Multi-Pollutant Emissions Standards for Model Years 2027 and Later Light-Duty and Medium-Duty Vehicles

Draft 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

NOTICE

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Executive Summary

Under its Clean Air Act Section 202 authority, the Environmental Protection Agency (EPA) is proposing new, more stringent emissions standards for criteria pollutants and greenhouse gases (GHG) for light-duty vehicles and Class 2b and 3 ("medium-duty") vehicles that would phase-in over model years 2027 through 2032. In addition, EPA is proposing GHG program revisions in several areas, including off-cycle and air conditioning credits, the treatment of zero emissions vehicles and plug-in hybrid electric vehicles in fleet average calculations, and vehicle certification and compliance. EPA is also proposing new standards to control refueling emissions from incomplete medium-duty vehicles, and battery durability and warranty requirements for light-duty plug-in vehicles.

This Draft Regulatory Impact Analysis (DRIA) contains supporting documentation for the EPA proposed rulemaking and addresses requirements in Clean Air Act Section 317. The preamble to the Federal Register notice associated with this document provides the full context for the EPA proposed rule, and it references this DRIA throughout.

DRIA Chapter Summary

This document contains the following Chapters:

<u>Chapter 1: Development of GHG Standards and BEV Durability Requirements</u>

This chapter provides technical details supporting the development of the proposed GHG standards for both Light Duty and Medium Duty Vehicles, and a separate section that provides additional background on development of EPA's proposed battery durability standards compared to those developed by the United Nations (UN) and California.

<u>Chapter 2: Tools and Inputs Used for Modeling Technologies and Adoption Towards Compliance</u>

This chapter summarizes the tools and inputs used for modeling technologies, adoption of technologies, and vehicle compliance with the proposed standards. This includes details regarding the OMEGA model, ALPHA vehicle simulation tools, and the Agency's approach to analyzing vehicle manufacturing costs, consumer demand, vehicle operational costs. The chapter also includes a summary of modeling inputs that reflect our assessment of impacts due to the implementation of the Inflation Reduction Act of 2022.

<u>Chapter 3: Analysis of Technologies for Reducing GHG and Criteria Pollutant Emissions</u>

This chapter provides EPA’s analysis of technologies available for further reducing both GHG and criteria pollutant emissions and current technology trends. It also provides EPA’s analysis supporting the proposed revisions for on-board diagnostics and PHEV accounting (i.e., revised utility factor).

<u>Chapter 4: Consumer Impacts and Related Economic Considerations</u>

This chapter discusses consumer impacts of this proposed rule, including the consumer purchase decision, the ownership experience, social benefits and costs, as well as the effect on new vehicle sales, and estimated employment effects. In the discussion of the purchase decision, we include costs consumers incorporate into their purchase decision, how consumer respond to costs, and how consumer perception of technologies change, or do not, over time. Within our discussion of ownership experience, we include vehicle use and the effect on private savings and expenses, including vehicle miles traveled, rebound, fueling costs, maintenance and repair, and noise and congestion costs due to this rule. Consumer related costs and benefits include components of social costs and benefits that are included in the benefit-cost analysis and that have direct consumer impacts. The discussion of new vehicle sales explains how vehicle sales were modeled, including an explanation of the elasticity of demand used in our analysis, as well as the estimated effect of the proposed rule on total vehicle sales. We conclude the chapter with a description of employment effects, including potential impacts of the growing prevalence of BEVs, a quantitative estimate of partial employment impacts on sectors directly impacted by this proposed rule, and discuss potential impacts on other related sectors.

Chapter 5: Electric Infrastructure Impacts

This chapter provides EPA's analysis of plug-in electric vehicle (PEV) charge demand and regional distribution, electric power sector modeling including estimating retail electricity prices, and EPA's assessment of current and future PEV charging infrastructure. Finally, this chapter discusses electric grid resiliency.

Chapter 6: [Blank]

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Chapter 7: Health and Welfare Impacts

The proposed rule will impact emissions of GHGs, criteria pollutants, and air toxic pollutants. There are health and welfare impacts associated with ambient concentrations of GHGs, criteria pollutants and air toxics which are described in this chapter.

Chapter 8: Illustrative Analysis of Air Quality Impacts of a Light- and Medium-Duty Vehicles Regulatory Scenario

This chapter provides information regarding current air quality including pollutant concentrations and EPA's assessment of air quality impacts. EPA conducted an air quality modeling analysis of an illustrative regulatory scenario involving light- and medium-duty vehicle emission reductions and corresponding changes in electric generating unit (EGU) emissions, refinery emissions, emissions from crude oil production sites and pipeline pumps, and emissions from natural gas production sites and pipeline pumps. This analysis does not represent the proposal's regulatory scenario, and it does not account for the impacts of the Inflation Reduction Act (IRA); however, it provides some insights into potential air quality impacts associated with emissions increases and decreases from these multiple sectors.

