	0%	0%
2031	34.9%	34.9%	34.9%	0%	0%	0%
2032	38.0%	39.0%	38.0%	0%	0%	0%
2033	41.2%	41.2%	41.2%	0%	0%	0%
2034	44.3%	44.3%	44.3%	0%	0%	0%
2035	47.4%	47.4%	47.4%	0%	0%	0%
2036	47.3%	47.3%	47.3%	0%	0%	0%
2037	47.3%	47.3%	47.3%	0%	0%	0%
2038	47.2%	47.2%	47.2%	0%	0%	0%
2039	47.1%	47.1%	47.1%	0%	0%	0%
2040	47.0%	47.0%	47.0%	0%	0%	0%
2041	47.0%	47.0%	47.0%	0%	0%	0%
2042	46.9%	46.9%	46.9%	0%	0%	0%
2043	46.9%	46.9%	46.9%	0%	0%	0%
2044	46.8%	46.8%	46.8%	0%	0%	0%
2045	46.7%	46.7%	46.7%	0%	0%	0%
2046	46.6%	46.6%	46.6%	0%	0%	0%
2047	46.5%	46.5%	46.5%	0%	0%	0%
2048	46.4%	46.4%	46.4%	0%	0%	0%
2049	46.4%	46.4%	46.4%	0%	0%	0%
2050	46.3%	46.3%	46.3%	0%	0%	0%
2051	46.2%	46.2%	46.2%	0%	0%	0%
2052	46.1%	46.1%	46.1%	0%	0%	0%
2053	46.1%	46.1%	46.1%	0%	0%	0%
2054	46.0%	46.0%	46.0%	0%	0%	0%
2055	46.0%	46.0%	46.0%	0%	0%	0%

Table B-11 ZEV sales percentages for Class 6-7 (regClassID 46) refuse trucks (sourceTypeID 51) in ACT states

Model Year	BEV Sales Percentage			FCEV Sales Percentage		
	Reference	Final Standards	Alternative	Reference	Final Standards	Alternative
2027	19.2%	20.0%	19.2%	0%	0%	0%
2028	28.9%	28.9%	28.9%	0%	0%	0%
2029	38.4%	38.4%	38.4%	0%	0%	0%
2030	47.8%	47.8%	47.8%	0%	0%	0%
2031	52.4%	52.4%	52.4%	0%	0%	0%
2032	57.1%	57.1%	57.1%	0%	0%	0%
2033	61.8%	61.8%	61.8%	0%	0%	0%
2034	66.5%	66.5%	66.5%	0%	0%	0%
2035	71.1%	71.1%	71.1%	0%	0%	0%
2036	71.0%	71.0%	71.0%	0%	0%	0%
2037	70.9%	70.9%	70.9%	0%	0%	0%
2038	70.8%	70.8%	70.8%	0%	0%	0%
2039	70.7%	70.7%	70.7%	0%	0%	0%
2040	70.6%	70.6%	70.6%	0%	0%	0%
2041	70.5%	70.5%	70.5%	0%	0%	0%
2042	70.4%	70.4%	70.4%	0%	0%	0%
2043	70.4%	70.4%	70.4%	0%	0%	0%
2044	70.2%	70.2%	70.2%	0%	0%	0%
2045	70.0%	70.0%	70.0%	0%	0%	0%
2046	69.8%	69.8%	69.8%	0%	0%	0%
2047	69.7%	69.7%	69.7%	0%	0%	0%
2048	69.7%	69.7%	69.7%	0%	0%	0%
2049	69.6%	69.6%	69.6%	0%	0%	0%
2050	69.5%	69.5%	69.5%	0%	0%	0%
2051	69.3%	69.3%	69.3%	0%	0%	0%
2052	69.2%	69.2%	69.2%	0%	0%	0%
2053	69.1%	69.1%	69.1%	0%	0%	0%
2054	69.0%	69.0%	69.0%	0%	0%	0%
2055	69.0%	69.0%	69.0%	0%	0%	0%

Table B-12 ZEV sales percentages for Class 8 (regClassID 47) refuse trucks (sourceTypeID 51) in ACT states

Model Year	BEV Sales Percentage			FCEV Sales Percentage		
	Reference	Final Standards	Alternative	Reference	Final Standards	Alternative
2027	12.8%	12.8%	12.8%	0%	0%	0%
2028	19.2%	19.2%	19.2%	0%	0%	0%
2029	25.6%	25.6%	25.6%	0%	0%	0%
2030	31.8%	31.8%	31.8%	0%	0%	0%
2031	34.9%	34.9%	34.9%	0%	0%	0%
2032	38.0%	39.0%	38.0%	0%	0%	0%
2033	41.2%	41.2%	41.2%	0%	0%	0%
2034	44.3%	44.3%	44.3%	0%	0%	0%
2035	47.4%	47.4%	47.4%	0%	0%	0%
2036	47.3%	47.3%	47.3%	0%	0%	0%
2037	47.3%	47.3%	47.3%	0%	0%	0%
2038	47.2%	47.2%	47.2%	0%	0%	0%
2039	47.1%	47.1%	47.1%	0%	0%	0%
2040	47.0%	47.0%	47.0%	0%	0%	0%
2041	47.0%	47.0%	47.0%	0%	0%	0%
2042	46.9%	46.9%	46.9%	0%	0%	0%
2043	46.9%	46.9%	46.9%	0%	0%	0%
2044	46.8%	46.8%	46.8%	0%	0%	0%
2045	46.7%	46.7%	46.7%	0%	0%	0%
2046	46.6%	46.6%	46.6%	0%	0%	0%
2047	46.5%	46.5%	46.5%	0%	0%	0%
2048	46.4%	46.4%	46.4%	0%	0%	0%
2049	46.4%	46.4%	46.4%	0%	0%	0%
2050	46.3%	46.3%	46.3%	0%	0%	0%
2051	46.2%	46.2%	46.2%	0%	0%	0%
2052	46.1%	46.1%	46.1%	0%	0%	0%
2053	46.1%	46.1%	46.1%	0%	0%	0%
2054	46.0%	46.0%	46.0%	0%	0%	0%
2055	46.0%	46.0%	46.0%	0%	0%	0%

Table B-13 ZEV sales percentages for Class 4-5 (regClassID 42) single-unit short-haul trucks (sourceTypeID 52) in ACT states

Model Year	BEV Sales Percentage			FCEV Sales Percentage		
	Reference	Final Standards	Alternative	Reference	Final Standards	Alternative
2027	25.6%	25.6%	25.6%	0%	0%	0%
2028	38.5%	38.5%	38.5%	0%	0%	0%
2029	51.2%	51.2%	51.2%	0%	0%	0%
2030	63.7%	63.7%	63.7%	0%	0%	0%
2031	69.8%	69.8%	69.8%	0%	0%	0%
2032	76.1%	76.1%	76.1%	0%	0%	0%
2033	82.4%	82.4%	82.4%	0%	0%	0%
2034	88.6%	88.6%	88.6%	0%	0%	0%
2035	94.8%	94.8%	94.8%	0%	0%	0%
2036	94.7%	94.7%	94.7%	0%	0%	0%
2037	94.6%	94.6%	94.6%	0%	0%	0%
2038	94.4%	94.4%	94.4%	0%	0%	0%
2039	94.2%	94.2%	94.2%	0%	0%	0%
2040	94.1%	94.1%	94.1%	0%	0%	0%
2041	94.0%	94.0%	94.0%	0%	0%	0%
2042	93.9%	93.9%	93.9%	0%	0%	0%
2043	93.8%	93.8%	93.8%	0%	0%	0%
2044	93.7%	93.7%	93.7%	0%	0%	0%
2045	93.4%	93.4%	93.4%	0%	0%	0%
2046	93.1%	93.1%	93.1%	0%	0%	0%
2047	93.0%	93.0%	93.0%	0%	0%	0%
2048	92.9%	92.9%	92.9%	0%	0%	0%
2049	92.7%	92.7%	92.7%	0%	0%	0%
2050	92.6%	92.6%	92.6%	0%	0%	0%
2051	92.4%	92.4%	92.4%	0%	0%	0%
2052	92.3%	92.3%	92.3%	0%	0%	0%
2053	92.2%	92.2%	92.2%	0%	0%	0%
2054	92.1%	92.1%	92.1%	0%	0%	0%
2055	91.9%	91.9%	91.9%	0%	0%	0%

Table B-14 ZEV sales percentages for Class 6-7 (regClassID 46) single-unit short-haul trucks (sourceTypeID 52) in ACT states

Model Year	BEV Sales Percentage			FCEV Sales Percentage		
	Reference	Final Standards	Alternative	Reference	Final Standards	Alternative
2027	19.2%	19.2%	19.2%	0%	0%	0%
2028	28.9%	28.9%	28.9%	0%	0%	0%
2029	38.4%	38.4%	38.4%	0%	0%	0%
2030	47.8%	47.8%	47.8%	0%	0%	0%
2031	52.4%	52.4%	52.4%	0%	0%	0%
2032	57.1%	57.1%	57.1%	0%	0%	0%
2033	61.8%	61.8%	61.8%	0%	0%	0%
2034	66.5%	66.5%	66.5%	0%	0%	0%
2035	71.1%	71.1%	71.1%	0%	0%	0%
2036	71.0%	71.0%	71.0%	0%	0%	0%
2037	70.9%	70.9%	70.9%	0%	0%	0%
2038	70.8%	70.8%	70.8%	0%	0%	0%
2039	70.7%	70.7%	70.7%	0%	0%	0%
2040	70.6%	70.6%	70.6%	0%	0%	0%
2041	70.5%	70.5%	70.5%	0%	0%	0%
2042	70.4%	70.4%	70.4%	0%	0%	0%
2043	70.4%	70.4%	70.4%	0%	0%	0%
2044	70.2%	70.2%	70.2%	0%	0%	0%
2045	70.0%	70.0%	70.0%	0%	0%	0%
2046	69.8%	69.8%	69.8%	0%	0%	0%
2047	69.7%	69.7%	69.7%	0%	0%	0%
2048	69.7%	69.7%	69.7%	0%	0%	0%
2049	69.6%	69.6%	69.6%	0%	0%	0%
2050	69.5%	69.5%	69.5%	0%	0%	0%
2051	69.3%	69.3%	69.3%	0%	0%	0%
2052	69.2%	69.2%	69.2%	0%	0%	0%
2053	69.1%	69.1%	69.1%	0%	0%	0%
2054	69.0%	69.0%	69.0%	0%	0%	0%
2055	69.0%	69.0%	69.0%	0%	0%	0%

Table B-15 ZEV sales percentages for Class 8 (regClassID 47) single-unit short-haul trucks (sourceTypeID 52) in ACT states

Model Year	BEV Sales Percentage			FCEV Sales Percentage		
	Reference	Final Standards	Alternative	Reference	Final Standards	Alternative
2027	12.8%	12.8%	12.8%	0%	0%	0%
2028	19.2%	19.2%	19.2%	0%	0%	0%
2029	25.6%	25.6%	25.6%	0%	0%	0%
2030	31.8%	31.8%	31.8%	0%	0%	0%
2031	34.9%	34.9%	34.9%	0%	0%	0%
2032	38.0%	38.0%	38.0%	0%	0%	0%
2033	41.2%	41.2%	41.2%	0%	0%	0%
2034	44.3%	44.3%	44.3%	0%	0%	0%
2035	47.4%	47.4%	47.4%	0%	0%	0%
2036	47.3%	47.3%	47.3%	0%	0%	0%
2037	47.3%	47.3%	47.3%	0%	0%	0%
2038	47.2%	47.2%	47.2%	0%	0%	0%
2039	47.1%	47.1%	47.1%	0%	0%	0%
2040	47.0%	47.0%	47.0%	0%	0%	0%
2041	47.0%	47.0%	47.0%	0%	0%	0%
2042	46.9%	46.9%	46.9%	0%	0%	0%
2043	46.9%	46.9%	46.9%	0%	0%	0%
2044	46.8%	46.8%	46.8%	0%	0%	0%
2045	46.7%	46.7%	46.7%	0%	0%	0%
2046	46.6%	46.6%	46.6%	0%	0%	0%
2047	46.5%	46.5%	46.5%	0%	0%	0%
2048	46.4%	46.4%	46.4%	0%	0%	0%
2049	46.4%	46.4%	46.4%	0%	0%	0%
2050	46.3%	46.3%	46.3%	0%	0%	0%
2051	46.2%	46.2%	46.2%	0%	0%	0%
2052	46.1%	46.1%	46.1%	0%	0%	0%
2053	46.1%	46.1%	46.1%	0%	0%	0%
2054	46.0%	46.0%	46.0%	0%	0%	0%
2055	46.0%	46.0%	46.0%	0%	0%	0%

Table B-16 ZEV sales percentages for Class 4-5 (regClassID 42) single-unit long-haul trucks (sourceTypeID 53) in ACT states

Model Year	BEV Sales Percentage			FCEV Sales Percentage		
	Reference	Final Standards	Alternative	Reference	Final Standards	Alternative
2027	25.6%	25.6%	25.6%	0%	0%	0%
2028	38.5%	38.5%	38.5%	0%	0%	0%
2029	51.2%	51.2%	51.2%	0%	0%	0%
2030	63.7%	63.7%	63.7%	0%	0%	0%
2031	69.8%	69.8%	69.8%	0%	0%	0%
2032	76.1%	76.1%	76.1%	0%	0%	0%
2033	82.4%	82.4%	82.4%	0%	0%	0%
2034	88.6%	88.6%	88.6%	0%	0%	0%
2035	94.8%	94.8%	94.8%	0%	0%	0%
2036	94.7%	94.7%	94.7%	0%	0%	0%
2037	94.6%	94.6%	94.6%	0%	0%	0%
2038	94.4%	94.4%	94.4%	0%	0%	0%
2039	94.2%	94.2%	94.2%	0%	0%	0%
2040	94.1%	94.1%	94.1%	0%	0%	0%
2041	94.0%	94.0%	94.0%	0%	0%	0%
2042	93.9%	93.9%	93.9%	0%	0%	0%
2043	93.8%	93.8%	93.8%	0%	0%	0%
2044	93.7%	93.7%	93.7%	0%	0%	0%
2045	93.4%	93.4%	93.4%	0%	0%	0%
2046	93.1%	93.1%	93.1%	0%	0%	0%
2047	93.0%	93.0%	93.0%	0%	0%	0%
2048	92.9%	92.9%	92.9%	0%	0%	0%
2049	92.7%	92.7%	92.7%	0%	0%	0%
2050	92.6%	92.6%	92.6%	0%	0%	0%
2051	92.4%	92.4%	92.4%	0%	0%	0%
2052	92.3%	92.3%	92.3%	0%	0%	0%
2053	92.2%	92.2%	92.2%	0%	0%	0%
2054	92.1%	92.1%	92.1%	0%	0%	0%
2055	91.9%	91.9%	91.9%	0%	0%	0%

Table B-17 ZEV sales percentages for Class 6-7 (regClassID 46) single-unit long-haul trucks (sourceTypeID 53) in ACT states

Model Year	BEV Sales Percentage			FCEV Sales Percentage		
	Reference	**Final Standards**	**Alternative**	**Reference**	**Final Standards**	**Alternative**
2027	19.2%	19.2%	19.2%	0%	0%	0%
2028	28.9%	28.9%	28.9%	0%	0%	0%
2029	38.4%	38.4%	38.4%	0%	0%	0%
2030	47.8%	47.8%	47.8%	0%	0%	0%
2031	52.4%	52.4%	52.4%	0%	0%	0%
2032	57.1%	57.1%	57.1%	0%	0%	0%
2033	61.8%	61.8%	61.8%	0%	0%	0%
2034	66.5%	66.5%	66.5%	0%	0%	0%
2035	71.1%	71.1%	71.1%	0%	0%	0%
2036	71.0%	71.0%	71.0%	0%	0%	0%
2037	70.9%	70.9%	70.9%	0%	0%	0%
2038	70.8%	70.8%	70.8%	0%	0%	0%
2039	70.7%	70.7%	70.7%	0%	0%	0%
2040	70.6%	70.6%	70.6%	0%	0%	0%
2041	70.5%	70.5%	70.5%	0%	0%	0%
2042	70.4%	70.4%	70.4%	0%	0%	0%
2043	70.4%	70.4%	70.4%	0%	0%	0%
2044	70.2%	70.2%	70.2%	0%	0%	0%
2045	70.0%	70.0%	70.0%	0%	0%	0%
2046	69.8%	69.8%	69.8%	0%	0%	0%
2047	69.7%	69.7%	69.7%	0%	0%	0%
2048	69.7%	69.7%	69.7%	0%	0%	0%
2049	69.6%	69.6%	69.6%	0%	0%	0%
2050	69.5%	69.5%	69.5%	0%	0%	0%
2051	69.3%	69.3%	69.3%	0%	0%	0%
2052	69.2%	69.2%	69.2%	0%	0%	0%
2053	69.1%	69.1%	69.1%	0%	0%	0%
2054	69.0%	69.0%	69.0%	0%	0%	0%
2055	69.0%	69.0%	69.0%	0%	0%	0%

Table B-18 ZEV sales percentages for Class 8 (regClassID 47) single-unit long-haul trucks (sourceTypeID 53) in ACT states

Model Year	BEV Sales Percentage			FCEV Sales Percentage		
	Reference	Final Standards	Alternative	Reference	Final Standards	Alternative
2027	12.8%	12.8%	12.8%	0%	0%	0%
2028	19.2%	19.2%	19.2%	0%	0%	0%
2029	25.6%	25.6%	25.6%	0%	0%	0%
2030	31.8%	31.8%	31.8%	0%	0%	0%
2031	34.9%	34.9%	34.9%	0%	0%	0%
2032	38.0%	39.0%	38.0%	0%	0%	0%
2033	41.2%	41.2%	41.2%	0%	0%	0%
2034	44.3%	44.3%	44.3%	0%	0%	0%
2035	47.4%	47.4%	47.4%	0%	0%	0%
2036	47.3%	47.3%	47.3%	0%	0%	0%
2037	47.3%	47.3%	47.3%	0%	0%	0%
2038	47.2%	47.2%	47.2%	0%	0%	0%
2039	47.1%	47.1%	47.1%	0%	0%	0%
2040	47.0%	47.0%	47.0%	0%	0%	0%
2041	47.0%	47.0%	47.0%	0%	0%	0%
2042	46.9%	46.9%	46.9%	0%	0%	0%
2043	46.9%	46.9%	46.9%	0%	0%	0%
2044	46.8%	46.8%	46.8%	0%	0%	0%
2045	46.7%	46.7%	46.7%	0%	0%	0%
2046	46.6%	46.6%	46.6%	0%	0%	0%
2047	46.5%	46.5%	46.5%	0%	0%	0%
2048	46.4%	46.4%	46.4%	0%	0%	0%
2049	46.4%	46.4%	46.4%	0%	0%	0%
2050	46.3%	46.3%	46.3%	0%	0%	0%
2051	46.2%	46.2%	46.2%	0%	0%	0%
2052	46.1%	46.1%	46.1%	0%	0%	0%
2053	46.1%	46.1%	46.1%	0%	0%	0%
2054	46.0%	46.0%	46.0%	0%	0%	0%
2055	46.0%	46.0%	46.0%	0%	0%	0%

Table B-19 ZEV sales percentages for Class 4-5 (regClassID 42) motor homes (sourceTypeID 54) in ACT states

Model Year	BEV Sales Percentage			FCEV Sales Percentage		
	Reference	Final Standards	Alternative	Reference	Final Standards	Alternative
2027	25.6%	25.6%	25.6%	0%	0%	0%
2028	38.5%	38.5%	38.5%	0%	0%	0%
2029	51.2%	51.2%	51.2%	0%	0%	0%
2030	63.7%	63.7%	63.7%	0%	0%	0%
2031	69.8%	69.8%	69.8%	0%	0%	0%
2032	76.1%	76.1%	76.1%	0%	0%	0%
2033	82.4%	82.4%	82.4%	0%	0%	0%
2034	88.6%	88.6%	88.6%	0%	0%	0%
2035	94.8%	94.8%	94.8%	0%	0%	0%
2036	94.7%	94.7%	94.7%	0%	0%	0%
2037	94.6%	94.6%	94.6%	0%	0%	0%
2038	94.4%	94.4%	94.4%	0%	0%	0%
2039	94.2%	94.2%	94.2%	0%	0%	0%
2040	94.1%	94.1%	94.1%	0%	0%	0%
2041	94.0%	94.0%	94.0%	0%	0%	0%
2042	93.9%	93.9%	93.9%	0%	0%	0%
2043	93.8%	93.8%	93.8%	0%	0%	0%
2044	93.7%	93.7%	93.7%	0%	0%	0%
2045	93.4%	93.4%	93.4%	0%	0%	0%
2046	93.1%	93.1%	93.1%	0%	0%	0%
2047	93.0%	93.0%	93.0%	0%	0%	0%
2048	92.9%	92.9%	92.9%	0%	0%	0%
2049	92.7%	92.7%	92.7%	0%	0%	0%
2050	92.6%	92.6%	92.6%	0%	0%	0%
2051	92.4%	92.4%	92.4%	0%	0%	0%
2052	92.3%	92.3%	92.3%	0%	0%	0%
2053	92.2%	92.2%	92.2%	0%	0%	0%
2054	92.1%	92.1%	92.1%	0%	0%	0%
2055	91.9%	91.9%	91.9%	0%	0%	0%

Table B-20 ZEV sales percentages for Class 6-7 (regClassID 46) motor homes (sourceTypeID 54) in ACT states

Model Year	BEV Sales Percentage			FCEV Sales Percentage		
	Reference	Final Standards	Alternative	Reference	Final Standards	Alternative
2027	19.2%	19.2%	19.2%	0%	0%	0%
2028	28.9%	28.9%	28.9%	0%	0%	0%
2029	38.4%	38.4%	38.4%	0%	0%	0%
2030	47.8%	47.8%	47.8%	0%	0%	0%
2031	52.4%	52.4%	52.4%	0%	0%	0%
2032	57.1%	57.1%	57.1%	0%	0%	0%
2033	61.8%	61.8%	61.8%	0%	0%	0%
2034	66.5%	66.5%	66.5%	0%	0%	0%
2035	71.1%	71.1%	71.1%	0%	0%	0%
2036	71.0%	71.0%	71.0%	0%	0%	0%
2037	70.9%	70.9%	70.9%	0%	0%	0%
2038	70.8%	70.8%	70.8%	0%	0%	0%
2039	70.7%	70.7%	70.7%	0%	0%	0%
2040	70.6%	70.6%	70.6%	0%	0%	0%
2041	70.5%	70.5%	70.5%	0%	0%	0%
2042	70.4%	70.4%	70.4%	0%	0%	0%
2043	70.4%	70.4%	70.4%	0%	0%	0%
2044	70.2%	70.2%	70.2%	0%	0%	0%
2045	70.0%	70.0%	70.0%	0%	0%	0%
2046	69.8%	69.8%	69.8%	0%	0%	0%
2047	69.7%	69.7%	69.7%	0%	0%	0%
2048	69.7%	69.7%	69.7%	0%	0%	0%
2049	69.6%	69.6%	69.6%	0%	0%	0%
2050	69.5%	69.5%	69.5%	0%	0%	0%
2051	69.3%	69.3%	69.3%	0%	0%	0%
2052	69.2%	69.2%	69.2%	0%	0%	0%
2053	69.1%	69.1%	69.1%	0%	0%	0%
2054	69.0%	69.0%	69.0%	0%	0%	0%
2055	69.0%	69.0%	69.0%	0%	0%	0%

Table B-21 ZEV sales percentages for Class 8 (regClassID 47) motor homes (sourceTypeID 54) in ACT states

Model Year	BEV Sales Percentage			FCEV Sales Percentage		
	Reference	Final Standards	Alternative	Reference	Final Standards	Alternative
2027	12.8%	12.8%	12.8%	0%	0%	0%
2028	19.2%	19.2%	19.2%	0%	0%	0%
2029	25.6%	25.6%	25.6%	0%	0%	0%
2030	31.8%	31.8%	31.8%	0%	0%	0%
2031	34.9%	34.9%	34.9%	0%	0%	0%
2032	38.0%	38.0%	38.0%	0%	0%	0%
2033	41.2%	41.2%	41.2%	0%	0%	0%
2034	44.3%	44.3%	44.3%	0%	0%	0%
2035	47.4%	47.4%	47.4%	0%	0%	0%
2036	47.3%	47.3%	47.3%	0%	0%	0%
2037	47.3%	47.3%	47.3%	0%	0%	0%
2038	47.2%	47.2%	47.2%	0%	0%	0%
2039	47.1%	47.1%	47.1%	0%	0%	0%
2040	47.0%	47.0%	47.0%	0%	0%	0%
2041	47.0%	47.0%	47.0%	0%	0%	0%
2042	46.9%	46.9%	46.9%	0%	0%	0%
2043	46.9%	46.9%	46.9%	0%	0%	0%
2044	46.8%	46.8%	46.8%	0%	0%	0%
2045	46.7%	46.7%	46.7%	0%	0%	0%
2046	46.6%	46.6%	46.6%	0%	0%	0%
2047	46.5%	46.5%	46.5%	0%	0%	0%
2048	46.4%	46.4%	46.4%	0%	0%	0%
2049	46.4%	46.4%	46.4%	0%	0%	0%
2050	46.3%	46.3%	46.3%	0%	0%	0%
2051	46.2%	46.2%	46.2%	0%	0%	0%
2052	46.1%	46.1%	46.1%	0%	0%	0%
2053	46.1%	46.1%	46.1%	0%	0%	0%
2054	46.0%	46.0%	46.0%	0%	0%	0%
2055	46.0%	46.0%	46.0%	0%	0%	0%

Table B-22 ZEV sales percentages for Class 6-7 (regClassID 46) single-unit short-haul trucks (sourceTypeID 61) in ACT states

Model Year	BEV Sales Percentage			FCEV Sales Percentage		
	Reference	Final Standards	Alternative	Reference	Final Standards	Alternative
2027	21.4%	21.4%	21.4%	0.0%	0.0%	0.0%
2028	27.9%	27.9%	27.9%	0.0%	0.0%	0.0%
2029	33.9%	33.9%	33.9%	0.0%	0.0%	0.0%
2030	29.8%	29.8%	29.8%	10.0%	10.0%	10.0%
2031	31.7%	31.7%	31.7%	10.7%	10.7%	10.7%
2032	35.4%	35.4%	35.4%	11.9%	11.9%	11.9%
2033	35.4%	35.4%	35.4%	11.9%	11.9%	11.9%
2034	35.4%	35.4%	35.4%	11.9%	11.9%	11.9%
2035	35.4%	35.4%	35.4%	11.9%	11.9%	11.9%
2036	35.4%	35.4%	35.4%	11.9%	11.9%	11.9%
2037	35.4%	35.4%	35.4%	11.9%	11.9%	11.9%
2038	35.4%	35.4%	35.4%	11.9%	11.9%	11.9%
2039	35.4%	35.4%	35.4%	11.9%	11.9%	11.9%
2040	35.4%	35.4%	35.4%	11.9%	11.9%	11.9%
2041	35.4%	35.4%	35.4%	11.9%	11.9%	11.9%
2042	35.4%	35.4%	35.4%	11.9%	11.9%	11.9%
2043	35.4%	35.4%	35.4%	11.9%	11.9%	11.9%
2044	35.4%	35.4%	35.4%	11.9%	11.9%	11.9%
2045	35.4%	35.4%	35.4%	11.9%	11.9%	11.9%
2046	35.4%	35.4%	35.4%	11.9%	11.9%	11.9%
2047	35.4%	35.4%	35.4%	11.9%	11.9%	11.9%
2048	35.4%	35.4%	35.4%	11.9%	11.9%	11.9%
2049	35.4%	35.4%	35.4%	11.9%	11.9%	11.9%
2050	35.4%	35.4%	35.4%	11.9%	11.9%	11.9%
2051	35.4%	35.4%	35.4%	11.9%	11.9%	11.9%
2052	35.4%	35.4%	35.4%	11.9%	11.9%	11.9%
2053	35.4%	35.4%	35.4%	11.9%	11.9%	11.9%
2054	35.4%	35.4%	35.4%	11.9%	11.9%	11.9%
2055	35.4%	35.4%	35.4%	11.9%	11.9%	11.9%

Table B-23 ZEV sales percentages for Class 8 (regClassID 47) single-unit short-haul trucks (sourceTypeID 61) in ACT states

Model Year	BEV Sales Percentage			FCEV Sales Percentage		
	Reference	Final Standards	Alternative	Reference	Final Standards	Alternative
2027	21.4%	21.4%	21.4%	0.0%	0.0%	0.0%
2028	27.9%	27.9%	27.9%	0.0%	0.0%	0.0%
2029	33.9%	33.9%	33.9%	0.0%	0.0%	0.0%
2030	38.3%	38.3%	38.3%	1.5%	1.5%	1.5%
2031	40.8%	40.8%	40.8%	1.6%	1.6%	1.6%
2032	45.6%	45.6%	45.6%	1.8%	1.8%	1.8%
2033	45.6%	45.6%	45.6%	1.8%	1.8%	1.8%
2034	45.6%	45.6%	45.6%	1.8%	1.8%	1.8%
2035	45.6%	45.6%	45.6%	1.8%	1.8%	1.8%
2036	45.5%	45.5%	45.5%	1.8%	1.8%	1.8%
2037	45.5%	45.5%	45.5%	1.8%	1.8%	1.8%
2038	45.5%	45.5%	45.5%	1.8%	1.8%	1.8%
2039	45.5%	45.5%	45.5%	1.8%	1.8%	1.8%
2040	45.5%	45.5%	45.5%	1.8%	1.8%	1.8%
2041	45.5%	45.5%	45.5%	1.8%	1.8%	1.8%
2042	45.5%	45.5%	45.5%	1.8%	1.8%	1.8%
2043	45.5%	45.5%	45.5%	1.8%	1.8%	1.8%
2044	45.5%	45.5%	45.5%	1.8%	1.8%	1.8%
2045	45.5%	45.5%	45.5%	1.8%	1.8%	1.8%
2046	45.5%	45.5%	45.5%	1.8%	1.8%	1.8%
2047	45.5%	45.5%	45.5%	1.8%	1.8%	1.8%
2048	45.5%	45.5%	45.5%	1.8%	1.8%	1.8%
2049	45.5%	45.5%	45.5%	1.8%	1.8%	1.8%
2050	45.5%	45.5%	45.5%	1.8%	1.8%	1.8%
2051	45.5%	45.5%	45.5%	1.8%	1.8%	1.8%
2052	45.5%	45.5%	45.5%	1.8%	1.8%	1.8%
2053	45.5%	45.5%	45.5%	1.8%	1.8%	1.8%
2054	45.5%	45.5%	45.5%	1.8%	1.8%	1.8%
2055	45.5%	45.5%	45.5%	1.8%	1.8%	1.8%

Table B-24 ZEV sales percentages for Class 6-7 (regClassID 46) single-unit long-haul trucks (sourceTypeID 62) in ACT states

Model Year	BEV Sales Percentage			FCEV Sales Percentage		
	Reference	Final Standards	Alternative	Reference	Final Standards	Alternative
2027	2.0%	2.0%	2.0%	0.0%	0.0%	0.0%
2028	4.0%	4.0%	4.0%	0.0%	0.0%	0.0%
2029	7.0%	7.0%	7.0%	0.0%	0.0%	0.0%
2030	6.3%	6.3%	6.3%	3.7%	3.7%	3.7%
2031	12.6%	12.6%	12.6%	7.4%	7.4%	7.4%
2032	15.8%	15.8%	15.8%	9.2%	9.2%	9.2%
2033	15.8%	15.8%	15.8%	9.2%	9.2%	9.2%
2034	15.8%	15.8%	15.8%	9.2%	9.2%	9.2%
2035	15.8%	15.8%	15.8%	9.2%	9.2%	9.2%
2036	15.8%	15.8%	15.8%	9.2%	9.2%	9.2%
2037	15.8%	15.8%	15.8%	9.2%	9.2%	9.2%
2038	15.8%	15.8%	15.8%	9.2%	9.2%	9.2%
2039	15.8%	15.8%	15.8%	9.2%	9.2%	9.2%
2040	15.8%	15.8%	15.8%	9.2%	9.2%	9.2%
2041	15.8%	15.8%	15.8%	9.2%	9.2%	9.2%
2042	15.8%	15.8%	15.8%	9.2%	9.2%	9.2%
2043	15.8%	15.8%	15.8%	9.2%	9.2%	9.2%
2044	15.8%	15.8%	15.8%	9.2%	9.2%	9.2%
2045	15.8%	15.8%	15.8%	9.2%	9.2%	9.2%
2046	15.8%	15.8%	15.8%	9.2%	9.2%	9.2%
2047	15.8%	15.8%	15.8%	9.2%	9.2%	9.2%
2048	15.8%	15.8%	15.8%	9.2%	9.2%	9.2%
2049	15.8%	15.8%	15.8%	9.2%	9.2%	9.2%
2050	15.8%	15.8%	15.8%	9.2%	9.2%	9.2%
2051	15.8%	15.8%	15.8%	9.2%	9.2%	9.2%
2052	15.8%	15.8%	15.8%	9.2%	9.2%	9.2%
2053	15.8%	15.8%	15.8%	9.2%	9.2%	9.2%
2054	15.8%	15.8%	15.8%	9.2%	9.2%	9.2%
2055	15.8%	15.8%	15.8%	9.2%	9.2%	9.2%

Table B-25 ZEV sales percentages for Class 8 (regClassID 47) single-unit long-haul trucks (sourceTypeID 62) in ACT states

Model Year	BEV Sales Percentage			FCEV Sales Percentage		
	Reference	Final Standards	Alternative	Reference	Final Standards	Alternative
2027	2.0%	2.0%	2.0%	0.0%	0.0%	0.0%
2028	4.0%	4.0%	4.0%	0.0%	0.0%	0.0%
2029	7.0%	7.0%	7.0%	0.0%	0.0%	0.0%
2030	6.3%	6.3%	6.3%	3.7%	3.7%	3.7%
2031	12.6%	12.6%	12.6%	7.4%	7.4%	7.4%
2032	15.8%	15.8%	15.8%	9.2%	9.2%	9.2%
2033	15.8%	15.8%	15.8%	9.2%	9.2%	9.2%
2034	15.8%	15.8%	15.8%	9.2%	9.2%	9.2%
2035	15.8%	15.8%	15.8%	9.2%	9.2%	9.2%
2036	15.8%	15.8%	15.8%	9.2%	9.2%	9.2%
2037	15.8%	15.8%	15.8%	9.2%	9.2%	9.2%
2038	15.8%	15.8%	15.8%	9.2%	9.2%	9.2%
2039	15.8%	15.8%	15.8%	9.2%	9.2%	9.2%
2040	15.8%	15.8%	15.8%	9.2%	9.2%	9.2%
2041	15.8%	15.8%	15.8%	9.2%	9.2%	9.2%
2042	15.8%	15.8%	15.8%	9.2%	9.2%	9.2%
2043	15.8%	15.8%	15.8%	9.2%	9.2%	9.2%
2044	15.8%	15.8%	15.8%	9.2%	9.2%	9.2%
2045	15.8%	15.8%	15.8%	9.2%	9.2%	9.2%
2046	15.8%	15.8%	15.8%	9.2%	9.2%	9.2%
2047	15.8%	15.8%	15.8%	9.2%	9.2%	9.2%
2048	15.8%	15.8%	15.8%	9.2%	9.2%	9.2%
2049	15.8%	15.8%	15.8%	9.2%	9.2%	9.2%
2050	15.8%	15.8%	15.8%	9.2%	9.2%	9.2%
2051	15.8%	15.8%	15.8%	9.2%	9.2%	9.2%
2052	15.8%	15.8%	15.8%	9.2%	9.2%	9.2%
2053	15.8%	15.8%	15.8%	9.2%	9.2%	9.2%
2054	15.8%	15.8%	15.8%	9.2%	9.2%	9.2%
2055	15.8%	15.8%	15.8%	9.2%	9.2%	9.2%

B.2 ZEV Sales Percentages in non-ACT States

Table B-26 ZEV sales percentages for Class 4-5 (regClassID 42) other buses (sourceTypeID 41) in non-ACT states

Model Year	BEV Sales Percentage			FCEV Sales Percentage		
	Reference	Final Standards	Alternative	Reference	Final Standards	Alternative
2027	4.9%	16.1%	10.5%	0%	0%	0%
2028	7.4%	15.9%	10.4%	0%	0%	0%
2029	9.8%	15.9%	10.4%	0%	0%	0%
2030	12.2%	16.0%	12.2%	0%	0%	0%
2031	13.4%	38.1%	14.9%	0%	0%	0%
2032	14.6%	60.1%	19.4%	0%	0%	0%
2033	16.5%	55.7%	16.5%	0%	0%	0%
2034	18.6%	51.4%	18.6%	0%	0%	0%
2035	20.9%	47.0%	20.9%	0%	0%	0%
2036	21.8%	47.2%	21.8%	0%	0%	0%
2037	22.7%	47.3%	22.7%	0%	0%	0%
2038	23.6%	47.4%	23.6%	0%	0%	0%
2039	24.5%	47.5%	24.5%	0%	0%	0%
2040	25.4%	47.6%	25.4%	0%	0%	0%
2041	26.3%	47.6%	26.3%	0%	0%	0%
2042	27.2%	47.7%	27.2%	0%	0%	0%
2043	28.1%	47.8%	28.1%	0%	0%	0%
2044	29.0%	47.9%	29.0%	0%	0%	0%
2045	29.9%	48.1%	29.9%	0%	0%	0%
2046	30.7%	48.2%	30.7%	0%	0%	0%
2047	31.6%	48.4%	31.6%	0%	0%	0%
2048	32.5%	48.4%	32.5%	0%	0%	0%
2049	33.4%	48.5%	33.4%	0%	0%	0%
2050	34.3%	48.6%	34.3%	0%	0%	0%
2051	35.1%	48.7%	35.1%	0%	0%	0%
2052	36.0%	48.8%	36.0%	0%	0%	0%
2053	36.9%	48.9%	36.9%	0%	0%	0%
2054	37.7%	49.0%	37.7%	0%	0%	0%
2055	38.6%	49.1%	38.6%	0%	0%	0%

Table B-27 ZEV sales percentages for Class 6-7 (regClassID 46) other buses (sourceTypeID 41) in non-ACT states

Model Year	BEV Sales Percentage			FCEV Sales Percentage		
	Reference	Final Standards	Alternative	Reference	Final Standards	Alternative
2027	3.7%	12.6%	8.3%	0%	0%	0%
2028	5.5%	9.9%	6.4%	0%	0%	0%
2029	7.4%	7.4%	7.4%	0%	0%	0%
2030	9.2%	9.2%	9.2%	0%	0%	0%
2031	10.1%	10.1%	10.1%	0%	0%	0%
2032	11.0%	11.0%	11.0%	0%	0%	0%
2033	12.4%	12.4%	12.4%	0%	0%	0%
2034	14.0%	14.0%	14.0%	0%	0%	0%
2035	15.6%	15.6%	15.6%	0%	0%	0%
2036	16.3%	16.3%	16.3%	0%	0%	0%
2037	17.0%	17.0%	17.0%	0%	0%	0%
2038	17.7%	17.7%	17.7%	0%	0%	0%
2039	18.4%	18.4%	18.4%	0%	0%	0%
2040	19.1%	19.1%	19.1%	0%	0%	0%
2041	19.7%	19.7%	19.7%	0%	0%	0%
2042	20.4%	20.4%	20.4%	0%	0%	0%
2043	21.1%	21.1%	21.1%	0%	0%	0%
2044	21.8%	21.8%	21.8%	0%	0%	0%
2045	22.4%	22.4%	22.4%	0%	0%	0%
2046	23.0%	23.0%	23.0%	0%	0%	0%
2047	23.7%	23.7%	23.7%	0%	0%	0%
2048	24.4%	24.4%	24.4%	0%	0%	0%
2049	25.0%	25.0%	25.0%	0%	0%	0%
2050	25.7%	25.7%	25.7%	0%	0%	0%
2051	26.3%	26.3%	26.3%	0%	0%	0%
2052	27.0%	27.0%	27.0%	0%	0%	0%
2053	27.7%	27.7%	27.7%	0%	0%	0%
2054	28.3%	28.3%	28.3%	0%	0%	0%
2055	29.0%	29.0%	29.0%	0%	0%	0%

Table B-28 ZEV sales percentages for Class 8 (regClassID 47) other buses (sourceTypeID 41) in non-ACT states

Model Year	BEV Sales Percentage			FCEV Sales Percentage		
	Reference	Final Standards	Alternative	Reference	Final Standards	Alternative
2027	1.2%	1.2%	1.2%	0.0%	0.0%	0.0%
2028	1.8%	1.8%	1.8%	0.0%	0.0%	0.0%
2029	2.5%	2.5%	2.5%	0.0%	0.0%	0.0%
2030	2.5%	2.5%	2.5%	0.6%	0.6%	0.6%
2031	2.5%	2.5%	2.5%	0.9%	0.9%	0.9%
2032	2.5%	2.5%	2.5%	1.2%	1.2%	1.2%
2033	2.6%	2.6%	2.6%	1.6%	1.6%	1.6%
2034	2.7%	2.7%	2.7%	2.0%	2.0%	2.0%
2035	2.8%	2.8%	2.8%	2.4%	2.4%	2.4%
2036	2.9%	2.9%	2.9%	2.5%	2.5%	2.5%
2037	3.1%	3.1%	3.1%	2.6%	2.6%	2.6%
2038	3.2%	3.2%	3.2%	2.7%	2.7%	2.7%
2039	3.3%	3.3%	3.3%	2.8%	2.8%	2.8%
2040	3.5%	3.5%	3.5%	2.9%	2.9%	2.9%
2041	3.6%	3.6%	3.6%	3.0%	3.0%	3.0%
2042	3.7%	3.7%	3.7%	3.1%	3.1%	3.1%
2043	3.8%	3.8%	3.8%	3.2%	3.2%	3.2%
2044	4.0%	4.0%	4.0%	3.3%	3.3%	3.3%
2045	4.1%	4.1%	4.1%	3.4%	3.4%	3.4%
2046	4.2%	4.2%	4.2%	3.5%	3.5%	3.5%
2047	4.3%	4.3%	4.3%	3.6%	3.6%	3.6%
2048	4.5%	4.5%	4.5%	3.7%	3.7%	3.7%
2049	4.6%	4.6%	4.6%	3.7%	3.7%	3.7%
2050	4.7%	4.7%	4.7%	3.8%	3.8%	3.8%
2051	4.9%	4.9%	4.9%	3.9%	3.9%	3.9%
2052	5.0%	5.0%	5.0%	4.0%	4.0%	4.0%
2053	5.1%	5.1%	5.1%	4.1%	4.1%	4.1%
2054	5.2%	5.2%	5.2%	4.2%	4.2%	4.2%
2055	5.4%	5.4%	5.4%	4.3%	4.3%	4.3%

Table B-29 ZEV sales percentages for Class 4-5 (regClassID 42) transit buses (sourceTypeID 42) in non-ACT states

Model Year	BEV Sales Percentage			FCEV Sales Percentage		
	Reference	Final Standards	Alternative	Reference	Final Standards	Alternative
2027	4.9%	16.1%	10.5%	0%	0%	0%
2028	7.4%	15.9%	10.4%	0%	0%	0%
2029	9.8%	15.9%	10.4%	0%	0%	0%
2030	12.2%	16.0%	12.2%	0%	0%	0%
2031	13.4%	38.1%	14.9%	0%	0%	0%
2032	14.6%	60.1%	19.4%	0%	0%	0%
2033	16.5%	55.7%	16.5%	0%	0%	0%
2034	18.6%	51.4%	18.6%	0%	0%	0%
2035	20.9%	47.0%	20.9%	0%	0%	0%
2036	21.8%	47.2%	21.8%	0%	0%	0%
2037	22.7%	47.3%	22.7%	0%	0%	0%
2038	23.6%	47.4%	23.6%	0%	0%	0%
2039	24.5%	47.5%	24.5%	0%	0%	0%
2040	25.4%	47.6%	25.4%	0%	0%	0%
2041	26.3%	47.6%	26.3%	0%	0%	0%
2042	27.2%	47.7%	27.2%	0%	0%	0%
2043	28.1%	47.8%	28.1%	0%	0%	0%
2044	29.0%	47.9%	29.0%	0%	0%	0%
2045	29.9%	48.1%	29.9%	0%	0%	0%
2046	30.7%	48.2%	30.7%	0%	0%	0%
2047	31.6%	48.4%	31.6%	0%	0%	0%
2048	32.5%	48.4%	32.5%	0%	0%	0%
2049	33.4%	48.5%	33.4%	0%	0%	0%
2050	34.3%	48.6%	34.3%	0%	0%	0%
2051	35.1%	48.7%	35.1%	0%	0%	0%
2052	36.0%	48.8%	36.0%	0%	0%	0%
2053	36.9%	48.9%	36.9%	0%	0%	0%
2054	37.7%	49.0%	37.7%	0%	0%	0%
2055	38.6%	49.1%	38.6%	0%	0%	0%

Table B-30 ZEV sales percentages for Class 6-7 (regClassID 46) transit buses (sourceTypeID 42) in non-ACT states

Model Year	BEV Sales Percentage			FCEV Sales Percentage		
	Reference	Final Standards	Alternative	Reference	Final Standards	Alternative
2027	3.7%	7.5%	4.4%	0%	0%	0%
2028	5.5%	6.6%	5.5%	0%	0%	0%
2029	7.4%	7.4%	7.4%	0%	0%	0%
2030	9.2%	9.2%	9.2%	0%	0%	0%
2031	10.1%	10.1%	10.1%	0%	0%	0%
2032	11.0%	12.8%	11.0%	0%	0%	0%
2033	12.4%	12.4%	12.4%	0%	0%	0%
2034	14.0%	14.0%	14.0%	0%	0%	0%
2035	15.6%	15.6%	15.6%	0%	0%	0%
2036	16.3%	16.3%	16.3%	0%	0%	0%
2037	17.0%	17.0%	17.0%	0%	0%	0%
2038	17.7%	17.7%	17.7%	0%	0%	0%
2039	18.4%	18.4%	18.4%	0%	0%	0%
2040	19.1%	19.1%	19.1%	0%	0%	0%
2041	19.7%	19.7%	19.7%	0%	0%	0%
2042	20.4%	20.4%	20.4%	0%	0%	0%
2043	21.1%	21.1%	21.1%	0%	0%	0%
2044	21.8%	21.8%	21.8%	0%	0%	0%
2045	22.4%	22.4%	22.4%	0%	0%	0%
2046	23.0%	23.0%	23.0%	0%	0%	0%
2047	23.7%	23.7%	23.7%	0%	0%	0%
2048	24.4%	24.4%	24.4%	0%	0%	0%
2049	25.0%	25.0%	25.0%	0%	0%	0%
2050	25.7%	25.7%	25.7%	0%	0%	0%
2051	26.3%	26.3%	26.3%	0%	0%	0%
2052	27.0%	27.0%	27.0%	0%	0%	0%
2053	27.7%	27.7%	27.7%	0%	0%	0%
2054	28.3%	28.3%	28.3%	0%	0%	0%
2055	29.0%	29.0%	29.0%	0%	0%	0%

Table B-31 ZEV sales percentages for urban buses (regClassID 48 and sourceTypeID 42) in non-ACT states

Model Year	BEV Sales Percentage			FCEV Sales Percentage		
	Reference	Final Standards	Alternative	Reference	Final Standards	Alternative
2027	1.2%	1.2%	1.2%	0%	0%	0%
2028	1.8%	10.3%	3.0%	0%	0%	0%
2029	2.5%	11.2%	3.9%	0%	0%	0%
2030	3.1%	12.1%	4.9%	0%	0%	0%
2031	3.4%	25.9%	7.8%	0%	0%	0%
2032	3.7%	39.0%	10.8%	0%	0%	0%
2033	4.1%	37.5%	8.6%	0%	0%	0%
2034	4.7%	35.2%	6.4%	0%	0%	0%
2035	5.2%	33.1%	5.2%	0%	0%	0%
2036	5.4%	33.1%	5.4%	0%	0%	0%
2037	5.7%	33.2%	5.7%	0%	0%	0%
2038	5.9%	33.2%	5.9%	0%	0%	0%
2039	6.1%	33.3%	6.1%	0%	0%	0%
2040	6.4%	33.3%	6.4%	0%	0%	0%
2041	6.6%	33.4%	6.6%	0%	0%	0%
2042	6.8%	33.4%	6.8%	0%	0%	0%
2043	7.0%	33.4%	7.0%	0%	0%	0%
2044	7.3%	33.5%	7.3%	0%	0%	0%
2045	7.5%	33.6%	7.5%	0%	0%	0%
2046	7.7%	33.7%	7.7%	0%	0%	0%
2047	7.9%	33.7%	7.9%	0%	0%	0%
2048	8.1%	33.8%	8.1%	0%	0%	0%
2049	8.3%	33.8%	8.3%	0%	0%	0%
2050	8.6%	33.8%	8.6%	0%	0%	0%
2051	8.8%	33.9%	8.8%	0%	0%	0%
2052	9.0%	34.0%	9.0%	0%	0%	0%
2053	9.2%	34.0%	9.2%	0%	0%	0%
2054	9.4%	34.0%	9.4%	0%	0%	0%
2055	9.7%	34.1%	9.7%	0%	0%	0%

Table B-32 ZEV sales percentages for Class 4-5 (regClassID 42) school buses (sourceTypeID 43) in non-ACT states

Model Year	BEV Sales Percentage			FCEV Sales Percentage		
	Reference	Final Standards	Alternative	Reference	Final Standards	Alternative
2027	4.9%	17.3%	12.4%	0%	0%	0%
2028	7.4%	18.7%	13.9%	0%	0%	0%
2029	9.8%	20.3%	15.5%	0%	0%	0%
2030	12.2%	21.9%	17.1%	0%	0%	0%
2031	13.4%	42.0%	21.8%	0%	0%	0%
2032	14.6%	62.1%	26.4%	0%	0%	0%
2033	16.5%	59.0%	23.4%	0%	0%	0%
2034	18.6%	56.0%	20.3%	0%	0%	0%
2035	20.9%	53.0%	20.9%	0%	0%	0%
2036	21.8%	53.1%	21.8%	0%	0%	0%
2037	22.7%	53.1%	22.7%	0%	0%	0%
2038	23.6%	53.2%	23.6%	0%	0%	0%
2039	24.5%	53.3%	24.5%	0%	0%	0%
2040	25.4%	53.4%	25.4%	0%	0%	0%
2041	26.3%	53.4%	26.3%	0%	0%	0%
2042	27.2%	53.5%	27.2%	0%	0%	0%
2043	28.1%	53.5%	28.1%	0%	0%	0%
2044	29.0%	53.6%	29.0%	0%	0%	0%
2045	29.9%	53.7%	29.9%	0%	0%	0%
2046	30.7%	53.8%	30.7%	0%	0%	0%
2047	31.6%	53.9%	31.6%	0%	0%	0%
2048	32.5%	54.0%	32.5%	0%	0%	0%
2049	33.4%	54.0%	33.4%	0%	0%	0%
2050	34.3%	54.1%	34.3%	0%	0%	0%
2051	35.1%	54.2%	35.1%	0%	0%	0%
2052	36.0%	54.2%	36.0%	0%	0%	0%
2053	36.9%	54.3%	36.9%	0%	0%	0%
2054	37.7%	54.4%	37.7%	0%	0%	0%
2055	38.6%	54.4%	38.6%	0%	0%	0%

Table B-33 ZEV sales percentages for Class 6-7 (regClassID 46) school buses (sourceTypeID 43) in non-ACT states

Model Year	BEV Sales Percentage			FCEV Sales Percentage		
	Reference	**Final Standards**	**Alternative**	**Reference**	**Final Standards**	**Alternative**
2027	3.7%	20.0%	14.3%	0%	0%	0%
2028	5.5%	24.8%	18.6%	0%	0%	0%
2029	7.4%	29.5%	23.1%	0%	0%	0%
2030	9.2%	34.1%	27.7%	0%	0%	0%
2031	10.1%	53.3%	34.3%	0%	0%	0%
2032	11.0%	70.0%	40.6%	0%	0%	0%
2033	12.4%	70.0%	39.5%	0%	0%	0%
2034	14.0%	70.0%	38.4%	0%	0%	0%
2035	15.6%	69.7%	37.4%	0%	0%	0%
2036	16.3%	69.8%	37.4%	0%	0%	0%
2037	17.0%	69.8%	37.4%	0%	0%	0%
2038	17.7%	69.8%	37.4%	0%	0%	0%
2039	18.4%	69.8%	37.5%	0%	0%	0%
2040	19.1%	69.9%	37.5%	0%	0%	0%
2041	19.7%	69.9%	37.5%	0%	0%	0%
2042	20.4%	69.9%	37.5%	0%	0%	0%
2043	21.1%	69.9%	37.5%	0%	0%	0%
2044	21.8%	69.9%	37.6%	0%	0%	0%
2045	22.4%	70.0%	37.6%	0%	0%	0%
2046	23.0%	70.0%	37.7%	0%	0%	0%
2047	23.7%	70.0%	37.7%	0%	0%	0%
2048	24.4%	70.0%	37.7%	0%	0%	0%
2049	25.0%	70.0%	37.7%	0%	0%	0%
2050	25.7%	70.0%	37.7%	0%	0%	0%
2051	26.3%	70.0%	37.8%	0%	0%	0%
2052	27.0%	70.0%	37.8%	0%	0%	0%
2053	27.7%	70.0%	37.8%	0%	0%	0%
2054	28.3%	70.0%	37.8%	0%	0%	0%
2055	29.0%	70.0%	37.9%	0%	0%	0%

Table B-34 ZEV sales percentages for Class 8 (regClassID 47) school buses (sourceTypeID 43) in non-ACT states

Model Year	BEV Sales Percentage			FCEV Sales Percentage		
	Reference	Final Standards	Alternative	Reference	Final Standards	Alternative
2027	1.2%	1.2%	1.2%	0%	0%	0%
2028	1.8%	15.7%	7.3%	0%	0%	0%
2029	2.5%	16.3%	8.5%	0%	0%	0%
2030	3.1%	16.9%	9.5%	0%	0%	0%
2031	3.4%	28.3%	10.7%	0%	0%	0%
2032	3.7%	39.0%	12.6%	0%	0%	0%
2033	4.1%	37.7%	10.7%	0%	0%	0%
2034	4.7%	35.8%	8.8%	0%	0%	0%
2035	5.2%	34.0%	7.0%	0%	0%	0%
2036	5.4%	34.0%	7.0%	0%	0%	0%
2037	5.7%	34.1%	7.1%	0%	0%	0%
2038	5.9%	34.1%	7.1%	0%	0%	0%
2039	6.1%	34.2%	7.2%	0%	0%	0%
2040	6.4%	34.2%	7.2%	0%	0%	0%
2041	6.6%	34.2%	7.2%	0%	0%	0%
2042	6.8%	34.3%	7.3%	0%	0%	0%
2043	7.0%	34.3%	7.3%	0%	0%	0%
2044	7.3%	34.4%	7.4%	0%	0%	0%
2045	7.5%	34.4%	7.5%	0%	0%	0%
2046	7.7%	34.5%	7.7%	0%	0%	0%
2047	7.9%	34.6%	7.9%	0%	0%	0%
2048	8.1%	34.6%	8.1%	0%	0%	0%
2049	8.3%	34.6%	8.3%	0%	0%	0%
2050	8.6%	34.7%	8.6%	0%	0%	0%
2051	8.8%	34.7%	8.8%	0%	0%	0%
2052	9.0%	34.8%	9.0%	0%	0%	0%
2053	9.2%	34.8%	9.2%	0%	0%	0%
2054	9.4%	34.8%	9.4%	0%	0%	0%
2055	9.7%	34.9%	9.7%	0%	0%	0%

Table B-35 ZEV sales percentages for Class 6-7 (regClassID 46) refuse trucks (sourceTypeID 51) in non-ACT states

Model Year	BEV Sales Percentage			FCEV Sales Percentage		
	Reference	Final Standards	Alternative	Reference	Final Standards	Alternative
2027	3.7%	20.0%	14.0%	0%	0%	0%
2028	5.5%	20.0%	14.4%	0%	0%	0%
2029	7.4%	19.9%	14.6%	0%	0%	0%
2030	9.2%	19.8%	14.8%	0%	0%	0%
2031	10.1%	26.6%	14.1%	0%	0%	0%
2032	11.0%	33.5%	14.3%	0%	0%	0%
2033	12.4%	32.0%	12.8%	0%	0%	0%
2034	14.0%	30.6%	14.0%	0%	0%	0%
2035	15.6%	29.2%	15.6%	0%	0%	0%
2036	16.3%	29.2%	16.3%	0%	0%	0%
2037	17.0%	29.2%	17.0%	0%	0%	0%
2038	17.7%	29.3%	17.7%	0%	0%	0%
2039	18.4%	29.3%	18.4%	0%	0%	0%
2040	19.1%	29.3%	19.1%	0%	0%	0%
2041	19.7%	29.4%	19.7%	0%	0%	0%
2042	20.4%	29.4%	20.4%	0%	0%	0%
2043	21.1%	29.4%	21.1%	0%	0%	0%
2044	21.8%	29.4%	21.8%	0%	0%	0%
2045	22.4%	29.5%	22.4%	0%	0%	0%
2046	23.0%	29.6%	23.0%	0%	0%	0%
2047	23.7%	29.6%	23.7%	0%	0%	0%
2048	24.4%	29.6%	24.4%	0%	0%	0%
2049	25.0%	29.6%	25.0%	0%	0%	0%
2050	25.7%	29.7%	25.7%	0%	0%	0%
2051	26.3%	29.7%	26.3%	0%	0%	0%
2052	27.0%	29.7%	27.0%	0%	0%	0%
2053	27.7%	29.8%	27.7%	0%	0%	0%
2054	28.3%	29.8%	28.3%	0%	0%	0%
2055	29.0%	29.8%	29.0%	0%	0%	0%

Table B-36 ZEV sales percentages for Class 8 (regClassID 47) refuse trucks (sourceTypeID 51) in non-ACT states

Model Year	BEV Sales Percentage			FCEV Sales Percentage		
	Reference	Final Standards	Alternative	Reference	Final Standards	Alternative
2027	1.2%	1.2%	1.2%	0%	0%	0%
2028	1.8%	12.7%	7.4%	0%	0%	0%
2029	2.5%	15.1%	9.8%	0%	0%	0%
2030	3.1%	17.4%	12.2%	0%	0%	0%
2031	3.4%	28.3%	15.1%	0%	0%	0%
2032	3.7%	39.0%	18.2%	0%	0%	0%
2033	4.1%	38.5%	17.4%	0%	0%	0%
2034	4.7%	37.7%	16.6%	0%	0%	0%
2035	5.2%	36.9%	15.9%	0%	0%	0%
2036	5.4%	37.0%	15.9%	0%	0%	0%
2037	5.7%	37.0%	15.9%	0%	0%	0%
2038	5.9%	37.0%	15.9%	0%	0%	0%
2039	6.1%	37.0%	15.9%	0%	0%	0%
2040	6.4%	37.0%	15.9%	0%	0%	0%
2041	6.6%	37.0%	16.0%	0%	0%	0%
2042	6.8%	37.1%	16.0%	0%	0%	0%
2043	7.0%	37.1%	16.0%	0%	0%	0%
2044	7.3%	37.1%	16.0%	0%	0%	0%
2045	7.5%	37.1%	16.0%	0%	0%	0%
2046	7.7%	37.2%	16.1%	0%	0%	0%
2047	7.9%	37.2%	16.1%	0%	0%	0%
2048	8.1%	37.2%	16.1%	0%	0%	0%
2049	8.3%	37.2%	16.1%	0%	0%	0%
2050	8.6%	37.2%	16.1%	0%	0%	0%
2051	8.8%	37.2%	16.2%	0%	0%	0%
2052	9.0%	37.3%	16.2%	0%	0%	0%
2053	9.2%	37.3%	16.2%	0%	0%	0%
2054	9.4%	37.3%	16.2%	0%	0%	0%
2055	9.7%	37.3%	16.2%	0%	0%	0%

Table B-37 ZEV sales percentages for Class 4-5 (regClassID 42) single-unit short-haul trucks (sourceTypeID 52) in non-ACT states

Model Year	BEV Sales Percentage			FCEV Sales Percentage		
	Reference	Final Standards	Alternative	Reference	Final Standards	Alternative
2027	4.9%	18.2%	13.9%	0%	0%	0%
2028	7.4%	21.0%	16.7%	0%	0%	0%
2029	9.8%	23.9%	19.6%	0%	0%	0%
2030	12.2%	26.7%	22.5%	0%	0%	0%
2031	13.4%	45.2%	27.3%	0%	0%	0%
2032	14.6%	63.7%	32.2%	0%	0%	0%
2033	16.5%	61.7%	30.2%	0%	0%	0%
2034	18.6%	59.8%	28.2%	0%	0%	0%
2035	20.9%	57.8%	26.3%	0%	0%	0%
2036	21.8%	57.9%	26.3%	0%	0%	0%
2037	22.7%	57.9%	26.4%	0%	0%	0%
2038	23.6%	58.0%	26.4%	0%	0%	0%
2039	24.5%	58.0%	26.5%	0%	0%	0%
2040	25.4%	58.1%	26.5%	0%	0%	0%
2041	26.3%	58.1%	26.5%	0%	0%	0%
2042	27.2%	58.1%	27.2%	0%	0%	0%
2043	28.1%	58.2%	28.1%	0%	0%	0%
2044	29.0%	58.2%	29.0%	0%	0%	0%
2045	29.9%	58.3%	29.9%	0%	0%	0%
2046	30.7%	58.4%	30.7%	0%	0%	0%
2047	31.6%	58.4%	31.6%	0%	0%	0%
2048	32.5%	58.4%	32.5%	0%	0%	0%
2049	33.4%	58.5%	33.4%	0%	0%	0%
2050	34.3%	58.5%	34.3%	0%	0%	0%
2051	35.1%	58.6%	35.1%	0%	0%	0%
2052	36.0%	58.6%	36.0%	0%	0%	0%
2053	36.9%	58.7%	36.9%	0%	0%	0%
2054	37.7%	58.7%	37.7%	0%	0%	0%
2055	38.6%	58.7%	38.6%	0%	0%	0%

Table B-38 ZEV sales percentages for Class 6-7 (regClassID 46) single-unit short-haul trucks (sourceTypeID 52) in non-ACT states

Model Year	BEV Sales Percentage			FCEV Sales Percentage		
	Reference	Final Standards	Alternative	Reference	Final Standards	Alternative
2027	3.7%	10.5%	6.8%	0%	0%	0%
2028	5.5%	11.1%	7.4%	0%	0%	0%
2029	7.4%	11.7%	8.1%	0%	0%	0%
2030	9.2%	12.4%	9.2%	0%	0%	0%
2031	10.1%	20.6%	10.5%	0%	0%	0%
2032	11.0%	28.7%	12.2%	0%	0%	0%
2033	12.4%	27.5%	12.4%	0%	0%	0%
2034	14.0%	26.2%	14.0%	0%	0%	0%
2035	15.6%	25.0%	15.6%	0%	0%	0%
2036	16.3%	25.0%	16.3%	0%	0%	0%
2037	17.0%	25.1%	17.0%	0%	0%	0%
2038	17.7%	25.1%	17.7%	0%	0%	0%
2039	18.4%	25.1%	18.4%	0%	0%	0%
2040	19.1%	25.2%	19.1%	0%	0%	0%
2041	19.7%	25.2%	19.7%	0%	0%	0%
2042	20.4%	25.2%	20.4%	0%	0%	0%
2043	21.1%	25.2%	21.1%	0%	0%	0%
2044	21.8%	25.2%	21.8%	0%	0%	0%
2045	22.4%	25.3%	22.4%	0%	0%	0%
2046	23.0%	25.3%	23.0%	0%	0%	0%
2047	23.7%	25.4%	23.7%	0%	0%	0%
2048	24.4%	25.4%	24.4%	0%	0%	0%
2049	25.0%	25.4%	25.0%	0%	0%	0%
2050	25.7%	25.7%	25.7%	0%	0%	0%
2051	26.3%	26.3%	26.3%	0%	0%	0%
2052	27.0%	27.0%	27.0%	0%	0%	0%
2053	27.7%	27.7%	27.7%	0%	0%	0%
2054	28.3%	28.3%	28.3%	0%	0%	0%
2055	29.0%	29.0%	29.0%	0%	0%	0%

Table B-39 ZEV sales percentages for Class 8 (regClassID 47) single-unit short-haul trucks (sourceTypeID 52) in non-ACT states

Model Year	BEV Sales Percentage			FCEV Sales Percentage		
	Reference	**Final Standards**	**Alternative**	**Reference**	**Final Standards**	**Alternative**
2027	1.2%	1.2%	1.2%	0%	0%	0%
2028	1.8%	5.9%	2.1%	0%	0%	0%
2029	2.5%	6.9%	3.0%	0%	0%	0%
2030	3.1%	7.9%	4.0%	0%	0%	0%
2031	3.4%	16.2%	6.2%	0%	0%	0%
2032	3.7%	24.4%	8.2%	0%	0%	0%
2033	4.1%	23.4%	7.2%	0%	0%	0%
2034	4.7%	22.3%	6.1%	0%	0%	0%
2035	5.2%	21.3%	5.2%	0%	0%	0%
2036	5.4%	21.3%	5.4%	0%	0%	0%
2037	5.7%	21.3%	5.7%	0%	0%	0%
2038	5.9%	21.4%	5.9%	0%	0%	0%
2039	6.1%	21.4%	6.1%	0%	0%	0%
2040	6.4%	21.4%	6.4%	0%	0%	0%
2041	6.6%	21.4%	6.6%	0%	0%	0%
2042	6.8%	21.4%	6.8%	0%	0%	0%
2043	7.0%	21.5%	7.0%	0%	0%	0%
2044	7.3%	21.5%	7.3%	0%	0%	0%
2045	7.5%	21.5%	7.5%	0%	0%	0%
2046	7.7%	21.6%	7.7%	0%	0%	0%
2047	7.9%	21.6%	7.9%	0%	0%	0%
2048	8.1%	21.6%	8.1%	0%	0%	0%
2049	8.3%	21.6%	8.3%	0%	0%	0%
2050	8.6%	21.7%	8.6%	0%	0%	0%
2051	8.8%	21.7%	8.8%	0%	0%	0%
2052	9.0%	21.7%	9.0%	0%	0%	0%
2053	9.2%	21.7%	9.2%	0%	0%	0%
2054	9.4%	21.8%	9.4%	0%	0%	0%
2055	9.7%	21.8%	9.7%	0%	0%	0%

Table B-40 ZEV sales percentages for Class 4-5 (regClassID 42) single-unit long-haul trucks (sourceTypeID 53) in non-ACT states

Model Year	BEV Sales Percentage			FCEV Sales Percentage		
	Reference	Final Standards	Alternative	Reference	Final Standards	Alternative
2027	4.9%	5.1%	4.9%	0%	0%	0%
2028	7.4%	7.4%	7.4%	0%	0%	0%
2029	9.8%	9.8%	9.8%	0%	0%	0%
2030	12.2%	12.2%	12.2%	0%	0%	0%
2031	13.4%	17.5%	13.4%	0%	0%	0%
2032	14.6%	28.7%	14.6%	0%	0%	0%
2033	16.5%	26.7%	16.5%	0%	0%	0%
2034	18.6%	24.8%	18.6%	0%	0%	0%
2035	20.9%	22.8%	20.9%	0%	0%	0%
2036	21.8%	22.9%	21.8%	0%	0%	0%
2037	22.7%	22.9%	22.7%	0%	0%	0%
2038	23.6%	23.6%	23.6%	0%	0%	0%
2039	24.5%	24.5%	24.5%	0%	0%	0%
2040	25.4%	25.4%	25.4%	0%	0%	0%
2041	26.3%	26.3%	26.3%	0%	0%	0%
2042	27.2%	27.2%	27.2%	0%	0%	0%
2043	28.1%	28.1%	28.1%	0%	0%	0%
2044	29.0%	29.0%	29.0%	0%	0%	0%
2045	29.9%	29.9%	29.9%	0%	0%	0%
2046	30.7%	30.7%	30.7%	0%	0%	0%
2047	31.6%	31.6%	31.6%	0%	0%	0%
2048	32.5%	32.5%	32.5%	0%	0%	0%
2049	33.4%	33.4%	33.4%	0%	0%	0%
2050	34.3%	34.3%	34.3%	0%	0%	0%
2051	35.1%	35.1%	35.1%	0%	0%	0%
2052	36.0%	36.0%	36.0%	0%	0%	0%
2053	36.9%	36.9%	36.9%	0%	0%	0%
2054	37.7%	37.7%	37.7%	0%	0%	0%
2055	38.6%	38.6%	38.6%	0%	0%	0%

Table B-41 ZEV sales percentages for Class 6-7 (regClassID 46) single-unit long-haul trucks (sourceTypeID 53) in non-ACT states

Model Year	BEV Sales Percentage			FCEV Sales Percentage		
	Reference	Final Standards	Alternative	Reference	Final Standards	Alternative
2027	3.7%	12.6%	8.4%	0%	0%	0%
2028	5.5%	13.6%	9.4%	0%	0%	0%
2029	7.4%	14.6%	10.5%	0%	0%	0%
2030	9.2%	15.6%	11.6%	0%	0%	0%
2031	10.1%	24.9%	13.6%	0%	0%	0%
2032	11.0%	34.2%	15.7%	0%	0%	0%
2033	12.4%	33.0%	14.4%	0%	0%	0%
2034	14.0%	31.8%	14.0%	0%	0%	0%
2035	15.6%	30.5%	15.6%	0%	0%	0%
2036	16.3%	30.6%	16.3%	0%	0%	0%
2037	17.0%	30.6%	17.0%	0%	0%	0%
2038	17.7%	30.6%	17.7%	0%	0%	0%
2039	18.4%	30.7%	18.4%	0%	0%	0%
2040	19.1%	30.7%	19.1%	0%	0%	0%
2041	19.7%	30.7%	19.7%	0%	0%	0%
2042	20.4%	30.7%	20.4%	0%	0%	0%
2043	21.1%	30.7%	21.1%	0%	0%	0%
2044	21.8%	30.8%	21.8%	0%	0%	0%
2045	22.4%	30.8%	22.4%	0%	0%	0%
2046	23.0%	30.9%	23.0%	0%	0%	0%
2047	23.7%	30.9%	23.7%	0%	0%	0%
2048	24.4%	30.9%	24.4%	0%	0%	0%
2049	25.0%	31.0%	25.0%	0%	0%	0%
2050	25.7%	31.0%	25.7%	0%	0%	0%
2051	26.3%	31.0%	26.3%	0%	0%	0%
2052	27.0%	31.0%	27.0%	0%	0%	0%
2053	27.7%	31.1%	27.7%	0%	0%	0%
2054	28.3%	31.1%	28.3%	0%	0%	0%
2055	29.0%	31.1%	29.0%	0%	0%	0%

Table B-42 ZEV sales percentages for Class 8 (regClassID 47) single-unit long-haul trucks (sourceTypeID 53) in non-ACT states

Model Year	BEV Sales Percentage			FCEV Sales Percentage		
	Reference	Final Standards	Alternative	Reference	Final Standards	Alternative
2027	1.2%	1.2%	1.2%	0%	0%	0%
2028	1.8%	1.8%	1.8%	0%	0%	0%
2029	2.5%	3.8%	2.5%	0%	0%	0%
2030	3.1%	7.3%	3.6%	0%	0%	0%
2031	3.4%	23.3%	10.8%	0%	0%	0%
2032	3.7%	39.0%	16.7%	0%	0%	0%
2033	4.1%	38.3%	15.6%	0%	0%	0%
2034	4.7%	37.2%	14.6%	0%	0%	0%
2035	5.2%	36.2%	13.5%	0%	0%	0%
2036	5.4%	36.2%	13.6%	0%	0%	0%
2037	5.7%	36.2%	13.6%	0%	0%	0%
2038	5.9%	36.2%	13.6%	0%	0%	0%
2039	6.1%	36.3%	13.6%	0%	0%	0%
2040	6.4%	36.3%	13.7%	0%	0%	0%
2041	6.6%	36.3%	13.7%	0%	0%	0%
2042	6.8%	36.3%	13.7%	0%	0%	0%
2043	7.0%	36.3%	13.7%	0%	0%	0%
2044	7.3%	36.4%	13.7%	0%	0%	0%
2045	7.5%	36.4%	13.8%	0%	0%	0%
2046	7.7%	36.5%	13.8%	0%	0%	0%
2047	7.9%	36.5%	13.9%	0%	0%	0%
2048	8.1%	36.5%	13.9%	0%	0%	0%
2049	8.3%	36.5%	13.9%	0%	0%	0%
2050	8.6%	36.5%	13.9%	0%	0%	0%
2051	8.8%	36.6%	13.9%	0%	0%	0%
2052	9.0%	36.6%	14.0%	0%	0%	0%
2053	9.2%	36.6%	14.0%	0%	0%	0%
2054	9.4%	36.6%	14.0%	0%	0%	0%
2055	9.7%	36.7%	14.0%	0%	0%	0%

Table B-43 ZEV sales percentages for Class 4-5 (regClassID 42) motor homes (sourceTypeID 54) in non-ACT states

Model Year	BEV Sales Percentage			FCEV Sales Percentage		
	Reference	Final Standards	Alternative	Reference	Final Standards	Alternative
2027	4.9%	4.9%	4.9%	0%	0%	0%
2028	7.4%	7.4%	7.4%	0%	0%	0%
2029	9.8%	9.8%	9.8%	0%	0%	0%
2030	12.2%	12.2%	12.2%	0%	0%	0%
2031	13.4%	13.4%	13.4%	0%	0%	0%
2032	14.6%	14.6%	14.6%	0%	0%	0%
2033	16.5%	16.5%	16.5%	0%	0%	0%
2034	18.6%	18.6%	18.6%	0%	0%	0%
2035	20.9%	20.9%	20.9%	0%	0%	0%
2036	21.8%	21.8%	21.8%	0%	0%	0%
2037	22.7%	22.7%	22.7%	0%	0%	0%
2038	23.6%	23.6%	23.6%	0%	0%	0%
2039	24.5%	24.5%	24.5%	0%	0%	0%
2040	25.4%	25.4%	25.4%	0%	0%	0%
2041	26.3%	26.3%	26.3%	0%	0%	0%
2042	27.2%	27.2%	27.2%	0%	0%	0%
2043	28.1%	28.1%	28.1%	0%	0%	0%
2044	29.0%	29.0%	29.0%	0%	0%	0%
2045	29.9%	29.9%	29.9%	0%	0%	0%
2046	30.7%	30.7%	30.7%	0%	0%	0%
2047	31.6%	31.6%	31.6%	0%	0%	0%
2048	32.5%	32.5%	32.5%	0%	0%	0%
2049	33.4%	33.4%	33.4%	0%	0%	0%
2050	34.3%	34.3%	34.3%	0%	0%	0%
2051	35.1%	35.1%	35.1%	0%	0%	0%
2052	36.0%	36.0%	36.0%	0%	0%	0%
2053	36.9%	36.9%	36.9%	0%	0%	0%
2054	37.7%	37.7%	37.7%	0%	0%	0%
2055	38.6%	38.6%	38.6%	0%	0%	0%

Table B-44 ZEV sales percentages for Class 6-7 (regClassID 46) motor homes (sourceTypeID 54) in non-ACT states

Model Year	BEV Sales Percentage			FCEV Sales Percentage		
	Reference	Final Standards	Alternative	Reference	Final Standards	Alternative
2027	3.7%	3.7%	3.7%	0%	0%	0%
2028	5.5%	5.5%	5.5%	0%	0%	0%
2029	7.4%	7.4%	7.4%	0%	0%	0%
2030	9.2%	9.2%	9.2%	0%	0%	0%
2031	10.1%	10.1%	10.1%	0%	0%	0%
2032	11.0%	11.0%	11.0%	0%	0%	0%
2033	12.4%	12.4%	12.4%	0%	0%	0%
2034	14.0%	14.0%	14.0%	0%	0%	0%
2035	15.6%	15.6%	15.6%	0%	0%	0%
2036	16.3%	16.3%	16.3%	0%	0%	0%
2037	17.0%	17.0%	17.0%	0%	0%	0%
2038	17.7%	17.7%	17.7%	0%	0%	0%
2039	18.4%	18.4%	18.4%	0%	0%	0%
2040	19.1%	19.1%	19.1%	0%	0%	0%
2041	19.7%	19.7%	19.7%	0%	0%	0%
2042	20.4%	20.4%	20.4%	0%	0%	0%
2043	21.1%	21.1%	21.1%	0%	0%	0%
2044	21.8%	21.8%	21.8%	0%	0%	0%
2045	22.4%	22.4%	22.4%	0%	0%	0%
2046	23.0%	23.0%	23.0%	0%	0%	0%
2047	23.7%	23.7%	23.7%	0%	0%	0%
2048	24.4%	24.4%	24.4%	0%	0%	0%
2049	25.0%	25.0%	25.0%	0%	0%	0%
2050	25.7%	25.7%	25.7%	0%	0%	0%
2051	26.3%	26.3%	26.3%	0%	0%	0%
2052	27.0%	27.0%	27.0%	0%	0%	0%
2053	27.7%	27.7%	27.7%	0%	0%	0%
2054	28.3%	28.3%	28.3%	0%	0%	0%
2055	29.0%	29.0%	29.0%	0%	0%	0%

Table B-45 ZEV sales percentages for Class 8 (regClassID 47) motor homes (sourceTypeID 54) in non-ACT states

Model Year	BEV Sales Percentage			FCEV Sales Percentage		
	Reference	Final Standards	Alternative	Reference	Final Standards	Alternative
2027	1.2%	1.2%	1.2%	0%	0%	0%
2028	1.8%	1.8%	1.8%	0%	0%	0%
2029	2.5%	2.5%	2.5%	0%	0%	0%
2030	3.1%	3.1%	3.1%	0%	0%	0%
2031	3.4%	3.4%	3.4%	0%	0%	0%
2032	3.7%	3.7%	3.7%	0%	0%	0%
2033	4.1%	4.1%	4.1%	0%	0%	0%
2034	4.7%	4.7%	4.7%	0%	0%	0%
2035	5.2%	5.2%	5.2%	0%	0%	0%
2036	5.4%	5.4%	5.4%	0%	0%	0%
2037	5.7%	5.7%	5.7%	0%	0%	0%
2038	5.9%	5.9%	5.9%	0%	0%	0%
2039	6.1%	6.1%	6.1%	0%	0%	0%
2040	6.4%	6.4%	6.4%	0%	0%	0%
2041	6.6%	6.6%	6.6%	0%	0%	0%
2042	6.8%	6.8%	6.8%	0%	0%	0%
2043	7.0%	7.0%	7.0%	0%	0%	0%
2044	7.3%	7.3%	7.3%	0%	0%	0%
2045	7.5%	7.5%	7.5%	0%	0%	0%
2046	7.7%	7.7%	7.7%	0%	0%	0%
2047	7.9%	7.9%	7.9%	0%	0%	0%
2048	8.1%	8.1%	8.1%	0%	0%	0%
2049	8.3%	8.3%	8.3%	0%	0%	0%
2050	8.6%	8.6%	8.6%	0%	0%	0%
2051	8.8%	8.8%	8.8%	0%	0%	0%
2052	9.0%	9.0%	9.0%	0%	0%	0%
2053	9.2%	9.2%	9.2%	0%	0%	0%
2054	9.4%	9.4%	9.4%	0%	0%	0%
2055	9.7%	9.7%	9.7%	0%	0%	0%

Table B-46 ZEV sales percentages for Class 6-7 (regClassID 46) single-unit short-haul trucks (sourceTypeID 61) in non-ACT states

Model Year	BEV Sales Percentage			FCEV Sales Percentage		
	Reference	Final Standards	Alternative	Reference	Final Standards	Alternative
2027	2.1%	4.3%	2.1%	0.0%	0.0%	0.0%
2028	2.7%	5.0%	2.7%	0.0%	0.0%	0.0%
2029	3.3%	5.8%	3.9%	0.0%	0.0%	0.0%
2030	2.9%	6.5%	4.5%	1.0%	2.2%	1.5%
2031	3.0%	12.1%	5.1%	1.0%	4.1%	1.7%
2032	3.4%	18.8%	6.5%	1.1%	6.4%	2.2%
2033	3.5%	18.8%	6.5%	1.2%	6.4%	2.2%
2034	3.7%	18.8%	6.5%	1.3%	6.4%	2.2%
2035	3.9%	18.8%	6.5%	1.3%	6.4%	2.2%
2036	4.1%	18.8%	6.5%	1.4%	6.4%	2.2%
2037	4.3%	18.8%	6.5%	1.4%	6.4%	2.2%
2038	4.4%	18.8%	6.5%	1.5%	6.4%	2.2%
2039	4.6%	18.8%	6.5%	1.6%	6.4%	2.2%
2040	4.8%	18.8%	6.5%	1.6%	6.4%	2.2%
2041	5.0%	18.8%	6.5%	1.7%	6.4%	2.2%
2042	5.1%	18.8%	6.5%	1.7%	6.4%	2.2%
2043	5.3%	18.8%	6.5%	1.8%	6.4%	2.2%
2044	5.5%	18.8%	6.5%	1.8%	6.4%	2.2%
2045	5.7%	18.8%	6.5%	1.9%	6.4%	2.2%
2046	5.8%	18.8%	6.5%	2.0%	6.4%	2.2%
2047	6.0%	18.9%	6.5%	2.0%	6.4%	2.2%
2048	6.2%	18.9%	6.5%	2.1%	6.4%	2.2%
2049	6.4%	18.9%	6.5%	2.1%	6.4%	2.2%
2050	6.5%	18.9%	6.5%	2.2%	6.4%	2.2%
2051	6.7%	18.9%	6.7%	2.3%	6.4%	2.3%
2052	6.9%	18.9%	6.9%	2.3%	6.4%	2.3%
2053	7.1%	18.9%	7.1%	2.4%	6.4%	2.4%
2054	7.3%	18.9%	7.3%	2.4%	6.4%	2.4%
2055	7.4%	18.9%	7.4%	2.5%	6.4%	2.5%

Table B-47 ZEV sales percentages for Class 8 (regClassID 47) single-unit short-haul trucks (sourceTypeID 61) in non-ACT states

Model Year	BEV Sales Percentage			FCEV Sales Percentage		
	Reference	Final Standards	Alternative	Reference	Final Standards	Alternative
2027	2.1%	2.1%	2.1%	0.0%	0.0%	0.0%
2028	2.7%	5.5%	3.4%	0.0%	0.0%	0.0%
2029	3.3%	9.7%	7.3%	0.0%	0.0%	0.0%
2030	3.7%	13.8%	10.5%	0.1%	0.5%	0.4%
2031	3.9%	28.4%	15.2%	0.2%	1.1%	0.6%
2032	4.4%	43.2%	19.0%	0.2%	1.7%	0.8%
2033	4.6%	43.2%	19.0%	0.2%	1.7%	0.8%
2034	4.8%	43.2%	19.0%	0.2%	1.7%	0.8%
2035	5.0%	43.2%	19.0%	0.2%	1.7%	0.8%
2036	5.2%	43.2%	19.0%	0.2%	1.7%	0.8%
2037	5.5%	43.2%	19.0%	0.2%	1.7%	0.8%
2038	5.7%	43.2%	19.0%	0.2%	1.7%	0.8%
2039	5.9%	43.2%	19.0%	0.2%	1.7%	0.8%
2040	6.1%	43.2%	19.0%	0.2%	1.7%	0.8%
2041	6.4%	43.2%	19.0%	0.3%	1.7%	0.8%
2042	6.6%	43.2%	19.0%	0.3%	1.7%	0.8%
2043	6.8%	43.2%	19.0%	0.3%	1.7%	0.8%
2044	7.1%	43.2%	19.0%	0.3%	1.7%	0.8%
2045	7.3%	43.2%	19.0%	0.3%	1.7%	0.8%
2046	7.5%	43.2%	19.0%	0.3%	1.7%	0.8%
2047	7.7%	43.2%	19.0%	0.3%	1.7%	0.8%
2048	8.0%	43.2%	19.0%	0.3%	1.7%	0.8%
2049	8.2%	43.2%	19.0%	0.3%	1.7%	0.8%
2050	8.4%	43.2%	19.0%	0.3%	1.7%	0.8%
2051	8.6%	43.2%	19.0%	0.3%	1.7%	0.8%
2052	8.9%	43.2%	19.0%	0.4%	1.7%	0.8%
2053	9.1%	43.2%	19.0%	0.4%	1.7%	0.8%
2054	9.3%	43.2%	19.0%	0.4%	1.7%	0.8%
2055	9.5%	43.2%	19.0%	0.4%	1.7%	0.8%

Table B-48 ZEV sales percentages for Class 6-7 (regClassID 46) single-unit long-haul trucks (sourceTypeID 62) in non-ACT states

Model Year	BEV Sales Percentage			FCEV Sales Percentage		
	Reference	Final Standards	Alternative	Reference	Final Standards	Alternative
2027	0.2%	0.2%	0.2%	0.0%	0.0%	0.0%
2028	0.4%	0.4%	0.4%	0.0%	0.0%	0.0%
2029	0.7%	0.7%	0.7%	0.0%	0.0%	0.0%
2030	0.6%	3.6%	2.7%	0.4%	2.1%	1.6%
2031	1.2%	7.2%	5.5%	0.7%	4.2%	3.2%
2032	1.5%	15.8%	8.6%	0.9%	9.2%	5.0%
2033	1.6%	15.8%	8.6%	0.9%	9.2%	5.0%
2034	1.7%	15.8%	8.6%	1.0%	9.2%	5.0%
2035	1.7%	15.8%	8.6%	1.0%	9.2%	5.0%
2036	1.8%	15.8%	8.6%	1.1%	9.2%	5.0%
2037	1.9%	15.8%	8.6%	1.1%	9.2%	5.0%
2038	2.0%	15.8%	8.6%	1.2%	9.2%	5.0%
2039	2.1%	15.8%	8.6%	1.2%	9.2%	5.0%
2040	2.1%	15.8%	8.6%	1.2%	9.2%	5.0%
2041	2.2%	15.8%	8.6%	1.3%	9.2%	5.0%
2042	2.3%	15.8%	8.6%	1.3%	9.2%	5.0%
2043	2.4%	15.8%	8.6%	1.4%	9.2%	5.0%
2044	2.4%	15.8%	8.6%	1.4%	9.2%	5.0%
2045	2.5%	15.8%	8.6%	1.5%	9.2%	5.0%
2046	2.6%	15.8%	8.6%	1.5%	9.2%	5.0%
2047	2.7%	15.8%	8.6%	1.6%	9.2%	5.0%
2048	2.8%	15.8%	8.6%	1.6%	9.2%	5.0%
2049	2.8%	15.8%	8.6%	1.7%	9.2%	5.0%
2050	2.9%	15.8%	8.6%	1.7%	9.2%	5.0%
2051	3.0%	15.8%	8.6%	1.8%	9.2%	5.0%
2052	3.1%	15.8%	8.6%	1.8%	9.2%	5.0%
2053	3.2%	15.8%	8.6%	1.8%	9.2%	5.0%
2054	3.2%	15.8%	8.6%	1.9%	9.2%	5.0%
2055	3.3%	15.8%	8.6%	1.9%	9.2%	5.0%

Table B-49 ZEV sales percentages for Class 8 (regClassID 47) single-unit long-haul trucks (sourceTypeID 62) in non-ACT states

Model Year	BEV Sales Percentage			FCEV Sales Percentage		
	Reference	Final Standards	Alternative	Reference	Final Standards	Alternative
2027	0.2%	0.2%	0.2%	0.0%	0.0%	0.0%
2028	0.4%	0.4%	0.4%	0.0%	0.0%	0.0%
2029	0.7%	0.7%	0.7%	0.0%	0.0%	0.0%
2030	0.6%	3.7%	2.8%	0.4%	2.1%	1.6%
2031	1.2%	7.4%	5.6%	0.7%	4.3%	3.3%
2032	1.5%	15.8%	8.8%	0.9%	9.2%	5.1%
2033	1.6%	15.8%	8.8%	0.9%	9.2%	5.1%
2034	1.7%	15.8%	8.8%	1.0%	9.2%	5.1%
2035	1.7%	15.8%	8.8%	1.0%	9.2%	5.1%
2036	1.8%	15.8%	8.8%	1.1%	9.2%	5.1%
2037	1.9%	15.8%	8.8%	1.1%	9.2%	5.1%
2038	2.0%	15.8%	8.8%	1.2%	9.2%	5.1%
2039	2.1%	15.8%	8.8%	1.2%	9.2%	5.1%
2040	2.1%	15.8%	8.8%	1.2%	9.2%	5.1%
2041	2.2%	15.8%	8.8%	1.3%	9.2%	5.1%
2042	2.3%	15.8%	8.8%	1.3%	9.2%	5.1%
2043	2.4%	15.8%	8.8%	1.4%	9.2%	5.1%
2044	2.4%	15.8%	8.8%	1.4%	9.2%	5.1%
2045	2.5%	15.8%	8.8%	1.5%	9.2%	5.1%
2046	2.6%	15.8%	8.8%	1.5%	9.2%	5.1%
2047	2.7%	15.8%	8.8%	1.6%	9.2%	5.1%
2048	2.8%	15.8%	8.8%	1.6%	9.2%	5.1%
2049	2.8%	15.8%	8.8%	1.7%	9.2%	5.1%
2050	2.9%	15.8%	8.8%	1.7%	9.2%	5.1%
2051	3.0%	15.8%	8.8%	1.8%	9.2%	5.1%
2052	3.1%	15.8%	8.8%	1.8%	9.2%	5.1%
2053	3.2%	15.8%	8.8%	1.8%	9.2%	5.1%
2054	3.2%	15.8%	8.8%	1.9%	9.2%	5.1%
2055	3.3%	15.8%	8.8%	1.9%	9.2%	5.1%

B.3 National ZEV Sales Percentages

Table B-50 National ZEV sales percentages for Class 4-5 (regClassID 42) other buses (sourceTypeID 41)

Model Year	BEV Sales Percentage			FCEV Sales Percentage		
	Reference	Final Standards	Alternative	Reference	Final Standards	Alternative
2027	13.4%	20.0%	16.7%	0%	0%	0%
2028	20.1%	25.2%	21.9%	0%	0%	0%
2029	26.8%	30.4%	27.1%	0%	0%	0%
2030	33.3%	35.6%	33.3%	0%	0%	0%
2031	36.6%	51.1%	37.5%	0%	0%	0%
2032	39.8%	66.7%	42.6%	0%	0%	0%
2033	43.5%	66.7%	43.5%	0%	0%	0%
2034	47.3%	66.7%	47.3%	0%	0%	0%
2035	51.2%	66.7%	51.2%	0%	0%	0%
2036	51.7%	66.7%	51.7%	0%	0%	0%
2037	52.2%	66.7%	52.2%	0%	0%	0%
2038	52.6%	66.7%	52.6%	0%	0%	0%
2039	53.1%	66.7%	53.1%	0%	0%	0%
2040	53.6%	66.7%	53.6%	0%	0%	0%
2041	54.1%	66.7%	54.1%	0%	0%	0%
2042	54.6%	66.7%	54.6%	0%	0%	0%
2043	55.1%	66.7%	55.1%	0%	0%	0%
2044	55.5%	66.7%	55.5%	0%	0%	0%
2045	55.9%	66.7%	55.9%	0%	0%	0%
2046	56.3%	66.7%	56.3%	0%	0%	0%
2047	56.8%	66.7%	56.8%	0%	0%	0%
2048	57.3%	66.7%	57.3%	0%	0%	0%
2049	57.7%	66.7%	57.7%	0%	0%	0%
2050	58.2%	66.7%	58.2%	0%	0%	0%
2051	58.6%	66.7%	58.6%	0%	0%	0%
2052	59.1%	66.7%	59.1%	0%	0%	0%
2053	59.6%	66.7%	59.6%	0%	0%	0%
2054	60.0%	66.7%	60.0%	0%	0%	0%
2055	60.5%	66.7%	60.5%	0%	0%	0%

Table B-51 National ZEV sales percentages for Class 6-7 (regClassID 46) other buses (sourceTypeID 41)

Model Year	BEV Sales Percentage			FCEV Sales Percentage		
	Reference	Final Standards	Alternative	Reference	Final Standards	Alternative
2027	7.0%	14.0%	10.6%	0%	0%	0%
2028	10.6%	14.0%	11.3%	0%	0%	0%
2029	14.0%	14.0%	14.0%	0%	0%	0%
2030	17.5%	17.5%	17.5%	0%	0%	0%
2031	19.2%	19.2%	19.2%	0%	0%	0%
2032	20.9%	20.9%	20.9%	0%	0%	0%
2033	23.0%	23.0%	23.0%	0%	0%	0%
2034	25.3%	25.3%	25.3%	0%	0%	0%
2035	27.6%	27.6%	27.6%	0%	0%	0%
2036	28.1%	28.1%	28.1%	0%	0%	0%
2037	28.6%	28.6%	28.6%	0%	0%	0%
2038	29.1%	29.1%	29.1%	0%	0%	0%
2039	29.6%	29.6%	29.6%	0%	0%	0%
2040	30.1%	30.1%	30.1%	0%	0%	0%
2041	30.7%	30.7%	30.7%	0%	0%	0%
2042	31.2%	31.2%	31.2%	0%	0%	0%
2043	31.7%	31.7%	31.7%	0%	0%	0%
2044	32.2%	32.2%	32.2%	0%	0%	0%
2045	32.6%	32.6%	32.6%	0%	0%	0%
2046	33.1%	33.1%	33.1%	0%	0%	0%
2047	33.6%	33.6%	33.6%	0%	0%	0%
2048	34.1%	34.1%	34.1%	0%	0%	0%
2049	34.6%	34.6%	34.6%	0%	0%	0%
2050	35.1%	35.1%	35.1%	0%	0%	0%
2051	35.6%	35.6%	35.6%	0%	0%	0%
2052	36.1%	36.1%	36.1%	0%	0%	0%
2053	36.6%	36.6%	36.6%	0%	0%	0%
2054	37.1%	37.1%	37.1%	0%	0%	0%
2055	37.6%	37.6%	37.6%	0%	0%	0%

Table B-52 National ZEV sales percentages for Class 8 (regClassID 47) other buses (sourceTypeID 41)

Model Year	BEV Sales Percentage			FCEV Sales Percentage		
	Reference	Final Standards	Alternative	Reference	Final Standards	Alternative
2027	6.0%	6.0%	6.0%	0.0%	0.0%	0.0%
2028	9.0%	9.0%	9.0%	0.0%	0.0%	0.0%
2029	12.0%	12.0%	12.0%	0.0%	0.0%	0.0%
2030	12.0%	12.0%	12.0%	2.9%	2.9%	2.9%
2031	12.0%	12.0%	12.0%	4.4%	4.4%	4.4%
2032	12.0%	12.0%	12.0%	5.9%	5.9%	5.9%
2033	12.1%	12.1%	12.1%	7.4%	7.4%	7.4%
2034	12.2%	12.2%	12.2%	8.9%	8.9%	8.9%
2035	12.2%	12.2%	12.2%	10.4%	10.4%	10.4%
2036	12.3%	12.3%	12.3%	10.5%	10.5%	10.5%
2037	12.4%	12.4%	12.4%	10.5%	10.5%	10.5%
2038	12.5%	12.5%	12.5%	10.5%	10.5%	10.5%
2039	12.5%	12.5%	12.5%	10.5%	10.5%	10.5%
2040	12.6%	12.6%	12.6%	10.6%	10.6%	10.6%
2041	12.7%	12.7%	12.7%	10.6%	10.6%	10.6%
2042	12.8%	12.8%	12.8%	10.7%	10.7%	10.7%
2043	12.8%	12.8%	12.8%	10.7%	10.7%	10.7%
2044	12.9%	12.9%	12.9%	10.7%	10.7%	10.7%
2045	13.0%	13.0%	13.0%	10.7%	10.7%	10.7%
2046	13.1%	13.1%	13.1%	10.7%	10.7%	10.7%
2047	13.1%	13.1%	13.1%	10.7%	10.7%	10.7%
2048	13.2%	13.2%	13.2%	10.8%	10.8%	10.8%
2049	13.3%	13.3%	13.3%	10.8%	10.8%	10.8%
2050	13.4%	13.4%	13.4%	10.8%	10.8%	10.8%
2051	13.4%	13.4%	13.4%	10.8%	10.8%	10.8%
2052	13.5%	13.5%	13.5%	10.9%	10.9%	10.9%
2053	13.6%	13.6%	13.6%	10.9%	10.9%	10.9%
2054	13.7%	13.7%	13.7%	10.9%	10.9%	10.9%
2055	13.7%	13.7%	13.7%	10.9%	10.9%	10.9%

Table B-53 National ZEV sales percentages for Class 4-5 (regClassID 42) transit buses (sourceTypeID 42)

Model Year	BEV Sales Percentage			FCEV Sales Percentage		
	Reference	Final Standards	Alternative	Reference	Final Standards	Alternative
2027	13.4%	20.0%	16.7%	0%	0%	0%
2028	20.1%	25.2%	21.9%	0%	0%	0%
2029	26.8%	30.4%	27.1%	0%	0%	0%
2030	33.3%	35.6%	33.3%	0%	0%	0%
2031	36.6%	51.1%	37.5%	0%	0%	0%
2032	39.8%	66.7%	42.6%	0%	0%	0%
2033	43.5%	66.7%	43.5%	0%	0%	0%
2034	47.3%	66.7%	47.3%	0%	0%	0%
2035	51.2%	66.7%	51.2%	0%	0%	0%
2036	51.7%	66.7%	51.7%	0%	0%	0%
2037	52.2%	66.7%	52.2%	0%	0%	0%
2038	52.6%	66.7%	52.6%	0%	0%	0%
2039	53.1%	66.7%	53.1%	0%	0%	0%
2040	53.6%	66.7%	53.6%	0%	0%	0%
2041	54.1%	66.7%	54.1%	0%	0%	0%
2042	54.6%	66.7%	54.6%	0%	0%	0%
2043	55.1%	66.7%	55.1%	0%	0%	0%
2044	55.5%	66.7%	55.5%	0%	0%	0%
2045	55.9%	66.7%	55.9%	0%	0%	0%
2046	56.3%	66.7%	56.3%	0%	0%	0%
2047	56.8%	66.7%	56.8%	0%	0%	0%
2048	57.3%	66.7%	57.3%	0%	0%	0%
2049	57.7%	66.7%	57.7%	0%	0%	0%
2050	58.2%	66.7%	58.2%	0%	0%	0%
2051	58.6%	66.7%	58.6%	0%	0%	0%
2052	59.1%	66.7%	59.1%	0%	0%	0%
2053	59.6%	66.7%	59.6%	0%	0%	0%
2054	60.0%	66.7%	60.0%	0%	0%	0%
2055	60.5%	66.7%	60.5%	0%	0%	0%

Table B-54 National ZEV sales percentages for Class 6-7 (regClassID 46) transit buses (sourceTypeID 42)

Model Year	BEV Sales Percentage			FCEV Sales Percentage		
	Reference	Final Standards	Alternative	Reference	Final Standards	Alternative
2027	7.0%	10.0%	7.6%	0%	0%	0%
2028	10.6%	11.4%	10.6%	0%	0%	0%
2029	14.0%	14.0%	14.0%	0%	0%	0%
2030	17.5%	17.5%	17.5%	0%	0%	0%
2031	19.2%	19.2%	19.2%	0%	0%	0%
2032	20.9%	22.3%	20.9%	0%	0%	0%
2033	23.0%	23.0%	23.0%	0%	0%	0%
2034	25.3%	25.3%	25.3%	0%	0%	0%
2035	27.6%	27.6%	27.6%	0%	0%	0%
2036	28.1%	28.1%	28.1%	0%	0%	0%
2037	28.6%	28.6%	28.6%	0%	0%	0%
2038	29.1%	29.1%	29.1%	0%	0%	0%
2039	29.6%	29.6%	29.6%	0%	0%	0%
2040	30.1%	30.1%	30.1%	0%	0%	0%
2041	30.7%	30.7%	30.7%	0%	0%	0%
2042	31.2%	31.2%	31.2%	0%	0%	0%
2043	31.7%	31.7%	31.7%	0%	0%	0%
2044	32.2%	32.2%	32.2%	0%	0%	0%
2045	32.6%	32.6%	32.6%	0%	0%	0%
2046	33.1%	33.1%	33.1%	0%	0%	0%
2047	33.6%	33.6%	33.6%	0%	0%	0%
2048	34.1%	34.1%	34.1%	0%	0%	0%
2049	34.6%	34.6%	34.6%	0%	0%	0%
2050	35.1%	35.1%	35.1%	0%	0%	0%
2051	35.6%	35.6%	35.6%	0%	0%	0%
2052	36.1%	36.1%	36.1%	0%	0%	0%
2053	36.6%	36.6%	36.6%	0%	0%	0%
2054	37.1%	37.1%	37.1%	0%	0%	0%
2055	37.6%	37.6%	37.6%	0%	0%	0%

Table B-55 National ZEV sales percentages for urban buses (regClassID 48 and sourceTypeID 42)

Model Year	BEV Sales Percentage			FCEV Sales Percentage		
	Reference	Final Standards	Alternative	Reference	Final Standards	Alternative
2027	6.0%	6.0%	6.0%	0%	0%	0%
2028	9.0%	14.0%	9.7%	0%	0%	0%
2029	12.0%	17.1%	12.9%	0%	0%	0%
2030	15.0%	20.2%	16.0%	0%	0%	0%
2031	16.4%	29.6%	19.0%	0%	0%	0%
2032	17.9%	39.0%	22.1%	0%	0%	0%
2033	19.5%	39.0%	22.1%	0%	0%	0%
2034	21.1%	39.0%	22.1%	0%	0%	0%
2035	22.7%	39.0%	22.7%	0%	0%	0%
2036	22.8%	39.0%	22.8%	0%	0%	0%
2037	22.9%	39.0%	22.9%	0%	0%	0%
2038	23.0%	39.0%	23.0%	0%	0%	0%
2039	23.1%	39.0%	23.1%	0%	0%	0%
2040	23.2%	39.0%	23.2%	0%	0%	0%
2041	23.3%	39.0%	23.3%	0%	0%	0%
2042	23.4%	39.0%	23.4%	0%	0%	0%
2043	23.5%	39.0%	23.5%	0%	0%	0%
2044	23.6%	39.0%	23.6%	0%	0%	0%
2045	23.7%	39.0%	23.7%	0%	0%	0%
2046	23.8%	39.0%	23.8%	0%	0%	0%
2047	23.9%	39.0%	23.9%	0%	0%	0%
2048	24.0%	39.0%	24.0%	0%	0%	0%
2049	24.1%	39.0%	24.1%	0%	0%	0%
2050	24.2%	39.0%	24.2%	0%	0%	0%
2051	24.3%	39.0%	24.3%	0%	0%	0%
2052	24.4%	39.0%	24.4%	0%	0%	0%
2053	24.5%	39.0%	24.5%	0%	0%	0%
2054	24.6%	39.0%	24.6%	0%	0%	0%
2055	24.7%	39.0%	24.7%	0%	0%	0%

Table B-56 National ZEV sales percentages for Class 4-5 (regClassID 42) school buses (sourceTypeID 43)

Model Year	BEV Sales Percentage			FCEV Sales Percentage		
	Reference	Final Standards	Alternative	Reference	Final Standards	Alternative
2027	11.7%	20.0%	16.7%	0%	0%	0%
2028	17.5%	25.2%	21.9%	0%	0%	0%
2029	23.3%	30.4%	27.1%	0%	0%	0%
2030	29.0%	35.6%	32.3%	0%	0%	0%
2031	31.8%	51.1%	37.5%	0%	0%	0%
2032	34.7%	66.7%	42.6%	0%	0%	0%
2033	38.0%	66.7%	42.6%	0%	0%	0%
2034	41.5%	66.7%	42.6%	0%	0%	0%
2035	45.0%	66.7%	45.0%	0%	0%	0%
2036	45.6%	66.7%	45.6%	0%	0%	0%
2037	46.1%	66.7%	46.1%	0%	0%	0%
2038	46.7%	66.7%	46.7%	0%	0%	0%
2039	47.3%	66.7%	47.3%	0%	0%	0%
2040	47.8%	66.7%	47.8%	0%	0%	0%
2041	48.4%	66.7%	48.4%	0%	0%	0%
2042	49.0%	66.7%	49.0%	0%	0%	0%
2043	49.6%	66.7%	49.6%	0%	0%	0%
2044	50.1%	66.7%	50.1%	0%	0%	0%
2045	50.6%	66.7%	50.6%	0%	0%	0%
2046	51.1%	66.7%	51.1%	0%	0%	0%
2047	51.6%	66.7%	51.6%	0%	0%	0%
2048	52.2%	66.7%	52.2%	0%	0%	0%
2049	52.8%	66.7%	52.8%	0%	0%	0%
2050	53.3%	66.7%	53.3%	0%	0%	0%
2051	53.8%	66.7%	53.8%	0%	0%	0%
2052	54.4%	66.7%	54.4%	0%	0%	0%
2053	54.9%	66.7%	54.9%	0%	0%	0%
2054	55.5%	66.7%	55.5%	0%	0%	0%
2055	56.0%	66.7%	56.0%	0%	0%	0%

Table B-57 National ZEV sales percentages for Class 6-7 (regClassID 46) school buses (sourceTypeID 43)

Model Year	BEV Sales Percentage			FCEV Sales Percentage		
	Reference	Final Standards	Alternative	Reference	Final Standards	Alternative
2027	6.6%	20.0%	15.2%	0%	0%	0%
2028	9.9%	25.6%	20.5%	0%	0%	0%
2029	13.1%	31.1%	26.0%	0%	0%	0%
2030	16.4%	36.7%	31.4%	0%	0%	0%
2031	17.9%	53.3%	37.7%	0%	0%	0%
2032	19.5%	70.0%	43.6%	0%	0%	0%
2033	21.6%	70.0%	43.6%	0%	0%	0%
2034	23.7%	70.0%	43.6%	0%	0%	0%
2035	26.0%	70.0%	43.6%	0%	0%	0%
2036	26.5%	70.0%	43.6%	0%	0%	0%
2037	27.0%	70.0%	43.6%	0%	0%	0%
2038	27.6%	70.0%	43.6%	0%	0%	0%
2039	28.1%	70.0%	43.6%	0%	0%	0%
2040	28.6%	70.0%	43.6%	0%	0%	0%
2041	29.2%	70.0%	43.6%	0%	0%	0%
2042	29.7%	70.0%	43.6%	0%	0%	0%
2043	30.3%	70.0%	43.6%	0%	0%	0%
2044	30.8%	70.0%	43.6%	0%	0%	0%
2045	31.3%	70.0%	43.6%	0%	0%	0%
2046	31.8%	70.0%	43.6%	0%	0%	0%
2047	32.3%	70.0%	43.6%	0%	0%	0%
2048	32.8%	70.0%	43.6%	0%	0%	0%
2049	33.3%	70.0%	43.6%	0%	0%	0%
2050	33.8%	70.0%	43.6%	0%	0%	0%
2051	34.3%	70.0%	43.6%	0%	0%	0%
2052	34.9%	70.0%	43.6%	0%	0%	0%
2053	35.4%	70.0%	43.6%	0%	0%	0%
2054	35.9%	70.0%	43.6%	0%	0%	0%
2055	36.4%	70.0%	43.6%	0%	0%	0%

Table B-58 National ZEV sales percentages for Class 8 (regClassID 47) school buses (sourceTypeID 43)

Model Year	BEV Sales Percentage			FCEV Sales Percentage		
	Reference	Final Standards	Alternative	Reference	Final Standards	Alternative
2027	5.6%	5.6%	5.6%	0%	0%	0%
2028	8.3%	17.0%	11.8%	0%	0%	0%
2029	11.1%	19.8%	14.9%	0%	0%	0%
2030	13.8%	22.5%	17.8%	0%	0%	0%
2031	15.1%	30.8%	19.7%	0%	0%	0%
2032	16.5%	39.0%	22.1%	0%	0%	0%
2033	17.9%	39.0%	22.1%	0%	0%	0%
2034	19.4%	39.0%	22.1%	0%	0%	0%
2035	20.9%	39.0%	22.1%	0%	0%	0%
2036	21.1%	39.0%	22.1%	0%	0%	0%
2037	21.2%	39.0%	22.1%	0%	0%	0%
2038	21.3%	39.0%	22.1%	0%	0%	0%
2039	21.4%	39.0%	22.1%	0%	0%	0%
2040	21.5%	39.0%	22.1%	0%	0%	0%
2041	21.6%	39.0%	22.1%	0%	0%	0%
2042	21.8%	39.0%	22.1%	0%	0%	0%
2043	21.9%	39.0%	22.1%	0%	0%	0%
2044	22.0%	39.0%	22.1%	0%	0%	0%
2045	22.1%	39.0%	22.1%	0%	0%	0%
2046	22.2%	39.0%	22.2%	0%	0%	0%
2047	22.3%	39.0%	22.3%	0%	0%	0%
2048	22.4%	39.0%	22.4%	0%	0%	0%
2049	22.5%	39.0%	22.5%	0%	0%	0%
2050	22.6%	39.0%	22.6%	0%	0%	0%
2051	22.7%	39.0%	22.7%	0%	0%	0%
2052	22.8%	39.0%	22.8%	0%	0%	0%
2053	23.0%	39.0%	23.0%	0%	0%	0%
2054	23.1%	39.0%	23.1%	0%	0%	0%
2055	23.2%	39.0%	23.2%	0%	0%	0%

Table B-59 National ZEV sales percentages for Class 6-7 (regClassID 46) refuse trucks (sourceTypeID 51)

Model Year	BEV Sales Percentage			FCEV Sales Percentage		
	Reference	Final Standards	Alternative	Reference	Final Standards	Alternative
2027	7.3%	20.0%	15.2%	0%	0%	0%
2028	11.0%	22.1%	17.8%	0%	0%	0%
2029	14.6%	24.2%	20.2%	0%	0%	0%
2030	18.2%	26.3%	22.6%	0%	0%	0%
2031	20.0%	32.7%	23.1%	0%	0%	0%
2032	21.8%	39.0%	24.3%	0%	0%	0%
2033	23.9%	39.0%	24.3%	0%	0%	0%
2034	26.3%	39.0%	26.3%	0%	0%	0%
2035	28.7%	39.0%	28.7%	0%	0%	0%
2036	29.2%	39.0%	29.2%	0%	0%	0%
2037	29.7%	39.0%	29.7%	0%	0%	0%
2038	30.1%	39.0%	30.1%	0%	0%	0%
2039	30.6%	39.0%	30.6%	0%	0%	0%
2040	31.1%	39.0%	31.1%	0%	0%	0%
2041	31.6%	39.0%	31.6%	0%	0%	0%
2042	32.1%	39.0%	32.1%	0%	0%	0%
2043	32.6%	39.0%	32.6%	0%	0%	0%
2044	33.1%	39.0%	33.1%	0%	0%	0%
2045	33.6%	39.0%	33.6%	0%	0%	0%
2046	34.0%	39.0%	34.0%	0%	0%	0%
2047	34.5%	39.0%	34.5%	0%	0%	0%
2048	35.0%	39.0%	35.0%	0%	0%	0%
2049	35.5%	39.0%	35.5%	0%	0%	0%
2050	36.0%	39.0%	36.0%	0%	0%	0%
2051	36.4%	39.0%	36.4%	0%	0%	0%
2052	36.9%	39.0%	36.9%	0%	0%	0%
2053	37.4%	39.0%	37.4%	0%	0%	0%
2054	37.9%	39.0%	37.9%	0%	0%	0%
2055	38.3%	39.0%	38.3%	0%	0%	0%

Table B-60 National ZEV sales percentages for Class 8 (regClassID 47) refuse trucks (sourceTypeID 51)

Model Year	BEV Sales Percentage			FCEV Sales Percentage		
	Reference	Final Standards	Alternative	Reference	Final Standards	Alternative
2027	3.5%	3.5%	3.5%	0%	0%	0%
2028	5.3%	14.0%	9.7%	0%	0%	0%
2029	7.0%	17.1%	12.9%	0%	0%	0%
2030	8.7%	20.2%	16.0%	0%	0%	0%
2031	9.6%	29.6%	19.0%	0%	0%	0%
2032	10.4%	39.0%	22.1%	0%	0%	0%
2033	11.4%	39.0%	22.1%	0%	0%	0%
2034	12.4%	39.0%	22.1%	0%	0%	0%
2035	13.5%	39.0%	22.1%	0%	0%	0%
2036	13.7%	39.0%	22.1%	0%	0%	0%
2037	13.8%	39.0%	22.1%	0%	0%	0%
2038	14.0%	39.0%	22.1%	0%	0%	0%
2039	14.2%	39.0%	22.1%	0%	0%	0%
2040	14.3%	39.0%	22.1%	0%	0%	0%
2041	14.5%	39.0%	22.1%	0%	0%	0%
2042	14.7%	39.0%	22.1%	0%	0%	0%
2043	14.9%	39.0%	22.1%	0%	0%	0%
2044	15.0%	39.0%	22.1%	0%	0%	0%
2045	15.2%	39.0%	22.1%	0%	0%	0%
2046	15.3%	39.0%	22.1%	0%	0%	0%
2047	15.5%	39.0%	22.1%	0%	0%	0%
2048	15.7%	39.0%	22.1%	0%	0%	0%
2049	15.8%	39.0%	22.1%	0%	0%	0%
2050	16.0%	39.0%	22.1%	0%	0%	0%
2051	16.1%	39.0%	22.1%	0%	0%	0%
2052	16.3%	39.0%	22.1%	0%	0%	0%
2053	16.5%	39.0%	22.1%	0%	0%	0%
2054	16.6%	39.0%	22.1%	0%	0%	0%
2055	16.8%	39.0%	22.1%	0%	0%	0%

Table B-61 National ZEV sales percentages for Class 4-5 (regClassID 42) single-unit short-haul trucks (sourceTypeID 52)

Model Year	BEV Sales Percentage			FCEV Sales Percentage		
	Reference	Final Standards	Alternative	Reference	Final Standards	Alternative
2027	9.9%	20.0%	16.7%	0%	0%	0%
2028	14.8%	25.2%	21.9%	0%	0%	0%
2029	19.7%	30.4%	27.1%	0%	0%	0%
2030	24.5%	35.6%	32.3%	0%	0%	0%
2031	26.9%	51.1%	37.5%	0%	0%	0%
2032	29.3%	66.7%	42.6%	0%	0%	0%
2033	32.2%	66.7%	42.6%	0%	0%	0%
2034	35.3%	66.7%	42.6%	0%	0%	0%
2035	38.5%	66.7%	42.6%	0%	0%	0%
2036	39.2%	66.7%	42.6%	0%	0%	0%
2037	39.8%	66.7%	42.6%	0%	0%	0%
2038	40.5%	66.7%	42.6%	0%	0%	0%
2039	41.1%	66.7%	42.6%	0%	0%	0%
2040	41.8%	66.7%	42.6%	0%	0%	0%
2041	42.5%	66.7%	42.6%	0%	0%	0%
2042	43.1%	66.7%	43.1%	0%	0%	0%
2043	43.8%	66.7%	43.8%	0%	0%	0%
2044	44.4%	66.7%	44.4%	0%	0%	0%
2045	45.0%	66.7%	45.0%	0%	0%	0%
2046	45.6%	66.7%	45.6%	0%	0%	0%
2047	46.2%	66.7%	46.2%	0%	0%	0%
2048	46.9%	66.7%	46.9%	0%	0%	0%
2049	47.5%	66.7%	47.5%	0%	0%	0%
2050	48.2%	66.7%	48.2%	0%	0%	0%
2051	48.8%	66.7%	48.8%	0%	0%	0%
2052	49.4%	66.7%	49.4%	0%	0%	0%
2053	50.1%	66.7%	50.1%	0%	0%	0%
2054	50.7%	66.7%	50.7%	0%	0%	0%
2055	51.3%	66.7%	51.3%	0%	0%	0%

Table B-62 National ZEV sales percentages for Class 6-7 (regClassID 46) single-unit short-haul trucks (sourceTypeID 52)

Model Year	BEV Sales Percentage			FCEV Sales Percentage		
	Reference	**Final Standards**	**Alternative**	**Reference**	**Final Standards**	**Alternative**
2027	6.9%	12.3%	9.4%	0%	0%	0%
2028	10.4%	14.8%	11.9%	0%	0%	0%
2029	13.8%	17.3%	14.4%	0%	0%	0%
2030	17.2%	19.8%	17.2%	0%	0%	0%
2031	18.9%	27.2%	19.2%	0%	0%	0%
2032	20.6%	34.6%	21.6%	0%	0%	0%
2033	22.7%	34.6%	22.7%	0%	0%	0%
2034	24.9%	34.6%	24.9%	0%	0%	0%
2035	27.2%	34.6%	27.2%	0%	0%	0%
2036	27.7%	34.6%	27.7%	0%	0%	0%
2037	28.3%	34.6%	28.3%	0%	0%	0%
2038	28.8%	34.6%	28.8%	0%	0%	0%
2039	29.3%	34.6%	29.3%	0%	0%	0%
2040	29.8%	34.6%	29.8%	0%	0%	0%
2041	30.3%	34.6%	30.3%	0%	0%	0%
2042	30.8%	34.6%	30.8%	0%	0%	0%
2043	31.4%	34.6%	31.4%	0%	0%	0%
2044	31.9%	34.6%	31.9%	0%	0%	0%
2045	32.3%	34.6%	32.3%	0%	0%	0%
2046	32.8%	34.6%	32.8%	0%	0%	0%
2047	33.3%	34.6%	33.3%	0%	0%	0%
2048	33.8%	34.6%	33.8%	0%	0%	0%
2049	34.3%	34.6%	34.3%	0%	0%	0%
2050	34.8%	34.8%	34.8%	0%	0%	0%
2051	35.3%	35.3%	35.3%	0%	0%	0%
2052	35.8%	35.8%	35.8%	0%	0%	0%
2053	36.3%	36.3%	36.3%	0%	0%	0%
2054	36.8%	36.8%	36.8%	0%	0%	0%
2055	37.3%	37.3%	37.3%	0%	0%	0%

Table B-63 National ZEV sales percentages for Class 8 (regClassID 47) single-unit short-haul trucks (sourceTypeID 52)

Model Year	BEV Sales Percentage			FCEV Sales Percentage		
	Reference	Final Standards	Alternative	Reference	Final Standards	Alternative
2027	4.1%	4.1%	4.1%	0%	0%	0%
2028	6.2%	9.2%	6.4%	0%	0%	0%
2029	8.3%	11.6%	8.7%	0%	0%	0%
2030	10.3%	13.9%	11.0%	0%	0%	0%
2031	11.3%	20.9%	13.4%	0%	0%	0%
2032	12.3%	27.9%	15.7%	0%	0%	0%
2033	13.4%	27.9%	15.7%	0%	0%	0%
2034	14.6%	27.9%	15.7%	0%	0%	0%
2035	15.8%	27.9%	15.8%	0%	0%	0%
2036	16.0%	27.9%	16.0%	0%	0%	0%
2037	16.1%	27.9%	16.1%	0%	0%	0%
2038	16.3%	27.9%	16.3%	0%	0%	0%
2039	16.4%	27.9%	16.4%	0%	0%	0%
2040	16.6%	27.9%	16.6%	0%	0%	0%
2041	16.7%	27.9%	16.7%	0%	0%	0%
2042	16.9%	27.9%	16.9%	0%	0%	0%
2043	17.1%	27.9%	17.1%	0%	0%	0%
2044	17.2%	27.9%	17.2%	0%	0%	0%
2045	17.3%	27.9%	17.3%	0%	0%	0%
2046	17.5%	27.9%	17.5%	0%	0%	0%
2047	17.6%	27.9%	17.6%	0%	0%	0%
2048	17.8%	27.9%	17.8%	0%	0%	0%
2049	17.9%	27.9%	17.9%	0%	0%	0%
2050	18.1%	27.9%	18.1%	0%	0%	0%
2051	18.2%	27.9%	18.2%	0%	0%	0%
2052	18.3%	27.9%	18.3%	0%	0%	0%
2053	18.5%	27.9%	18.5%	0%	0%	0%
2054	18.6%	27.9%	18.6%	0%	0%	0%
2055	18.8%	27.9%	18.8%	0%	0%	0%

Table B-64 National ZEV sales percentages for Class 4-5 (regClassID 42) single-unit long-haul trucks (sourceTypeID 53)

Model Year	BEV Sales Percentage			FCEV Sales Percentage		
	Reference	Final Standards	Alternative	Reference	Final Standards	Alternative
2027	9.9%	10.0%	9.9%	0%	0%	0%
2028	14.8%	14.8%	14.8%	0%	0%	0%
2029	19.7%	19.7%	19.7%	0%	0%	0%
2030	24.5%	24.5%	24.5%	0%	0%	0%
2031	26.9%	30.0%	26.9%	0%	0%	0%
2032	29.3%	40.0%	29.3%	0%	0%	0%
2033	32.2%	40.0%	32.2%	0%	0%	0%
2034	35.3%	40.0%	35.3%	0%	0%	0%
2035	38.5%	40.0%	38.5%	0%	0%	0%
2036	39.2%	40.0%	39.2%	0%	0%	0%
2037	39.8%	40.0%	39.8%	0%	0%	0%
2038	40.5%	40.5%	40.5%	0%	0%	0%
2039	41.1%	41.1%	41.1%	0%	0%	0%
2040	41.8%	41.8%	41.8%	0%	0%	0%
2041	42.5%	42.5%	42.5%	0%	0%	0%
2042	43.1%	43.1%	43.1%	0%	0%	0%
2043	43.8%	43.8%	43.8%	0%	0%	0%
2044	44.4%	44.4%	44.4%	0%	0%	0%
2045	45.0%	45.0%	45.0%	0%	0%	0%
2046	45.6%	45.6%	45.6%	0%	0%	0%
2047	46.2%	46.2%	46.2%	0%	0%	0%
2048	46.9%	46.9%	46.9%	0%	0%	0%
2049	47.5%	47.5%	47.5%	0%	0%	0%
2050	48.2%	48.2%	48.2%	0%	0%	0%
2051	48.8%	48.8%	48.8%	0%	0%	0%
2052	49.4%	49.4%	49.4%	0%	0%	0%
2053	50.1%	50.1%	50.1%	0%	0%	0%
2054	50.7%	50.7%	50.7%	0%	0%	0%
2055	51.3%	51.3%	51.3%	0%	0%	0%

Table B-65 National ZEV sales percentages for Class 6-7 (regClassID 46) single-unit long-haul trucks (sourceTypeID 53)

Model Year	BEV Sales Percentage			FCEV Sales Percentage		
	Reference	Final Standards	Alternative	Reference	Final Standards	Alternative
2027	6.9%	14.0%	10.6%	0%	0%	0%
2028	10.4%	16.8%	13.5%	0%	0%	0%
2029	13.8%	19.6%	16.3%	0%	0%	0%
2030	17.2%	22.3%	19.1%	0%	0%	0%
2031	18.9%	30.7%	21.7%	0%	0%	0%
2032	20.6%	39.0%	24.3%	0%	0%	0%
2033	22.7%	39.0%	24.3%	0%	0%	0%
2034	24.9%	39.0%	24.9%	0%	0%	0%
2035	27.2%	39.0%	27.2%	0%	0%	0%
2036	27.7%	39.0%	27.7%	0%	0%	0%
2037	28.3%	39.0%	28.3%	0%	0%	0%
2038	28.8%	39.0%	28.8%	0%	0%	0%
2039	29.3%	39.0%	29.3%	0%	0%	0%
2040	29.8%	39.0%	29.8%	0%	0%	0%
2041	30.3%	39.0%	30.3%	0%	0%	0%
2042	30.8%	39.0%	30.8%	0%	0%	0%
2043	31.4%	39.0%	31.4%	0%	0%	0%
2044	31.9%	39.0%	31.9%	0%	0%	0%
2045	32.3%	39.0%	32.3%	0%	0%	0%
2046	32.8%	39.0%	32.8%	0%	0%	0%
2047	33.3%	39.0%	33.3%	0%	0%	0%
2048	33.8%	39.0%	33.8%	0%	0%	0%
2049	34.3%	39.0%	34.3%	0%	0%	0%
2050	34.8%	39.0%	34.8%	0%	0%	0%
2051	35.3%	39.0%	35.3%	0%	0%	0%
2052	35.8%	39.0%	35.8%	0%	0%	0%
2053	36.3%	39.0%	36.3%	0%	0%	0%
2054	36.8%	39.0%	36.8%	0%	0%	0%
2055	37.3%	39.0%	37.3%	0%	0%	0%

Table B-66 National ZEV sales percentages for Class 8 (regClassID 47) single-unit long-haul trucks (sourceTypeID 53)

Model Year	BEV Sales Percentage			FCEV Sales Percentage		
	Reference	Final Standards	Alternative	Reference	Final Standards	Alternative
2027	4.1%	4.1%	4.1%	0%	0%	0%
2028	6.2%	6.2%	6.2%	0%	0%	0%
2029	8.3%	9.3%	8.3%	0%	0%	0%
2030	10.3%	13.5%	10.7%	0%	0%	0%
2031	11.3%	26.3%	16.8%	0%	0%	0%
2032	12.3%	39.0%	22.1%	0%	0%	0%
2033	13.4%	39.0%	22.1%	0%	0%	0%
2034	14.6%	39.0%	22.1%	0%	0%	0%
2035	15.8%	39.0%	22.1%	0%	0%	0%
2036	16.0%	39.0%	22.1%	0%	0%	0%
2037	16.1%	39.0%	22.1%	0%	0%	0%
2038	16.3%	39.0%	22.1%	0%	0%	0%
2039	16.4%	39.0%	22.1%	0%	0%	0%
2040	16.6%	39.0%	22.1%	0%	0%	0%
2041	16.7%	39.0%	22.1%	0%	0%	0%
2042	16.9%	39.0%	22.1%	0%	0%	0%
2043	17.1%	39.0%	22.1%	0%	0%	0%
2044	17.2%	39.0%	22.1%	0%	0%	0%
2045	17.3%	39.0%	22.1%	0%	0%	0%
2046	17.5%	39.0%	22.1%	0%	0%	0%
2047	17.6%	39.0%	22.1%	0%	0%	0%
2048	17.8%	39.0%	22.1%	0%	0%	0%
2049	17.9%	39.0%	22.1%	0%	0%	0%
2050	18.1%	39.0%	22.1%	0%	0%	0%
2051	18.2%	39.0%	22.1%	0%	0%	0%
2052	18.3%	39.0%	22.1%	0%	0%	0%
2053	18.5%	39.0%	22.1%	0%	0%	0%
2054	18.6%	39.0%	22.1%	0%	0%	0%
2055	18.8%	39.0%	22.1%	0%	0%	0%

Table B-67 National ZEV sales percentages for Class 4-5 (regClassID 42) motor homes (sourceTypeID 54)

Model Year	BEV Sales Percentage			FCEV Sales Percentage		
	Reference	Final Standards	Alternative	Reference	Final Standards	Alternative
2027	10.7%	10.7%	10.7%	0%	0%	0%
2028	16.1%	16.1%	16.1%	0%	0%	0%
2029	21.4%	21.4%	21.4%	0%	0%	0%
2030	26.7%	26.7%	26.7%	0%	0%	0%
2031	29.3%	29.3%	29.3%	0%	0%	0%
2032	31.9%	31.9%	31.9%	0%	0%	0%
2033	35.0%	35.0%	35.0%	0%	0%	0%
2034	38.3%	38.3%	38.3%	0%	0%	0%
2035	41.6%	41.6%	41.6%	0%	0%	0%
2036	42.2%	42.2%	42.2%	0%	0%	0%
2037	42.9%	42.9%	42.9%	0%	0%	0%
2038	43.5%	43.5%	43.5%	0%	0%	0%
2039	44.1%	44.1%	44.1%	0%	0%	0%
2040	44.7%	44.7%	44.7%	0%	0%	0%
2041	45.3%	45.3%	45.3%	0%	0%	0%
2042	45.9%	45.9%	45.9%	0%	0%	0%
2043	46.6%	46.6%	46.6%	0%	0%	0%
2044	47.2%	47.2%	47.2%	0%	0%	0%
2045	47.7%	47.7%	47.7%	0%	0%	0%
2046	48.2%	48.2%	48.2%	0%	0%	0%
2047	48.8%	48.8%	48.8%	0%	0%	0%
2048	49.5%	49.5%	49.5%	0%	0%	0%
2049	50.0%	50.0%	50.0%	0%	0%	0%
2050	50.6%	50.6%	50.6%	0%	0%	0%
2051	51.2%	51.2%	51.2%	0%	0%	0%
2052	51.8%	51.8%	51.8%	0%	0%	0%
2053	52.4%	52.4%	52.4%	0%	0%	0%
2054	53.0%	53.0%	53.0%	0%	0%	0%
2055	53.6%	53.6%	53.6%	0%	0%	0%

Table B-68 National ZEV sales percentages for Class 6-7 (regClassID 46) motor homes (sourceTypeID 54)

Model Year	BEV Sales Percentage			FCEV Sales Percentage		
	Reference	Final Standards	Alternative	Reference	Final Standards	Alternative
2027	7.5%	7.5%	7.5%	0%	0%	0%
2028	11.2%	11.2%	11.2%	0%	0%	0%
2029	14.9%	14.9%	14.9%	0%	0%	0%
2030	18.6%	18.6%	18.6%	0%	0%	0%
2031	20.4%	20.4%	20.4%	0%	0%	0%
2032	22.2%	22.2%	22.2%	0%	0%	0%
2033	24.4%	24.4%	24.4%	0%	0%	0%
2034	26.7%	26.7%	26.7%	0%	0%	0%
2035	29.2%	29.2%	29.2%	0%	0%	0%
2036	29.7%	29.7%	29.7%	0%	0%	0%
2037	30.1%	30.1%	30.1%	0%	0%	0%
2038	30.6%	30.6%	30.6%	0%	0%	0%
2039	31.1%	31.1%	31.1%	0%	0%	0%
2040	31.6%	31.6%	31.6%	0%	0%	0%
2041	32.1%	32.1%	32.1%	0%	0%	0%
2042	32.6%	32.6%	32.6%	0%	0%	0%
2043	33.1%	33.1%	33.1%	0%	0%	0%
2044	33.6%	33.6%	33.6%	0%	0%	0%
2045	34.0%	34.0%	34.0%	0%	0%	0%
2046	34.4%	34.4%	34.4%	0%	0%	0%
2047	34.9%	34.9%	34.9%	0%	0%	0%
2048	35.4%	35.4%	35.4%	0%	0%	0%
2049	35.9%	35.9%	35.9%	0%	0%	0%
2050	36.4%	36.4%	36.4%	0%	0%	0%
2051	36.8%	36.8%	36.8%	0%	0%	0%
2052	37.3%	37.3%	37.3%	0%	0%	0%
2053	37.8%	37.8%	37.8%	0%	0%	0%
2054	38.2%	38.2%	38.2%	0%	0%	0%
2055	38.7%	38.7%	38.7%	0%	0%	0%

Table B-69 National ZEV sales percentages for Class 8 (regClassID 47) motor homes (sourceTypeID 54)

Model Year	BEV Sales Percentage			FCEV Sales Percentage		
	Reference	Final Standards	Alternative	Reference	Final Standards	Alternative
2027	3.5%	3.5%	3.5%	0%	0%	0%
2028	5.2%	5.2%	5.2%	0%	0%	0%
2029	7.0%	7.0%	7.0%	0%	0%	0%
2030	8.7%	8.7%	8.7%	0%	0%	0%
2031	9.5%	9.5%	9.5%	0%	0%	0%
2032	10.4%	10.4%	10.4%	0%	0%	0%
2033	11.4%	11.4%	11.4%	0%	0%	0%
2034	12.4%	12.4%	12.4%	0%	0%	0%
2035	13.5%	13.5%	13.5%	0%	0%	0%
2036	13.6%	13.6%	13.6%	0%	0%	0%
2037	13.8%	13.8%	13.8%	0%	0%	0%
2038	14.0%	14.0%	14.0%	0%	0%	0%
2039	14.1%	14.1%	14.1%	0%	0%	0%
2040	14.3%	14.3%	14.3%	0%	0%	0%
2041	14.5%	14.5%	14.5%	0%	0%	0%
2042	14.6%	14.6%	14.6%	0%	0%	0%
2043	14.8%	14.8%	14.8%	0%	0%	0%
2044	15.0%	15.0%	15.0%	0%	0%	0%
2045	15.1%	15.1%	15.1%	0%	0%	0%
2046	15.3%	15.3%	15.3%	0%	0%	0%
2047	15.4%	15.4%	15.4%	0%	0%	0%
2048	15.6%	15.6%	15.6%	0%	0%	0%
2049	15.8%	15.8%	15.8%	0%	0%	0%
2050	15.9%	15.9%	15.9%	0%	0%	0%
2051	16.1%	16.1%	16.1%	0%	0%	0%
2052	16.2%	16.2%	16.2%	0%	0%	0%
2053	16.4%	16.4%	16.4%	0%	0%	0%
2054	16.6%	16.6%	16.6%	0%	0%	0%
2055	16.7%	16.7%	16.7%	0%	0%	0%

Table B-70 National ZEV sales percentages for Class 6-7 (regClassID 46) single-unit short-haul trucks (sourceTypeID 61)

Model Year	BEV Sales Percentage			FCEV Sales Percentage		
	Reference	Final Standards	Alternative	Reference	Final Standards	Alternative
2027	5.1%	7.0%	5.1%	0.0%	0.0%	0.0%
2028	6.6%	8.6%	6.7%	0.0%	0.0%	0.0%
2029	8.1%	10.2%	8.6%	0.0%	0.0%	0.0%
2030	7.1%	10.2%	8.5%	2.4%	3.4%	2.8%
2031	7.5%	15.1%	9.3%	2.5%	5.1%	3.1%
2032	8.4%	21.4%	11.0%	2.8%	7.2%	3.7%
2033	8.6%	21.4%	11.0%	2.9%	7.2%	3.7%
2034	8.7%	21.4%	11.0%	2.9%	7.2%	3.7%
2035	8.8%	21.4%	11.0%	3.0%	7.2%	3.7%
2036	9.0%	21.4%	11.0%	3.0%	7.2%	3.7%
2037	9.1%	21.4%	11.0%	3.1%	7.2%	3.7%
2038	9.3%	21.4%	11.0%	3.1%	7.2%	3.7%
2039	9.4%	21.4%	11.0%	3.2%	7.2%	3.7%
2040	9.6%	21.4%	11.0%	3.2%	7.2%	3.7%
2041	9.7%	21.4%	11.0%	3.3%	7.2%	3.7%
2042	9.9%	21.4%	11.0%	3.3%	7.2%	3.7%
2043	10.0%	21.4%	11.0%	3.4%	7.2%	3.7%
2044	10.2%	21.4%	11.0%	3.4%	7.2%	3.7%
2045	10.3%	21.4%	11.0%	3.5%	7.2%	3.7%
2046	10.5%	21.4%	11.0%	3.5%	7.2%	3.7%
2047	10.6%	21.4%	11.0%	3.6%	7.2%	3.7%
2048	10.8%	21.4%	11.0%	3.6%	7.2%	3.7%
2049	10.9%	21.4%	11.0%	3.7%	7.2%	3.7%
2050	11.1%	21.4%	11.1%	3.7%	7.2%	3.7%
2051	11.2%	21.4%	11.2%	3.8%	7.2%	3.8%
2052	11.4%	21.4%	11.4%	3.8%	7.2%	3.8%
2053	11.5%	21.4%	11.5%	3.9%	7.2%	3.9%
2054	11.7%	21.4%	11.7%	3.9%	7.2%	3.9%
2055	11.8%	21.4%	11.8%	4.0%	7.2%	4.0%

Table B-71 National ZEV sales percentages for Class 8 (regClassID 47) single-unit short-haul trucks (sourceTypeID 61)

Model Year	BEV Sales Percentage			FCEV Sales Percentage		
	Reference	**Final Standards**	**Alternative**	**Reference**	**Final Standards**	**Alternative**
2027	4.5%	4.5%	4.5%	0.0%	0.0%	0.0%
2028	5.9%	8.3%	6.5%	0.0%	0.0%	0.0%
2029	7.1%	12.7%	10.7%	0.0%	0.0%	0.0%
2030	8.1%	16.9%	14.0%	0.3%	0.7%	0.6%
2031	8.6%	30.0%	18.4%	0.3%	1.2%	0.7%
2032	9.6%	43.5%	22.4%	0.4%	1.7%	0.9%
2033	9.7%	43.5%	22.4%	0.4%	1.7%	0.9%
2034	9.9%	43.5%	22.4%	0.4%	1.7%	0.9%
2035	10.1%	43.5%	22.4%	0.4%	1.7%	0.9%
2036	10.3%	43.5%	22.4%	0.4%	1.7%	0.9%
2037	10.5%	43.5%	22.4%	0.4%	1.7%	0.9%
2038	10.7%	43.5%	22.4%	0.4%	1.7%	0.9%
2039	10.9%	43.5%	22.4%	0.4%	1.7%	0.9%
2040	11.1%	43.5%	22.4%	0.4%	1.7%	0.9%
2041	11.3%	43.5%	22.4%	0.5%	1.7%	0.9%
2042	11.5%	43.5%	22.4%	0.5%	1.7%	0.9%
2043	11.7%	43.5%	22.4%	0.5%	1.7%	0.9%
2044	11.9%	43.5%	22.4%	0.5%	1.7%	0.9%
2045	12.1%	43.5%	22.4%	0.5%	1.7%	0.9%
2046	12.3%	43.5%	22.4%	0.5%	1.7%	0.9%
2047	12.5%	43.5%	22.4%	0.5%	1.7%	0.9%
2048	12.7%	43.5%	22.4%	0.5%	1.7%	0.9%
2049	12.9%	43.5%	22.4%	0.5%	1.7%	0.9%
2050	13.1%	43.5%	22.4%	0.5%	1.7%	0.9%
2051	13.3%	43.5%	22.4%	0.5%	1.7%	0.9%
2052	13.5%	43.5%	22.4%	0.5%	1.7%	0.9%
2053	13.7%	43.5%	22.4%	0.5%	1.7%	0.9%
2054	13.9%	43.5%	22.4%	0.6%	1.7%	0.9%
2055	14.1%	43.5%	22.4%	0.6%	1.7%	0.9%

Table B-72 National ZEV sales percentages for Class 6-7 (regClassID 46) single-unit long-haul trucks (sourceTypeID 62)

Model Year	BEV Sales Percentage			FCEV Sales Percentage		
	Reference	Final Standards	Alternative	Reference	Final Standards	Alternative
2027	0.4%	0.4%	0.4%	0.0%	0.0%	0.0%
2028	0.8%	0.8%	0.8%	0.0%	0.0%	0.0%
2029	1.4%	1.4%	1.4%	0.0%	0.0%	0.0%
2030	1.3%	3.9%	3.2%	0.8%	2.3%	1.8%
2031	2.6%	7.9%	6.3%	1.5%	4.6%	3.7%
2032	3.2%	15.8%	9.5%	1.9%	9.2%	5.5%
2033	3.3%	15.8%	9.5%	1.9%	9.2%	5.5%
2034	3.4%	15.8%	9.5%	2.0%	9.2%	5.5%
2035	3.4%	15.8%	9.5%	2.0%	9.2%	5.5%
2036	3.5%	15.8%	9.5%	2.0%	9.2%	5.5%
2037	3.6%	15.8%	9.5%	2.1%	9.2%	5.5%
2038	3.6%	15.8%	9.5%	2.1%	9.2%	5.5%
2039	3.7%	15.8%	9.5%	2.2%	9.2%	5.5%
2040	3.8%	15.8%	9.5%	2.2%	9.2%	5.5%
2041	3.8%	15.8%	9.5%	2.2%	9.2%	5.5%
2042	3.9%	15.8%	9.5%	2.3%	9.2%	5.5%
2043	4.0%	15.8%	9.5%	2.3%	9.2%	5.5%
2044	4.0%	15.8%	9.5%	2.4%	9.2%	5.5%
2045	4.1%	15.8%	9.5%	2.4%	9.2%	5.5%
2046	4.2%	15.8%	9.5%	2.4%	9.2%	5.5%
2047	4.3%	15.8%	9.5%	2.5%	9.2%	5.5%
2048	4.3%	15.8%	9.5%	2.5%	9.2%	5.5%
2049	4.4%	15.8%	9.5%	2.6%	9.2%	5.5%
2050	4.5%	15.8%	9.5%	2.6%	9.2%	5.5%
2051	4.5%	15.8%	9.5%	2.6%	9.2%	5.5%
2052	4.6%	15.8%	9.5%	2.7%	9.2%	5.5%
2053	4.7%	15.8%	9.5%	2.7%	9.2%	5.5%
2054	4.7%	15.8%	9.5%	2.8%	9.2%	5.5%
2055	4.8%	15.8%	9.5%	2.8%	9.2%	5.5%

Table B-73 National ZEV sales percentages for Class 8 (regClassID 47) single-unit long-haul trucks (sourceTypeID 62)

Model Year	BEV Sales Percentage			FCEV Sales Percentage		
	Reference	Final Standards	Alternative	Reference	Final Standards	Alternative
2027	0.4%	0.4%	0.4%	0.0%	0.0%	0.0%
2028	0.7%	0.7%	0.7%	0.0%	0.0%	0.0%
2029	1.3%	1.3%	1.3%	0.0%	0.0%	0.0%
2030	1.2%	3.9%	3.2%	0.7%	2.3%	1.8%
2031	2.4%	7.9%	6.3%	1.4%	4.6%	3.7%
2032	2.9%	15.8%	9.5%	1.7%	9.2%	5.5%
2033	3.0%	15.8%	9.5%	1.7%	9.2%	5.5%
2034	3.1%	15.8%	9.5%	1.8%	9.2%	5.5%
2035	3.1%	15.8%	9.5%	1.8%	9.2%	5.5%
2036	3.2%	15.8%	9.5%	1.9%	9.2%	5.5%
2037	3.3%	15.8%	9.5%	1.9%	9.2%	5.5%
2038	3.4%	15.8%	9.5%	2.0%	9.2%	5.5%
2039	3.4%	15.8%	9.5%	2.0%	9.2%	5.5%
2040	3.5%	15.8%	9.5%	2.0%	9.2%	5.5%
2041	3.6%	15.8%	9.5%	2.1%	9.2%	5.5%
2042	3.6%	15.8%	9.5%	2.1%	9.2%	5.5%
2043	3.7%	15.8%	9.5%	2.2%	9.2%	5.5%
2044	3.8%	15.8%	9.5%	2.2%	9.2%	5.5%
2045	3.9%	15.8%	9.5%	2.2%	9.2%	5.5%
2046	3.9%	15.8%	9.5%	2.3%	9.2%	5.5%
2047	4.0%	15.8%	9.5%	2.3%	9.2%	5.5%
2048	4.1%	15.8%	9.5%	2.4%	9.2%	5.5%
2049	4.1%	15.8%	9.5%	2.4%	9.2%	5.5%
2050	4.2%	15.8%	9.5%	2.5%	9.2%	5.5%
2051	4.3%	15.8%	9.5%	2.5%	9.2%	5.5%
2052	4.3%	15.8%	9.5%	2.5%	9.2%	5.5%
2053	4.4%	15.8%	9.5%	2.6%	9.2%	5.5%
2054	4.5%	15.8%	9.5%	2.6%	9.2%	5.5%
2055	4.6%	15.8%	9.5%	2.7%	9.2%	5.5%

B.4 Reference Case ZEV Adoption Sensitivity Sales Percentages

In the reference case HD ZEV adoption sensitivity analysis (presented in RIA Chapter 4.10), we analyzed HD ZEV adoption only at the national level, instead of grouping states into ACT or non-ACT states.

Table B-74 National ZEV sales percentages for Class 4-5 (regClassID 42) other buses (sourceTypeID 41) in the reference case ZEV adoption sensitivity analysis

Model Year	BEV Sales Percentage		FCEV Sales Percentage	
	Sensitivity Reference	Sensitivity Control	Sensitivity Reference	Sensitivity Control
2027	10.5%	20.0%	0%	0%
2028	15.8%	25.2%	0%	0%
2029	21.0%	30.4%	0%	0%
2030	26.1%	35.6%	0%	0%
2031	28.6%	51.1%	0%	0%
2032	31.2%	66.7%	0%	0%
2033	33.8%	66.7%	0%	0%
2034	36.4%	66.7%	0%	0%
2035	38.9%	66.7%	0%	0%
2036	38.8%	66.7%	0%	0%
2037	38.8%	66.7%	0%	0%
2038	38.7%	66.7%	0%	0%
2039	38.7%	66.7%	0%	0%
2040	38.6%	66.7%	0%	0%
2041	38.6%	66.7%	0%	0%
2042	38.5%	66.7%	0%	0%
2043	38.5%	66.7%	0%	0%
2044	38.4%	66.7%	0%	0%
2045	38.3%	66.7%	0%	0%
2046	38.2%	66.7%	0%	0%
2047	38.1%	66.7%	0%	0%
2048	38.1%	66.7%	0%	0%
2049	38.0%	66.7%	0%	0%
2050	38.0%	66.7%	0%	0%
2051	37.9%	66.7%	0%	0%
2052	37.9%	66.7%	0%	0%
2053	37.8%	66.7%	0%	0%
2054	37.8%	66.7%	0%	0%
2055	37.7%	66.7%	0%	0%

Table B-75 National ZEV sales percentages for Class 6-7 (regClassID 46) other buses (sourceTypeID 41) in the reference case ZEV adoption sensitivity analysis

Model Year	BEV Sales Percentage		FCEV Sales Percentage	
	Sensitivity Reference	Sensitivity Control	Sensitivity Reference	Sensitivity Control
2027	4.1%	14.0%	0%	0%
2028	6.2%	14.0%	0%	0%
2029	8.3%	14.0%	0%	0%
2030	10.3%	14.0%	0%	0%
2031	11.3%	14.0%	0%	0%
2032	12.3%	14.0%	0%	0%
2033	13.3%	14.0%	0%	0%
2034	14.3%	14.3%	0%	0%
2035	15.3%	15.3%	0%	0%
2036	15.3%	15.3%	0%	0%
2037	15.3%	15.3%	0%	0%
2038	15.2%	15.2%	0%	0%
2039	15.2%	15.2%	0%	0%
2040	15.2%	15.2%	0%	0%
2041	15.2%	15.2%	0%	0%
2042	15.1%	15.1%	0%	0%
2043	15.1%	15.1%	0%	0%
2044	15.1%	15.1%	0%	0%
2045	15.1%	15.1%	0%	0%
2046	15.0%	15.0%	0%	0%
2047	15.0%	15.0%	0%	0%
2048	15.0%	15.0%	0%	0%
2049	15.0%	15.0%	0%	0%
2050	14.9%	14.9%	0%	0%
2051	14.9%	14.9%	0%	0%
2052	14.9%	14.9%	0%	0%
2053	14.9%	14.9%	0%	0%
2054	14.8%	14.8%	0%	0%
2055	14.8%	14.8%	0%	0%

Table B-76 National ZEV sales percentages for Class 8 (regClassID 47) other buses (sourceTypeID 41) in the reference case ZEV adoption sensitivity analysis

Model Year	BEV Sales Percentage		FCEV Sales Percentage	
	Sensitivity Reference	Sensitivity Control	Sensitivity Reference	Sensitivity Control
2027	5.3%	5.3%	0.0%	0.0%
2028	8.0%	8.0%	0.0%	0.0%
2029	10.6%	10.6%	0.0%	0.0%
2030	10.6%	10.6%	2.6%	2.6%
2031	10.6%	10.6%	3.9%	3.9%
2032	10.6%	10.6%	5.2%	5.2%
2033	10.6%	10.6%	6.5%	6.5%
2034	10.6%	10.6%	7.8%	7.8%
2035	10.6%	10.6%	9.0%	9.0%
2036	10.6%	10.6%	9.0%	9.0%
2037	10.6%	10.6%	9.0%	9.0%
2038	10.6%	10.6%	8.9%	8.9%
2039	10.6%	10.6%	8.9%	8.9%
2040	10.6%	10.6%	8.9%	8.9%
2041	10.6%	10.6%	8.9%	8.9%
2042	10.6%	10.6%	8.8%	8.8%
2043	10.6%	10.6%	8.8%	8.8%
2044	10.6%	10.6%	8.8%	8.8%
2045	10.6%	10.6%	8.7%	8.7%
2046	10.6%	10.6%	8.7%	8.7%
2047	10.6%	10.6%	8.6%	8.6%
2048	10.6%	10.6%	8.6%	8.6%
2049	10.6%	10.6%	8.6%	8.6%
2050	10.6%	10.6%	8.6%	8.6%
2051	10.6%	10.6%	8.5%	8.5%
2052	10.6%	10.6%	8.5%	8.5%
2053	10.6%	10.6%	8.5%	8.5%
2054	10.6%	10.6%	8.5%	8.5%
2055	10.6%	10.6%	8.4%	8.4%

Table B-77 National ZEV sales percentages for Class 4-5 (regClassID 42) transit buses (sourceTypeID 42) in the reference case ZEV adoption sensitivity analysis

Model Year	BEV Sales Percentage		FCEV Sales Percentage	
	Sensitivity Reference	Sensitivity Control	Sensitivity Reference	Sensitivity Control
2027	10.5%	20.0%	0%	0%
2028	15.8%	25.2%	0%	0%
2029	21.0%	30.4%	0%	0%
2030	26.1%	35.6%	0%	0%
2031	28.6%	51.1%	0%	0%
2032	31.2%	66.7%	0%	0%
2033	33.8%	66.7%	0%	0%
2034	36.4%	66.7%	0%	0%
2035	38.9%	66.7%	0%	0%
2036	38.8%	66.7%	0%	0%
2037	38.8%	66.7%	0%	0%
2038	38.7%	66.7%	0%	0%
2039	38.7%	66.7%	0%	0%
2040	38.6%	66.7%	0%	0%
2041	38.6%	66.7%	0%	0%
2042	38.5%	66.7%	0%	0%
2043	38.5%	66.7%	0%	0%
2044	38.4%	66.7%	0%	0%
2045	38.3%	66.7%	0%	0%
2046	38.2%	66.7%	0%	0%
2047	38.1%	66.7%	0%	0%
2048	38.1%	66.7%	0%	0%
2049	38.0%	66.7%	0%	0%
2050	38.0%	66.7%	0%	0%
2051	37.9%	66.7%	0%	0%
2052	37.9%	66.7%	0%	0%
2053	37.8%	66.7%	0%	0%
2054	37.8%	66.7%	0%	0%
2055	37.7%	66.7%	0%	0%

Table B-78 National ZEV sales percentages for Class 6-7 (regClassID 46) transit buses (sourceTypeID 42) in the reference case ZEV adoption sensitivity analysis

Model Year	BEV Sales Percentage		FCEV Sales Percentage	
	Sensitivity Reference	Sensitivity Control	Sensitivity Reference	Sensitivity Control
2027	4.1%	10.0%	0%	0%
2028	6.2%	11.4%	0%	0%
2029	8.3%	12.7%	0%	0%
2030	10.3%	14.1%	0%	0%
2031	11.3%	18.2%	0%	0%
2032	12.3%	22.3%	0%	0%
2033	13.3%	22.3%	0%	0%
2034	14.3%	22.3%	0%	0%
2035	15.3%	22.3%	0%	0%
2036	15.3%	22.3%	0%	0%
2037	15.3%	22.3%	0%	0%
2038	15.2%	22.3%	0%	0%
2039	15.2%	22.3%	0%	0%
2040	15.2%	22.3%	0%	0%
2041	15.2%	22.3%	0%	0%
2042	15.1%	22.3%	0%	0%
2043	15.1%	22.3%	0%	0%
2044	15.1%	22.3%	0%	0%
2045	15.1%	22.3%	0%	0%
2046	15.0%	22.3%	0%	0%
2047	15.0%	22.3%	0%	0%
2048	15.0%	22.3%	0%	0%
2049	15.0%	22.3%	0%	0%
2050	14.9%	22.3%	0%	0%
2051	14.9%	22.3%	0%	0%
2052	14.9%	22.3%	0%	0%
2053	14.9%	22.3%	0%	0%
2054	14.8%	22.3%	0%	0%
2055	14.8%	22.3%	0%	0%

Table B-79 National ZEV sales percentages for urban buses (regClassID 48 and sourceTypeID 42) in the reference case ZEV adoption sensitivity analysis

Model Year	BEV Sales Percentage		FCEV Sales Percentage	
	Sensitivity Reference	Sensitivity Control	Sensitivity Reference	Sensitivity Control
2027	5.3%	5.3%	0%	0%
2028	8.0%	14.0%	0%	0%
2029	10.6%	17.1%	0%	0%
2030	13.2%	20.3%	0%	0%
2031	14.4%	29.6%	0%	0%
2032	15.7%	39.0%	0%	0%
2033	17.0%	39.0%	0%	0%
2034	18.3%	39.0%	0%	0%
2035	19.6%	39.0%	0%	0%
2036	19.6%	39.0%	0%	0%
2037	19.6%	39.0%	0%	0%
2038	19.5%	39.0%	0%	0%
2039	19.5%	39.0%	0%	0%
2040	19.5%	39.0%	0%	0%
2041	19.4%	39.0%	0%	0%
2042	19.4%	39.0%	0%	0%
2043	19.4%	39.0%	0%	0%
2044	19.4%	39.0%	0%	0%
2045	19.3%	39.0%	0%	0%
2046	19.3%	39.0%	0%	0%
2047	19.2%	39.0%	0%	0%
2048	19.2%	39.0%	0%	0%
2049	19.2%	39.0%	0%	0%
2050	19.2%	39.0%	0%	0%
2051	19.1%	39.0%	0%	0%
2052	19.1%	39.0%	0%	0%
2053	19.1%	39.0%	0%	0%
2054	19.0%	39.0%	0%	0%
2055	19.0%	39.0%	0%	0%

Table B-80 National ZEV sales percentages for Class 4-5 (regClassID 42) school buses (sourceTypeID 43) in the reference case ZEV adoption sensitivity analysis

Model Year	BEV Sales Percentage		FCEV Sales Percentage	
	Sensitivity Reference	Sensitivity Control	Sensitivity Reference	Sensitivity Control
2027	8.4%	20.0%	0%	0%
2028	12.6%	25.2%	0%	0%
2029	16.7%	30.4%	0%	0%
2030	20.8%	35.6%	0%	0%
2031	22.8%	51.1%	0%	0%
2032	24.8%	66.7%	0%	0%
2033	26.9%	66.7%	0%	0%
2034	28.9%	66.7%	0%	0%
2035	30.9%	66.7%	0%	0%
2036	30.9%	66.7%	0%	0%
2037	30.9%	66.7%	0%	0%
2038	30.8%	66.7%	0%	0%
2039	30.7%	66.7%	0%	0%
2040	30.7%	66.7%	0%	0%
2041	30.7%	66.7%	0%	0%
2042	30.6%	66.7%	0%	0%
2043	30.6%	66.7%	0%	0%
2044	30.6%	66.7%	0%	0%
2045	30.5%	66.7%	0%	0%
2046	30.4%	66.7%	0%	0%
2047	30.3%	66.7%	0%	0%
2048	30.3%	66.7%	0%	0%
2049	30.3%	66.7%	0%	0%
2050	30.2%	66.7%	0%	0%
2051	30.2%	66.7%	0%	0%
2052	30.1%	66.7%	0%	0%
2053	30.1%	66.7%	0%	0%
2054	30.0%	66.7%	0%	0%
2055	30.0%	66.7%	0%	0%

Table B-81 National ZEV sales percentages for Class 6-7 (regClassID 46) school buses (sourceTypeID 43) in the reference case ZEV adoption sensitivity analysis

Model Year	BEV Sales Percentage		FCEV Sales Percentage	
	Sensitivity Reference	Sensitivity Control	Sensitivity Reference	Sensitivity Control
2027	3.6%	20.0%	0%	0%
2028	5.4%	25.6%	0%	0%
2029	7.1%	31.1%	0%	0%
2030	8.9%	36.7%	0%	0%
2031	9.7%	53.3%	0%	0%
2032	10.6%	70.0%	0%	0%
2033	11.5%	70.0%	0%	0%
2034	12.4%	70.0%	0%	0%
2035	13.2%	70.0%	0%	0%
2036	13.2%	70.0%	0%	0%
2037	13.2%	70.0%	0%	0%
2038	13.2%	70.0%	0%	0%
2039	13.1%	70.0%	0%	0%
2040	13.1%	70.0%	0%	0%
2041	13.1%	70.0%	0%	0%
2042	13.1%	70.0%	0%	0%
2043	13.1%	70.0%	0%	0%
2044	13.1%	70.0%	0%	0%
2045	13.0%	70.0%	0%	0%
2046	13.0%	70.0%	0%	0%
2047	13.0%	70.0%	0%	0%
2048	13.0%	70.0%	0%	0%
2049	12.9%	70.0%	0%	0%
2050	12.9%	70.0%	0%	0%
2051	12.9%	70.0%	0%	0%
2052	12.9%	70.0%	0%	0%
2053	12.9%	70.0%	0%	0%
2054	12.8%	70.0%	0%	0%
2055	12.8%	70.0%	0%	0%

Table B-82 National ZEV sales percentages for Class 8 (regClassID 47) school buses (sourceTypeID 43) in the reference case ZEV adoption sensitivity analysis

Model Year	BEV Sales Percentage		FCEV Sales Percentage	
	Sensitivity Reference	Sensitivity Control	Sensitivity Reference	Sensitivity Control
2027	4.8%	4.8%	0%	0%
2028	7.2%	17.0%	0%	0%
2029	9.5%	19.7%	0%	0%
2030	11.9%	22.5%	0%	0%
2031	13.0%	30.8%	0%	0%
2032	14.2%	39.0%	0%	0%
2033	15.3%	39.0%	0%	0%
2034	16.5%	39.0%	0%	0%
2035	17.7%	39.0%	0%	0%
2036	17.6%	39.0%	0%	0%
2037	17.6%	39.0%	0%	0%
2038	17.6%	39.0%	0%	0%
2039	17.6%	39.0%	0%	0%
2040	17.5%	39.0%	0%	0%
2041	17.5%	39.0%	0%	0%
2042	17.5%	39.0%	0%	0%
2043	17.5%	39.0%	0%	0%
2044	17.4%	39.0%	0%	0%
2045	17.4%	39.0%	0%	0%
2046	17.3%	39.0%	0%	0%
2047	17.3%	39.0%	0%	0%
2048	17.3%	39.0%	0%	0%
2049	17.3%	39.0%	0%	0%
2050	17.3%	39.0%	0%	0%
2051	17.2%	39.0%	0%	0%
2052	17.2%	39.0%	0%	0%
2053	17.2%	39.0%	0%	0%
2054	17.1%	39.0%	0%	0%
2055	17.1%	39.0%	0%	0%

Table B-83 National ZEV sales percentages for Class 6-7 (regClassID 46) refuse trucks (sourceTypeID 51) in the reference case ZEV adoption sensitivity analysis

Model Year	BEV Sales Percentage		FCEV Sales Percentage	
	Sensitivity Reference	Sensitivity Control	Sensitivity Reference	Sensitivity Control
2027	4.5%	20.0%	0%	0%
2028	6.8%	22.1%	0%	0%
2029	9.0%	24.2%	0%	0%
2030	11.2%	26.3%	0%	0%
2031	12.3%	32.7%	0%	0%
2032	13.4%	39.0%	0%	0%
2033	14.5%	39.0%	0%	0%
2034	15.6%	39.0%	0%	0%
2035	16.7%	39.0%	0%	0%
2036	16.6%	39.0%	0%	0%
2037	16.6%	39.0%	0%	0%
2038	16.6%	39.0%	0%	0%
2039	16.6%	39.0%	0%	0%
2040	16.5%	39.0%	0%	0%
2041	16.5%	39.0%	0%	0%
2042	16.5%	39.0%	0%	0%
2043	16.5%	39.0%	0%	0%
2044	16.5%	39.0%	0%	0%
2045	16.4%	39.0%	0%	0%
2046	16.4%	39.0%	0%	0%
2047	16.3%	39.0%	0%	0%
2048	16.3%	39.0%	0%	0%
2049	16.3%	39.0%	0%	0%
2050	16.3%	39.0%	0%	0%
2051	16.2%	39.0%	0%	0%
2052	16.2%	39.0%	0%	0%
2053	16.2%	39.0%	0%	0%
2054	16.2%	39.0%	0%	0%
2055	16.2%	39.0%	0%	0%

Table B-84 National ZEV sales percentages for Class 8 (regClassID 47) refuse trucks (sourceTypeID 51) in the reference case ZEV adoption sensitivity analysis

Model Year	BEV Sales Percentage		FCEV Sales Percentage	
	Sensitivity Reference	Sensitivity Control	Sensitivity Reference	Sensitivity Control
2027	2.5%	2.5%	0%	0%
2028	3.8%	14.0%	0%	0%
2029	5.0%	17.1%	0%	0%
2030	6.3%	20.3%	0%	0%
2031	6.9%	29.6%	0%	0%
2032	7.5%	39.0%	0%	0%
2033	8.1%	39.0%	0%	0%
2034	8.7%	39.0%	0%	0%
2035	9.3%	39.0%	0%	0%
2036	9.3%	39.0%	0%	0%
2037	9.3%	39.0%	0%	0%
2038	9.3%	39.0%	0%	0%
2039	9.3%	39.0%	0%	0%
2040	9.2%	39.0%	0%	0%
2041	9.2%	39.0%	0%	0%
2042	9.2%	39.0%	0%	0%
2043	9.2%	39.0%	0%	0%
2044	9.2%	39.0%	0%	0%
2045	9.2%	39.0%	0%	0%
2046	9.1%	39.0%	0%	0%
2047	9.1%	39.0%	0%	0%
2048	9.1%	39.0%	0%	0%
2049	9.1%	39.0%	0%	0%
2050	9.1%	39.0%	0%	0%
2051	9.1%	39.0%	0%	0%
2052	9.1%	39.0%	0%	0%
2053	9.1%	39.0%	0%	0%
2054	9.0%	39.0%	0%	0%
2055	9.0%	39.0%	0%	0%

Table B-85 National ZEV sales percentages for Class 4-5 (regClassID 42) single-unit short-haul trucks (sourceTypeID 52) in the reference case ZEV adoption sensitivity analysis

Model Year	BEV Sales Percentage		FCEV Sales Percentage	
	Sensitivity Reference	Sensitivity Control	Sensitivity Reference	Sensitivity Control
2027	6.1%	20.0%	0%	0%
2028	9.2%	25.2%	0%	0%
2029	12.2%	30.4%	0%	0%
2030	15.2%	35.6%	0%	0%
2031	16.6%	51.1%	0%	0%
2032	18.1%	66.7%	0%	0%
2033	19.6%	66.7%	0%	0%
2034	21.1%	66.7%	0%	0%
2035	22.6%	66.7%	0%	0%
2036	22.6%	66.7%	0%	0%
2037	22.5%	66.7%	0%	0%
2038	22.5%	66.7%	0%	0%
2039	22.5%	66.7%	0%	0%
2040	22.4%	66.7%	0%	0%
2041	22.4%	66.7%	0%	0%
2042	22.4%	66.7%	0%	0%
2043	22.4%	66.7%	0%	0%
2044	22.3%	66.7%	0%	0%
2045	22.3%	66.7%	0%	0%
2046	22.2%	66.7%	0%	0%
2047	22.2%	66.7%	0%	0%
2048	22.1%	66.7%	0%	0%
2049	22.1%	66.7%	0%	0%
2050	22.1%	66.7%	0%	0%
2051	22.0%	66.7%	0%	0%
2052	22.0%	66.7%	0%	0%
2053	22.0%	66.7%	0%	0%
2054	21.9%	66.7%	0%	0%
2055	21.9%	66.7%	0%	0%

Table B-86 National ZEV sales percentages for Class 6-7 (regClassID 46) single-unit short-haul trucks (sourceTypeID 52) in the reference case ZEV adoption sensitivity analysis

Model Year	BEV Sales Percentage		FCEV Sales Percentage	
	Sensitivity Reference	Sensitivity Control	Sensitivity Reference	Sensitivity Control
2027	4.0%	12.3%	0%	0%
2028	6.0%	14.8%	0%	0%
2029	8.0%	17.3%	0%	0%
2030	10.0%	19.8%	0%	0%
2031	10.9%	27.2%	0%	0%
2032	11.9%	34.6%	0%	0%
2033	12.9%	34.6%	0%	0%
2034	13.9%	34.6%	0%	0%
2035	14.8%	34.6%	0%	0%
2036	14.8%	34.6%	0%	0%
2037	14.8%	34.6%	0%	0%
2038	14.8%	34.6%	0%	0%
2039	14.7%	34.6%	0%	0%
2040	14.7%	34.6%	0%	0%
2041	14.7%	34.6%	0%	0%
2042	14.7%	34.6%	0%	0%
2043	14.7%	34.6%	0%	0%
2044	14.6%	34.6%	0%	0%
2045	14.6%	34.6%	0%	0%
2046	14.6%	34.6%	0%	0%
2047	14.5%	34.6%	0%	0%
2048	14.5%	34.6%	0%	0%
2049	14.5%	34.6%	0%	0%
2050	14.5%	34.6%	0%	0%
2051	14.4%	34.6%	0%	0%
2052	14.4%	34.6%	0%	0%
2053	14.4%	34.6%	0%	0%
2054	14.4%	34.6%	0%	0%
2055	14.4%	34.6%	0%	0%

Table B-87 National ZEV sales percentages for Class 8 (regClassID 47) single-unit short-haul trucks (sourceTypeID 52) in the reference case ZEV adoption sensitivity analysis

Model Year	BEV Sales Percentage		FCEV Sales Percentage	
	Sensitivity Reference	Sensitivity Control	Sensitivity Reference	Sensitivity Control
2027	3.2%	3.2%	0%	0%
2028	4.8%	9.2%	0%	0%
2029	6.4%	11.6%	0%	0%
2030	8.0%	13.9%	0%	0%
2031	8.8%	20.9%	0%	0%
2032	9.6%	27.9%	0%	0%
2033	10.4%	27.9%	0%	0%
2034	11.1%	27.9%	0%	0%
2035	11.9%	27.9%	0%	0%
2036	11.9%	27.9%	0%	0%
2037	11.9%	27.9%	0%	0%
2038	11.9%	27.9%	0%	0%
2039	11.8%	27.9%	0%	0%
2040	11.8%	27.9%	0%	0%
2041	11.8%	27.9%	0%	0%
2042	11.8%	27.9%	0%	0%
2043	11.8%	27.9%	0%	0%
2044	11.8%	27.9%	0%	0%
2045	11.7%	27.9%	0%	0%
2046	11.7%	27.9%	0%	0%
2047	11.7%	27.9%	0%	0%
2048	11.7%	27.9%	0%	0%
2049	11.7%	27.9%	0%	0%
2050	11.6%	27.9%	0%	0%
2051	11.6%	27.9%	0%	0%
2052	11.6%	27.9%	0%	0%
2053	11.6%	27.9%	0%	0%
2054	11.6%	27.9%	0%	0%
2055	11.6%	27.9%	0%	0%

Table B-88 National ZEV sales percentages for Class 4-5 (regClassID 42) single-unit long-haul trucks (sourceTypeID 53) in the reference case ZEV adoption sensitivity analysis

Model Year	BEV Sales Percentage		FCEV Sales Percentage	
	Sensitivity Reference	Sensitivity Control	Sensitivity Reference	Sensitivity Control
2027	6.1%	10.0%	0%	0%
2028	9.2%	13.3%	0%	0%
2029	12.2%	16.7%	0%	0%
2030	15.2%	20.0%	0%	0%
2031	16.6%	30.0%	0%	0%
2032	18.1%	40.0%	0%	0%
2033	19.6%	40.0%	0%	0%
2034	21.1%	40.0%	0%	0%
2035	22.6%	40.0%	0%	0%
2036	22.6%	40.0%	0%	0%
2037	22.5%	40.0%	0%	0%
2038	22.5%	40.0%	0%	0%
2039	22.5%	40.0%	0%	0%
2040	22.4%	40.0%	0%	0%
2041	22.4%	40.0%	0%	0%
2042	22.4%	40.0%	0%	0%
2043	22.4%	40.0%	0%	0%
2044	22.3%	40.0%	0%	0%
2045	22.3%	40.0%	0%	0%
2046	22.2%	40.0%	0%	0%
2047	22.2%	40.0%	0%	0%
2048	22.1%	40.0%	0%	0%
2049	22.1%	40.0%	0%	0%
2050	22.1%	40.0%	0%	0%
2051	22.0%	40.0%	0%	0%
2052	22.0%	40.0%	0%	0%
2053	22.0%	40.0%	0%	0%
2054	21.9%	40.0%	0%	0%
2055	21.9%	40.0%	0%	0%

Table B-89 National ZEV sales percentages for Class 6-7 (regClassID 46) single-unit long-haul trucks (sourceTypeID 53) in the reference case ZEV adoption sensitivity analysis

Model Year	BEV Sales Percentage		FCEV Sales Percentage	
	Sensitivity Reference	Sensitivity Control	Sensitivity Reference	Sensitivity Control
2027	4.0%	14.0%	0%	0%
2028	6.0%	16.8%	0%	0%
2029	8.0%	19.6%	0%	0%
2030	10.0%	22.3%	0%	0%
2031	10.9%	30.7%	0%	0%
2032	11.9%	39.0%	0%	0%
2033	12.9%	39.0%	0%	0%
2034	13.9%	39.0%	0%	0%
2035	14.8%	39.0%	0%	0%
2036	14.8%	39.0%	0%	0%
2037	14.8%	39.0%	0%	0%
2038	14.8%	39.0%	0%	0%
2039	14.7%	39.0%	0%	0%
2040	14.7%	39.0%	0%	0%
2041	14.7%	39.0%	0%	0%
2042	14.7%	39.0%	0%	0%
2043	14.7%	39.0%	0%	0%
2044	14.6%	39.0%	0%	0%
2045	14.6%	39.0%	0%	0%
2046	14.6%	39.0%	0%	0%
2047	14.5%	39.0%	0%	0%
2048	14.5%	39.0%	0%	0%
2049	14.5%	39.0%	0%	0%
2050	14.5%	39.0%	0%	0%
2051	14.4%	39.0%	0%	0%
2052	14.4%	39.0%	0%	0%
2053	14.4%	39.0%	0%	0%
2054	14.4%	39.0%	0%	0%
2055	14.4%	39.0%	0%	0%

Table B-90 National ZEV sales percentages for Class 8 (regClassID 47) single-unit long-haul trucks (sourceTypeID 53) in the reference case ZEV adoption sensitivity analysis

Model Year	BEV Sales Percentage		FCEV Sales Percentage	
	Sensitivity Reference	Sensitivity Control	Sensitivity Reference	Sensitivity Control
2027	3.2%	3.2%	0%	0%
2028	4.8%	5.0%	0%	0%
2029	6.4%	9.3%	0%	0%
2030	8.0%	13.5%	0%	0%
2031	8.8%	26.3%	0%	0%
2032	9.6%	39.0%	0%	0%
2033	10.4%	39.0%	0%	0%
2034	11.1%	39.0%	0%	0%
2035	11.9%	39.0%	0%	0%
2036	11.9%	39.0%	0%	0%
2037	11.9%	39.0%	0%	0%
2038	11.9%	39.0%	0%	0%
2039	11.8%	39.0%	0%	0%
2040	11.8%	39.0%	0%	0%
2041	11.8%	39.0%	0%	0%
2042	11.8%	39.0%	0%	0%
2043	11.8%	39.0%	0%	0%
2044	11.8%	39.0%	0%	0%
2045	11.7%	39.0%	0%	0%
2046	11.7%	39.0%	0%	0%
2047	11.7%	39.0%	0%	0%
2048	11.7%	39.0%	0%	0%
2049	11.7%	39.0%	0%	0%
2050	11.6%	39.0%	0%	0%
2051	11.6%	39.0%	0%	0%
2052	11.6%	39.0%	0%	0%
2053	11.6%	39.0%	0%	0%
2054	11.6%	39.0%	0%	0%
2055	11.6%	39.0%	0%	0%

Table B-91 National ZEV sales percentages for Class 4-5 (regClassID 42) motor homes (sourceTypeID 54) in the reference case ZEV adoption sensitivity analysis

Model Year	BEV Sales Percentage		FCEV Sales Percentage	
	Sensitivity Reference	Sensitivity Control	Sensitivity Reference	Sensitivity Control
2027	7.2%	7.2%	0%	0%
2028	10.8%	10.8%	0%	0%
2029	14.4%	14.4%	0%	0%
2030	17.9%	17.9%	0%	0%
2031	19.6%	19.6%	0%	0%
2032	21.4%	21.4%	0%	0%
2033	23.1%	23.1%	0%	0%
2034	24.9%	24.9%	0%	0%
2035	26.6%	26.6%	0%	0%
2036	26.6%	26.6%	0%	0%
2037	26.5%	26.5%	0%	0%
2038	26.5%	26.5%	0%	0%
2039	26.5%	26.5%	0%	0%
2040	26.4%	26.4%	0%	0%
2041	26.4%	26.4%	0%	0%
2042	26.4%	26.4%	0%	0%
2043	26.3%	26.3%	0%	0%
2044	26.3%	26.3%	0%	0%
2045	26.2%	26.2%	0%	0%
2046	26.1%	26.1%	0%	0%
2047	26.1%	26.1%	0%	0%
2048	26.1%	26.1%	0%	0%
2049	26.0%	26.0%	0%	0%
2050	26.0%	26.0%	0%	0%
2051	25.9%	25.9%	0%	0%
2052	25.9%	25.9%	0%	0%
2053	25.9%	25.9%	0%	0%
2054	25.8%	25.8%	0%	0%
2055	25.8%	25.8%	0%	0%

Table B-92 National ZEV sales percentages for Class 6-7 (regClassID 46) motor homes (sourceTypeID 54) in the reference case ZEV adoption sensitivity analysis

Model Year	BEV Sales Percentage		FCEV Sales Percentage	
	Sensitivity Reference	Sensitivity Control	Sensitivity Reference	Sensitivity Control
2027	4.7%	4.7%	0%	0%
2028	7.0%	7.0%	0%	0%
2029	9.3%	9.3%	0%	0%
2030	11.6%	11.6%	0%	0%
2031	12.8%	12.8%	0%	0%
2032	13.9%	13.9%	0%	0%
2033	15.0%	15.0%	0%	0%
2034	16.2%	16.2%	0%	0%
2035	17.3%	17.3%	0%	0%
2036	17.3%	17.3%	0%	0%
2037	17.3%	17.3%	0%	0%
2038	17.2%	17.2%	0%	0%
2039	17.2%	17.2%	0%	0%
2040	17.2%	17.2%	0%	0%
2041	17.2%	17.2%	0%	0%
2042	17.1%	17.1%	0%	0%
2043	17.1%	17.1%	0%	0%
2044	17.1%	17.1%	0%	0%
2045	17.1%	17.1%	0%	0%
2046	17.0%	17.0%	0%	0%
2047	17.0%	17.0%	0%	0%
2048	17.0%	17.0%	0%	0%
2049	16.9%	16.9%	0%	0%
2050	16.9%	16.9%	0%	0%
2051	16.9%	16.9%	0%	0%
2052	16.9%	16.9%	0%	0%
2053	16.8%	16.8%	0%	0%
2054	16.8%	16.8%	0%	0%
2055	16.8%	16.8%	0%	0%

Table B-93 National ZEV sales percentages for Class 8 (regClassID 47) motor homes (sourceTypeID 54) in the reference case ZEV adoption sensitivity analysis

Model Year	BEV Sales Percentage		FCEV Sales Percentage	
	Sensitivity Reference	Sensitivity Control	Sensitivity Reference	Sensitivity Control
2027	2.5%	2.5%	0%	0%
2028	3.8%	3.8%	0%	0%
2029	5.0%	5.0%	0%	0%
2030	6.2%	6.2%	0%	0%
2031	6.8%	6.8%	0%	0%
2032	7.4%	7.4%	0%	0%
2033	8.0%	8.0%	0%	0%
2034	8.6%	8.6%	0%	0%
2035	9.3%	9.3%	0%	0%
2036	9.2%	9.2%	0%	0%
2037	9.2%	9.2%	0%	0%
2038	9.2%	9.2%	0%	0%
2039	9.2%	9.2%	0%	0%
2040	9.2%	9.2%	0%	0%
2041	9.2%	9.2%	0%	0%
2042	9.2%	9.2%	0%	0%
2043	9.2%	9.2%	0%	0%
2044	9.1%	9.1%	0%	0%
2045	9.1%	9.1%	0%	0%
2046	9.1%	9.1%	0%	0%
2047	9.1%	9.1%	0%	0%
2048	9.1%	9.1%	0%	0%
2049	9.0%	9.0%	0%	0%
2050	9.0%	9.0%	0%	0%
2051	9.0%	9.0%	0%	0%
2052	9.0%	9.0%	0%	0%
2053	9.0%	9.0%	0%	0%
2054	9.0%	9.0%	0%	0%
2055	9.0%	9.0%	0%	0%

Table B-94 National ZEV sales percentages for Class 6-7 (regClassID 46) single-unit short-haul trucks (sourceTypeID 61) in the reference case ZEV adoption sensitivity analysis

Model Year	BEV Sales Percentage		FCEV Sales Percentage	
	Sensitivity Reference	Sensitivity Control	Sensitivity Reference	Sensitivity Control
2027	3.4%	7.0%	0.0%	0.0%
2028	4.4%	8.6%	0.0%	0.0%
2029	5.3%	10.2%	0.0%	0.0%
2030	4.7%	10.2%	1.6%	3.4%
2031	5.0%	15.1%	1.7%	5.1%
2032	5.6%	21.4%	1.9%	7.2%
2033	5.6%	21.4%	1.9%	7.2%
2034	5.6%	21.4%	1.9%	7.2%
2035	5.6%	21.4%	1.9%	7.2%
2036	5.6%	21.4%	1.9%	7.2%
2037	5.6%	21.4%	1.9%	7.2%
2038	5.6%	21.4%	1.9%	7.2%
2039	5.6%	21.4%	1.9%	7.2%
2040	5.6%	21.4%	1.9%	7.2%
2041	5.6%	21.4%	1.9%	7.2%
2042	5.6%	21.4%	1.9%	7.2%
2043	5.6%	21.4%	1.9%	7.2%
2044	5.6%	21.4%	1.9%	7.2%
2045	5.6%	21.4%	1.9%	7.2%
2046	5.6%	21.4%	1.9%	7.2%
2047	5.6%	21.4%	1.9%	7.2%
2048	5.6%	21.4%	1.9%	7.2%
2049	5.6%	21.4%	1.9%	7.2%
2050	5.6%	21.4%	1.9%	7.2%
2051	5.6%	21.4%	1.9%	7.2%
2052	5.6%	21.4%	1.9%	7.2%
2053	5.6%	21.4%	1.9%	7.2%
2054	5.6%	21.4%	1.9%	7.2%
2055	5.6%	21.4%	1.9%	7.2%

Table B-95 National ZEV sales percentages for Class 8 (regClassID 47) single-unit short-haul trucks (sourceTypeID 61) in the reference case ZEV adoption sensitivity analysis

Model Year	BEV Sales Percentage		FCEV Sales Percentage	
	Sensitivity Reference	Sensitivity Control	Sensitivity Reference	Sensitivity Control
2027	2.7%	4.0%	0.0%	0.0%
2028	3.5%	8.3%	0.0%	0.0%
2029	4.3%	12.7%	0.0%	0.0%
2030	4.8%	16.9%	0.2%	0.7%
2031	5.1%	30.0%	0.2%	1.2%
2032	5.8%	43.5%	0.2%	1.7%
2033	5.8%	43.5%	0.2%	1.7%
2034	5.8%	43.5%	0.2%	1.7%
2035	5.8%	43.5%	0.2%	1.7%
2036	5.8%	43.5%	0.2%	1.7%
2037	5.8%	43.5%	0.2%	1.7%
2038	5.8%	43.5%	0.2%	1.7%
2039	5.8%	43.5%	0.2%	1.7%
2040	5.8%	43.5%	0.2%	1.7%
2041	5.7%	43.5%	0.2%	1.7%
2042	5.7%	43.5%	0.2%	1.7%
2043	5.7%	43.5%	0.2%	1.7%
2044	5.7%	43.5%	0.2%	1.7%
2045	5.7%	43.5%	0.2%	1.7%
2046	5.7%	43.5%	0.2%	1.7%
2047	5.7%	43.5%	0.2%	1.7%
2048	5.7%	43.5%	0.2%	1.7%
2049	5.7%	43.5%	0.2%	1.7%
2050	5.7%	43.5%	0.2%	1.7%
2051	5.7%	43.5%	0.2%	1.7%
2052	5.7%	43.5%	0.2%	1.7%
2053	5.7%	43.5%	0.2%	1.7%
2054	5.7%	43.5%	0.2%	1.7%
2055	5.7%	43.5%	0.2%	1.7%

Table B-96 National ZEV sales percentages for Class 6-7 (regClassID 46) single-unit long-haul trucks (sourceTypeID 62) in the reference case ZEV adoption sensitivity analysis

Model Year	BEV Sales Percentage		FCEV Sales Percentage	
	Sensitivity Reference	Sensitivity Control	Sensitivity Reference	Sensitivity Control
2027	0.2%	0.2%	0.0%	0.0%
2028	0.5%	0.5%	0.0%	0.0%
2029	0.8%	0.8%	0.0%	0.0%
2030	0.8%	3.9%	0.4%	2.3%
2031	1.5%	7.9%	0.9%	4.6%
2032	1.9%	15.8%	1.1%	9.2%
2033	1.9%	15.8%	1.1%	9.2%
2034	1.9%	15.8%	1.1%	9.2%
2035	1.9%	15.8%	1.1%	9.2%
2036	1.9%	15.8%	1.1%	9.2%
2037	1.9%	15.8%	1.1%	9.2%
2038	1.9%	15.8%	1.1%	9.2%
2039	1.9%	15.8%	1.1%	9.2%
2040	1.9%	15.8%	1.1%	9.2%
2041	1.9%	15.8%	1.1%	9.2%
2042	1.9%	15.8%	1.1%	9.2%
2043	1.9%	15.8%	1.1%	9.2%
2044	1.9%	15.8%	1.1%	9.2%
2045	1.9%	15.8%	1.1%	9.2%
2046	1.9%	15.8%	1.1%	9.2%
2047	1.9%	15.8%	1.1%	9.2%
2048	1.9%	15.8%	1.1%	9.2%
2049	1.9%	15.8%	1.1%	9.2%
2050	1.9%	15.8%	1.1%	9.2%
2051	1.9%	15.8%	1.1%	9.2%
2052	1.9%	15.8%	1.1%	9.2%
2053	1.9%	15.8%	1.1%	9.2%
2054	1.9%	15.8%	1.1%	9.2%
2055	1.9%	15.8%	1.1%	9.2%

Table B-97 National ZEV sales percentages for Class 8 (regClassID 47) single-unit long-haul trucks (sourceTypeID 62) in the reference case ZEV adoption sensitivity analysis

Model Year	BEV Sales Percentage		FCEV Sales Percentage	
	Sensitivity Reference	Sensitivity Control	Sensitivity Reference	Sensitivity Control
2027	0.2%	0.2%	0.0%	0.0%
2028	0.4%	0.4%	0.0%	0.0%
2029	0.7%	0.7%	0.0%	0.0%
2030	0.6%	3.9%	0.4%	2.3%
2031	1.3%	7.9%	0.7%	4.6%
2032	1.6%	15.8%	0.9%	9.2%
2033	1.6%	15.8%	0.9%	9.2%
2034	1.6%	15.8%	0.9%	9.2%
2035	1.6%	15.8%	0.9%	9.2%
2036	1.6%	15.8%	0.9%	9.2%
2037	1.6%	15.8%	0.9%	9.2%
2038	1.6%	15.8%	0.9%	9.2%
2039	1.6%	15.8%	0.9%	9.2%
2040	1.6%	15.8%	0.9%	9.2%
2041	1.6%	15.8%	0.9%	9.2%
2042	1.6%	15.8%	0.9%	9.2%
2043	1.6%	15.8%	0.9%	9.2%
2044	1.6%	15.8%	0.9%	9.2%
2045	1.6%	15.8%	0.9%	9.2%
2046	1.6%	15.8%	0.9%	9.2%
2047	1.6%	15.8%	0.9%	9.2%
2048	1.6%	15.8%	0.9%	9.2%
2049	1.6%	15.8%	0.9%	9.2%
2050	1.6%	15.8%	0.9%	9.2%
2051	1.6%	15.8%	0.9%	9.2%
2052	1.6%	15.8%	0.9%	9.2%
2053	1.6%	15.8%	0.9%	9.2%
2054	1.6%	15.8%	0.9%	9.2%
2055	1.6%	15.8%	0.9%	9.2%

Appendix C – Additional Benefits

This Appendix C presents the climate benefits of the final standards using the interim Social Cost of Greenhouse Gas (SC-GHG) values used in the NPRM. We have updated the interim values to 2022 dollars for the analysis in this RIA. The updated interim SC-GHG values are presented in Table C-1. The climate benefits using these values are presented in Table C-2 through Table C-5 for the reductions in CO_2, CH_4, N_2O and all GHGs, respectively. Table C-6 presents the summary of cost and benefits of the final standards using the 3% average benefits across the GHGs.

Table C-1 Interim Social Cost of GHG Values, 2027-2055 (2022 $/metric ton)

CY	CO_2				CH_4				N_2O			
	5% Avg	**3% Avg**	**2.5% Avg**	**3% 95th pctile**	**5% Avg**	**3% Avg**	**2.5% Avg**	**3% 95th pctile**	**5% Avg**	**3% Avg**	**2.5% Avg**	**3% 95th pctile**
2027	$20	$66	$96	$197	$959	$2,030	$2,621	$5,379	$8,053	$24,029	$34,734	$63,484
2028	$21	$67	$97	$201	$989	$2,083	$2,683	$5,523	$8,279	$24,518	$35,358	$64,836
2029	$21	$68	$99	$205	$1,020	$2,135	$2,745	$5,667	$8,505	$25,008	$35,981	$66,188
2030	$22	$69	$100	$209	$1,050	$2,188	$2,807	$5,810	$8,731	$25,497	$36,604	$67,540
2031	$22	$70	$102	$213	$1,089	$2,250	$2,879	$5,983	$9,008	$26,048	$37,288	$69,062
2032	$23	$72	$103	$218	$1,127	$2,312	$2,950	$6,155	$9,285	$26,598	$37,973	$70,583
2033	$24	$73	$105	$222	$1,165	$2,374	$3,022	$6,327	$9,563	$27,149	$38,657	$72,105
2034	$24	$74	$106	$226	$1,204	$2,436	$3,093	$6,499	$9,840	$27,700	$39,342	$73,626
2035	$25	$76	$108	$230	$1,242	$2,498	$3,165	$6,671	$10,117	$28,250	$40,026	$75,148
2036	$26	$77	$109	$235	$1,281	$2,560	$3,236	$6,843	$10,395	$28,801	$40,711	$76,669
2037	$26	$78	$111	$239	$1,319	$2,622	$3,308	$7,015	$10,672	$29,352	$41,395	$78,191
2038	$27	$79	$112	$243	$1,358	$2,684	$3,379	$7,188	$10,949	$29,902	$42,079	$79,712
2039	$28	$81	$114	$248	$1,396	$2,746	$3,451	$7,360	$11,227	$30,453	$42,764	$81,234
2040	$28	$82	$115	$252	$1,435	$2,808	$3,522	$7,532	$11,504	$31,004	$43,448	$82,755
2041	$29	$83	$117	$256	$1,477	$2,870	$3,593	$7,694	$11,829	$31,596	$44,169	$84,349
2042	$30	$85	$118	$260	$1,519	$2,933	$3,663	$7,856	$12,154	$32,189	$44,891	$85,944
2043	$30	$86	$120	$264	$1,561	$2,996	$3,734	$8,018	$12,479	$32,781	$45,612	$87,538
2044	$31	$87	$121	$267	$1,603	$3,058	$3,804	$8,180	$12,803	$33,374	$46,333	$89,132
2045	$32	$88	$123	$271	$1,645	$3,121	$3,875	$8,342	$13,128	$33,967	$47,054	$90,727
2046	$33	$90	$124	$275	$1,687	$3,183	$3,946	$8,504	$13,453	$34,559	$47,775	$92,321
2047	$33	$91	$126	$279	$1,729	$3,246	$4,016	$8,666	$13,778	$35,152	$48,496	$93,915
2048	$34	$92	$127	$283	$1,771	$3,309	$4,087	$8,828	$14,103	$35,745	$49,217	$95,510
2049	$35	$93	$129	$287	$1,813	$3,371	$4,157	$8,990	$14,428	$36,337	$49,939	$97,104
2050	$35	$95	$130	$291	$1,855	$3,434	$4,228	$9,152	$14,753	$36,930	$50,660	$98,698
2051	$36	$95	$132	$292	$1,887	$3,478	$4,276	$9,204	$15,141	$37,548	$51,366	$99,533
2052	$37	$96	$133	$293	$1,913	$3,513	$4,314	$9,243	$15,500	$38,141	$52,071	$101,081
2053	$38	$97	$135	$294	$1,939	$3,548	$4,352	$9,282	$15,859	$38,735	$52,775	$102,629
2054	$38	$99	$136	$295	$1,965	$3,584	$4,390	$9,320	$16,219	$39,329	$53,480	$104,177
2055	$39	$100	$137	$298	$1,991	$3,619	$4,428	$9,359	$16,578	$39,922	$54,184	$105,724

Note: The 2027-2055 values are identical to those reported in the 2016 TSD (IWG 2016a) adjusted to 2022 dollars using the annual GDP Implicit Price Deflator values used elsewhere in the analysis presented in this RIA. This table displays the values rounded to the nearest dollar; the annual unrounded values used in the calculations in this analysis are available on OMB's website: https://www.whitehouse.gov/omb/information-regulatory-affairs/regulatory-matters/#scghgs. The estimates were extended for the period 2051 to 2055 using methods, assumptions, and parameters identical to the 2020-2050 estimates. The values are stated in $/metric ton and vary depending on the year.

Table C-2 Benefits of reduced CO2 emissions from the final standards using the interim SC-GHG values (Millions of 2022 dollars)

CY	Discount Rate			
	5% Avg	3% Avg	2.5% Avg	3% 95th percentile
2027	$5.7	$19	$27	$56
2028	$12	$40	$59	$120
2029	$20	$64	$93	$190
2030	$25	$79	$110	$240
2031	$38	$120	$170	$360
2032	$54	$170	$240	$520
2033	$69	$210	$310	$650
2034	$81	$250	$360	$760
2035	$89	$270	$380	$820
2036	$240	$710	$1,000	$2,200
2037	$440	$1,300	$1,800	$4,000
2038	$680	$2,000	$2,800	$6,200
2039	$970	$2,800	$4,000	$8,700
2040	$1,300	$3,800	$5,300	$12,000
2041	$1,400	$4,000	$5,700	$12,000
2042	$1,500	$4,200	$5,900	$13,000
2043	$1,600	$4,400	$6,100	$14,000
2044	$1,600	$4,500	$6,300	$14,000
2045	$1,700	$4,600	$6,500	$14,000
2046	$1,800	$4,800	$6,700	$15,000
2047	$1,800	$5,000	$6,900	$15,000
2048	$1,900	$5,100	$7,100	$16,000
2049	$2,000	$5,300	$7,300	$16,000
2050	$2,000	$5,400	$7,500	$17,000
2051	$2,100	$5,500	$7,600	$17,000
2052	$2,100	$5,600	$7,700	$17,000
2053	$2,200	$5,600	$7,800	$17,000
2054	$2,200	$5,700	$7,900	$17,000
2055	$2,300	$5,800	$7,900	$17,000
PV	$12,000	$48,000	$73,000	$150,000
AV	$780	$2,500	$3,600	$7,600

Note: Climate benefits are based on changes (reductions) in CO_2 emissions and are calculated using the IWG interim SC-GHG estimates from (IWG 2021). Climate benefits include changes in vehicle, EGU, and refinery CO_2 emissions.

Table C-3 Benefits of reduced CH_4 emissions from the final standards using the interim SC-GHG values (Millions of 2022 dollars)

CY	Discount Rate			
	5% Avg	**3% Avg**	**2.5% Avg**	**3% 95th percentile**
2027	$0.0062	$0.013	$0.017	$0.035
2028	$0.043	$0.091	$0.12	$0.24
2029	$0.076	$0.16	$0.21	$0.42
2030	$0.074	$0.15	$0.2	$0.41
2031	$0.071	$0.15	$0.19	$0.39
2032	$0.023	$0.048	$0.061	$0.13
2033	-$0.031	-$0.063	-$0.08	-$0.17
2034	-$0.039	-$0.078	-$0.099	-$0.21
2035	-$0.052	-$0.1	-$0.13	-$0.28
2036	$0.39	$0.79	$1	$2.1
2037	$1.1	$2.2	$2.8	$6
2038	$2.2	$4.3	$5.4	$11
2039	$3.4	$6.6	$8.3	$18
2040	$4.7	$9.3	$12	$25
2041	$5.6	$11	$14	$29
2042	$6.5	$13	$16	$34
2043	$7.4	$14	$18	$38
2044	$8.4	$16	$20	$43
2045	$9.4	$18	$22	$47
2046	$10	$19	$24	$52
2047	$11	$21	$26	$56
2048	$12	$22	$28	$60
2049	$13	$24	$30	$64
2050	$14	$26	$32	$69
2051	$15	$27	$34	$72
2052	$16	$29	$35	$76
2053	$17	$30	$37	$79
2054	$18	$32	$39	$83
2055	$18	$34	$41	$87
PV	$65	$190	$260	$490
AV	$4.3	$9.7	$13	$26

Note: Climate benefits are based on changes (reductions) in CH_4 emissions and are calculated using the IWG interim SC-GHG estimates from (IWG 2021). Climate benefits include changes in vehicle, EGU, and refinery CH_4 emissions.

Table C-4 Benefits of reduced N_2O emissions from the final standards using the interim SC-GHG values (Millions of 2022 dollars)

CY	Discount Rate			
	5% Avg	**3% Avg**	**2.5% Avg**	**3% 95th percentile**
2027	$0.44	$1.3	$1.9	$3.5
2028	$1.2	$3.5	$5	$9.2
2029	$2.2	$6.5	$9.3	$17
2030	$4.2	$12	$18	$33
2031	$8.9	$26	$37	$68
2032	$18	$50	$72	$130
2033	$27	$76	$110	$200
2034	$36	$100	$140	$270
2035	$45	$130	$180	$340
2036	$55	$150	$220	$410
2037	$65	$180	$250	$470
2038	$74	$200	$280	$540
2039	$83	$230	$320	$600
2040	$92	$250	$350	$660
2041	$100	$270	$380	$720
2042	$110	$290	$400	$770
2043	$120	$310	$420	$810
2044	$120	$320	$440	$860
2045	$130	$330	$460	$890
2046	$130	$340	$480	$920
2047	$140	$350	$490	$950
2048	$140	$360	$500	$970
2049	$150	$370	$510	$990
2050	$150	$380	$520	$1,000
2051	$160	$390	$530	$1,000
2052	$160	$400	$540	$1,000
2053	$160	$400	$550	$1,100
2054	$170	$410	$560	$1,100
2055	$170	$420	$560	$1,100
PV	$1,000	$3,800	$5,800	$10,000
AV	$67	$200	$280	$530

Note: Climate benefits are based on changes (reductions) in N_2O emissions and are calculated using the IWG interim SC-GHG estimates from (IWG 2021). Climate benefits include changes in vehicle, EGU, and refinery N_2O emissions.

Table C-5 Benefits of reduced GHG emissions from the final standards using the interim SC-GHG values (Millions of 2022 dollars)

CY	Discount Rate			
	5% Avg	**3% Avg**	**2.5% Avg**	**3% 95th percentile**
2027	$6.1	$20	$29	$59
2028	$14	$44	$64	$130
2029	$22	$71	$100	$210
2030	$29	$92	$130	$270
2031	$46	$140	$210	$430
2032	$72	$220	$320	$650
2033	$96	$290	$420	$850
2034	$120	$350	$500	$1,000
2035	$130	$400	$560	$1,200
2036	$290	$870	$1,200	$2,600
2037	$500	$1,500	$2,100	$4,400
2038	$760	$2,200	$3,100	$6,700
2039	$1,100	$3,100	$4,300	$9,300
2040	$1,400	$4,000	$5,700	$12,000
2041	$1,500	$4,300	$6,000	$13,000
2042	$1,600	$4,500	$6,300	$14,000
2043	$1,700	$4,700	$6,600	$14,000
2044	$1,800	$4,900	$6,800	$15,000
2045	$1,800	$5,000	$6,900	$15,000
2046	$1,900	$5,200	$7,200	$16,000
2047	$2,000	$5,400	$7,400	$16,000
2048	$2,000	$5,500	$7,600	$17,000
2049	$2,100	$5,700	$7,800	$17,000
2050	$2,200	$5,800	$8,000	$18,000
2051	$2,300	$5,900	$8,200	$18,000
2052	$2,300	$6,000	$8,300	$18,000
2053	$2,400	$6,100	$8,400	$18,000
2054	$2,400	$6,100	$8,500	$18,000
2055	$2,500	$6,200	$8,500	$18,000
PV	$13,000	$52,000	$79,000	$160,000
AV	$850	$2,700	$3,900	$8,100

Note: Climate benefits are based on changes (reductions) in GHG emissions and are calculated using the IWG interim SC-GHG estimates from (IWG 2021). Climate benefits include changes in vehicle, EGU, and refinery GHG emissions.

Table C-6 Summary of costs, fuel savings and benefits of the final standards (billions of 2022 dollars)

	CY 2055	**PV, 2%**	**PV, 3%**	**PV, 7%**	**AV, 2%**	**AV, 3%**	**AV, 7%**
Vehicle Technology Package RPE	-$0.59	-$4.2	-$3.2	-$1	-$0.19	-$0.17	-$0.083
EVSE RPE	$1.1	$28	$25	$15	$1.3	$1.3	$1.3
Sum of Vehicle Costs	$0.55	$24	$22	$14	$1.1	$1.1	$1.2
Pre-tax Fuel Savings	-$0.35	-$9.5	-$7.9	-$3.9	-$0.43	-$0.41	-$0.31
Diesel Exhaust Fluid Savings	$1.8	$21	$17	$8.7	$0.95	$0.9	$0.71
Repair & Maintenance Savings	$6.9	$73	$60	$30	$3.3	$3.1	$2.4
Insurance Savings	$0.25	$1.3	$1	$0.46	$0.06	$0.055	$0.038
Vehicle Replacement Savings	$0.14	$1.9	$1.5	$0.72	$0.086	$0.08	$0.058
EVSE Replacement Savings	-$1.3	-$11	-$8.7	-$3.7	-$0.5	-$0.45	-$0.3
Sum of Operating Savings	$7.4	$76	$63	$32	$3.5	$3.3	$2.6
Energy Security Benefits	$0.8	$9.8	$8.2	$4.2	$0.45	$0.43	$0.34
Climate Benefits – 3% Average[a]	$6.2	$52	$52	$52	$2.7	$2.7	$2.7
$PM_{2.5}$ Health Benefits[b]	$1.9	$6.5	$4.2	-$0.4	$0.3	$0.22	-$0.032
Sum of Benefits[c]	$8.7	$68	$64	$55	$3.4	$3.3	$3
Net Benefits[c]	$16	$120	$110	$73	$5.8	$5.5	$4.4

[a, b, c] See footnotes to Table 8-8 in Chapter 8 of this RIA.

Appendix D – List of Abbreviations, Acronyms, and Symbols

Acronym	Definition
°C	Degrees Celsius
µg	Microgram
µm	Micrometers
20xx$	U.S. Dollars in calendar year 20xx
A/C	Air Conditioning
ABTC	American Battery Technology Company
AC	Alternating Current
ACT	California Advanced Clean Truck
AEO	Annual Energy Outlook
AFDC	Alternative Fuels Data Center
AHS	American Housing Survey
ANL	Argonne National Laboratory
APU	Auxiliary Power Unit
ARCHES	Alliance for Regional Clean Hydrogen Energy Systems
ARPA	Advanced Research Projects Agency
ATR	Autothermal Reforming
ATRI	American Transportation Research Institute
ATSDR	Agency for Toxic Substances and Disease Registry
AV	Annualized value
Avg	Average
BEA	Bureau of Economic Analysis
BenMAP	Benefits Mapping and Analysis Program
BenMAP-CE	Benefits Mapping and Analysis Program-Community Edition
BEV	Battery Electric Vehicle
bhp	Brake Horsepower
bhp-hr	Brake Horsepower Hour
BIL	Bipartisan Infrastructure Law
BLS	Bureau of Labor Statistics
BNEF	Bloomberg New Energy Finance
BOP	Balance of Plant
BP	British Petroleum
BPT	Benefit Per Ton
BTU	British Thermal Unit
CAA	Clean Air Act
CAFE	Corporate Average Fuel Economy
CARB	California Air Resources Board
CASAC	Clean Air Scientific Advisory Committee
CCS	Combined Charging System
CDC	Center for Disease Control
CEC	California Energy Commission
CFI	Charging and Fueling Infrastructure
CFR	Code of Federal Regulations
CH_4	Methane
CHPS	Clean Hydrogen Production Standard
CI	Compression-Ignition
CMI	Critical Minerals Institute
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO_2	Carbon Dioxide

Acronym	**Definition**
CO_2eq	CO_2 Equivalent
COI	Cost-of-illness
CONUS	Contiguous US
COP	Coefficient of Performance
COPD	Chronic Obstructive Pulmonary Disease
CRC	Coordinating Research Council
CSB	Clean School Bus
CY	Calendar Year
DC	Direct Current
DCFC	Direct Current Fast Charger
DEF	Diesel Exhaust Fluid
DER	Distributed Energy Resources
DFH	Direct Fired Heaters
DHHS	Department of Health and Human Services
DICE	Dynamic Integrated Climate and Economy
DMC	Direct Manufacturing Costs
DOC	Diesel Oxidation Catalyst
DOE	Department of Energy
DOT	Department of Transportation
DPA	Defense Production Act
DPF	Diesel Particulate Filter
DRIA	Draft Regulatory Impact Analysis
DSCIM	Data-driven Spatial Climate Impact Model
DTNA	Daimler Truck North America
EC	Elemental Carbon
EDF	Environmental Defense Fund
EEAC	Environmental Economics Advisory Committee
EER	Energy Efficiency Ratio
EGR	Exhaust Gas Recirculation
EGU	Electricity Generation Unit
EIA	Energy Information Administration
EJ	Environmental Justice
EMF	Energy Modeling Forum
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
ERM	Employment Requirements Matrix
EV	Electric Vehicle
EVSE	Electric Vehicle Supply Equipment
FAF	Freight Analysis Framework
FaIR	Finite Amplitude Impulse Response
FCEV	Fuel Cell Electric Vehicle
FCT	Fuel Cell Truck
FEL	Family Emission Limit
FERC	Federal Energy Regulatory Commission
FET	Federal Excise Tax
FHWA	Federal Highway Administration
FMVSS	Federal Motor Vehicle Safety Standards
FOH	Fuel Operated Heaters
FR	Federal Register
FrEDI	Framework for Evaluating Damages and Impacts
FRM	Final Rulemaking

Acronym	**Definition**
FTA	Federal Transit Administration
FTP	Federal Test Procedure
FUND	Framework for Uncertainty, Negotiation, and Distribution
FY	Fiscal Year
g	Gram
g/s	Gram-per-second
g/ton-mile	Grams emitted to move one ton (2000 pounds) of freight over one mile
gal	Gallon
gal/1000 ton-mile	Gallons of fuel used to move one ton of payload (2,000 pounds) over 1000 miles
GAO	Government Accountability Office
GDP	Gross Domestic Product
GE	General Electric
GEM	Greenhouse Gas Emissions Model
GHG	Greenhouse Gas
GIVE	Greenhouse Gas Impact Value Estimator
GM	General Motors
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation
GTP	Global Temperature Potential
GTR	Global Technical Regulation
GVWR	Gross Weight Vehicle Rating
GW	Gigawatt
GWP	Global Warming Potential
HAD	Health Assessment Document
HCM	Hosting Capacity Maps
HH	Heavy-haul
HD	Heavy-duty
HDV	Heavy-duty Vehicle
HEI	Health Effects Institute
HEV	Hybrid Electric Vehicle
HFC	Hydrofluorocarbon
HHD	Heavy Heavy-duty
HHDV	Heavy Heavy-duty vehicle
hrs	Hours
HVAC	Heating, Ventilation, Air Conditioning
HVIP	Hybrid Voucher Incentives Project
hz	Hertz
IAM	Integrated Assessment Model
IARC	International Agency for Research on Cancer
ICCT	International Council for Clean Transportation
ICE	Internal Combustion Engine
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IIHS	Insurance Institute for Highway Safety
IPCC	Intergovernmental Panel on Climate Change
IPM	Integrated Planning Model
IRA	Inflation Reduction Act
IRIS	Integrated Risk Information System
ISA	Integrated Science Assessment
ISO	International Standards Organization
IWG	Interagency Working Group
JOET	Joint Office of Energy and Transportation

Acronym	**Definition**
K	Potassium
kg	Kilogram
km	Kilometer
km/h	Kilometers per Hour
lb	Pound
LBNL	Lawrence Berkeley National Laboratory
LD	Light-duty
LDT	Light-duty truck
LDV	Light-duty vehicle
LHDV	Light heavy-duty vehicle
LFP	Lithium Iron-Phosphate
LHD	Light Heavy-duty
Li	Lithium
LLC	Limited Liability Company
LMDV	Light- and Medium-Duty Vehicle (rule), which is a reference to the Multi-Pollutant Emissions Standards for Model Years 2027 and Later Light-Duty and Medium-Duty Vehicles
LNG	Liquefied natural gas
m^2	Square Meters
m^3	Cubic Meters
m^3	Cubic Meters
MARAD	Maritime Administration
MCS	Megawatt Charging System
MD	Medium-duty
MEA	Membrane Electrode Assemblies
MFR	Manufacturer
Mg	Magnesium
MH	Medium Heavy
MHD	Medium Heavy-duty
MHDV	Medium Heavy-duty vehicle
MINER	Mining Innovations for Negative Emissions Resource Recovery
MMBD	Million barrels of oil per day
MMT	Million metric tons
Mn	Manganese
MOU	Memorandum of Understanding
MOVES	Motor Vehicle Emission Simulator
MP	Multi-Purpose
MRL	Minimal Risk Level
MSP	Minerals Security Partnership
MW	Megawatt
MY	Model Year
NAAQS	National Ambient Air Quality Standards
NACS	North American Charging Standard
NAICS	North American Industry Classification System
NASA	National Aeronautics and Space Administration
NCA	Nickel-Cobalt-Aluminum
NCA4	4th National Climate Assessment
NEC	National Electric Code
NEI	National Emissions Inventory
NEMS	National Energy Modeling System
NERC	North American Electric Reliability Corporation

Acronym	**Definition**
NESCAUM	Northeast States for Coordinated Air Use Management
NEVI	National Electric Vehicle Infrastructure
NHFN	National Highway Freight Network
NHIS	National Health Interview Survey
NHTSA	National Highway Traffic Safety Administration
NMC	Nickel-Manganese-Cobalt
NO	Nitric Oxide
NO_2	Nitrogen Dioxide
NO_X	Nitrogen Oxides
NPRM	Notice of Proposed Rulemaking
NRC	National Research Council
NREL	National Renewable Energy Laboratory
NTP	National Toxicology Program
NYC	New York City
NZEV	Near Zero-emission Vehicle
O_3	Ozone
OECD	Organisation for Economic Co-operation and Development
OEM	Original Equipment Manufacturers
OMB	Office of Management Budget
OMEGA	Optimization Model for reducing Emissions of Greenhouse Gases from Automobiles
OPEC	Organization of Petroleum Exporting Countries
ORNL	Oak Ridge National Laboratory
OSHA	Occupational Safety and Health Administration
PAGE	Policy Analysis of the Greenhouse Gas Effect
PBPK	Physiologically based pharmacokinetic
PEM	Polymer Electrolyte Membrane
PEV	Plug-in Electric Vehicle
PFC	Perfluorocarbon
PFG	Performance Food Group
PHEV	Plug-in Hybrid Electric Vehicles
PM	Particulate Matter
PM_{10}	Coarse Particulate Matter (diameter of 10 µm or less)
$PM_{2.5}$	Fine Particulate Matter (diameter of 2.5 µm or less)
PNNL	Pacific Northwest National Laboratory
PNW	Pacific Northwest
PPE	Personal Protection Equipment
PTC	Production Tax Credit
PTO	Power Takeoff
PV	Present Values
RFA	Regulatory Flexibility Act
RFF-SPs	Resources for the Future socioeconomic projections
RFS	Renewable Fuel Standard
RIA	Regulatory Impact Analysis
RPE	Retail Price Equivalent
RTC	Response to Comment (Document)
SAB	Science Advisory Board
SABERS	Solid-state Architecture Batteries for Enhanced Rechargeability and Safety
SAE	Society of Automotive Engineers
SAFE	Securing America’s Future Energy
SBA	Small Business Administration
SBREFA	Small Business Regulatory Enforcement Fairness Act

Acronym	**Definition**
SC-GHG	Social Cost of Greenhouse Gases
SCR	Selective Catalytic Reduction
SES	Socioeconomic status
SET	Supplemental Emission Test
SF_6	Sulfur Hexafluoride
SI	Spark-Ignition
SMR	Steam Methane Reforming
SO_2	Sulfur Dioxide
SOH	State-of-health
SO_X	Oxides of Sulfur
SOX	Sulfur Oxides
SPR	Strategic Petroleum Reserve
T3CO	NREL's Transportation Technology Total Cost of Ownership
TCO	Total Cost of Ownership
TEIS	Multi-State Transportation Electrification Impact Study
TEMPO	NREL's Transportation Energy & Mobility Pathway Options Model
TIGER	Topologically Integrated Geographic Encoding and Referencing system
TOU	Time of use
TPRD	Thermally activated pressure relief device
TRUCS	Technology Resource Use Case Scenario
TSD	Technical Support Document
TW	Terawatt
U.S.	United States
UAW	United Auto Workers
UFP	Ultrafine Particles
UN	United Nations
UN ECE	United Nations Economic Commission for Europe
UNFCCC	United Nations Framework Convention on Climate Change
URE	Unit Risk Estimate
USA	United States of America
USABC	US Automotive Battery Consortium
USC	Unites States Code
USD	United States Dollars
USDOT	United States Department of Transportation
USGCRP	Unites States Global Change Research Program
USGS	United States Geological Survey
USPS	United States Postal Service
VIN	Vehicle Identification Number
VIUS	Vehicle Inventory Use Survey
VMT	Vehicle Miles Traveled
VOC	Volatile Organic Compound
VPP	Virtual Power Plant
VSL	Value of Statistical Life
WTI	West Texas Intermediate
WTP	Willingness To Pay
ZEP	Zero Emission Powertrain
ZETI	Zero-Emission Technology Inventory
ZEV	Zero-Emission Vehicles