Chapter 9: OMEGA Physical Effects of the Proposed Standards and Alternatives

This chapter describes the methods and approaches used within the OMEGA model to estimate physical effects of the proposed standards. Physical effects refer to emission inventories, fuel consumption, oil imports, vehicle miles traveled including effects associated with the rebound effect, and safety effects. The cost and benefits of the proposal are tied directly to these physical effects and are discussed in Chapter 11 of this draft RIA.

Chapter 10: Costs and Benefits of the Proposed Standards in OMEGA

This chapter presents the costs and benefits calculated within OMEGA. The results presented here show the estimated annual costs, fuel savings and benefits of the program for the indicated calendar years (CY). The results also show the present-values (PV) of those costs and the equivalent annualized values (EAV) for the calendar years 2027–2055 using both 3 percent and 7 percent discount rates. For the estimation of the stream of costs and benefits, we assume that after implementation of the MY 2027 and later standards, the MY 2032 standards apply to each year thereafter.

Chapter 11: Energy Security Impacts

This chapter provides EPA's evaluation of the energy security impacts of the light- and medium-duty vehicle proposed rule. It provides a review of historical and recent energy security literature and EPA assessment of potential electricity and oil security impacts.

Chapter 12: Small Business Flexibilities

This chapter discusses the flexibilities EPA proposes to provide to small businesses for model years 2027 and later for both the proposed GHG and criteria pollutant emissions standards.

Chapter 13: Compliance Effects

This chapter summarizes the outputs from OMEGA related to the proposed standards and the two alternatives which were presented in III.E of the preamble. It provides EPA's detailed modeling results of GHG targets, projected achieved compliance GHG rates, as well as vehicle costs and technology penetrations. These projections are grouped by car and truck regulatory classes, and in select tables, using EPA's classification of body style in its OMEGA model.

Summary of Emission Reductions, Costs, and Benefits

This section of the Executive Summary summarizes our analysis of the proposal's estimated emission impacts, costs, and monetized benefits, which is described in more detail in DRIA Chapters 9, 10, and 13; and also in Sections V through VIII of the Preamble to the proposed rule.

The proposed standards would result in net reductions of emissions of criteria air pollutants and GHGs in 2055, considering the impacts from light- and medium-duty vehicles, power plants (i.e., electric generating units (EGUs)), and refineries. Table 1 shows the GHG emission impacts in 2055 while Table 2 shows the cumulative impacts for the years 2027 through 2055. We show cumulative impacts for GHGs as elevated concentrations of GHGs in the atmosphere are resulting in warming and changes in the Earth's climate. Table 3 shows the criteria pollutant emissions impacts in 2055. As shown in Table 4, we also predict reductions in air toxic emissions from light-and medium-duty vehicles. We project that GHG and criteria pollutant emissions from EGUs would increase as a result of the increased demand for electricity associated with the proposal, although those projected impacts decrease over time because of projected increases in renewables in the future power generation mix. We also project that GHG and criteria pollutant emissions from refineries would decrease as a result of the lower demand for liquid fuel associated with the proposed GHG standards. Chapters 8, 9 and 10 of the DRIA and also Sections VI and VII of the Preamble to the proposed rule provide more information on the projected emission reductions for the proposed standards and alternatives.

Table 1: Projected GHG emission impacts in 2055 from the proposed rule, light-duty and medium-duty (Million metric tons)

Pollutant	Vehicle	EGU	Refinery*	Net Impact	Net Impact (%)
CO_2	-440	16	0	-420	-47%
CH_4	-0.0088	0.00038	0	-0.0084	-45%
N_2O	-0.0077	0.00003	0	-0.0077	-41%

Table 2: Projected cumulative GHG emission impacts through 2055 from the proposed rule, light-duty and medium-duty (Million metric tons)

Pollutant	Vehicle	EGU	Refinery*	Net Impact	Net Impact (%)
CO_2	-8,000	710	0	-7,300	-26%
CH_4	-0.16	0.035	0	-0.12	-17%
N_2O	-0.14	0.0045	0	-0.13	-25%

Table 3: Projected criteria air pollutant impacts in 2055 from the proposed rule, light-duty and medium-duty (US tons)

Pollutant	Vehicle	EGU	Refinery	Net Impact	Net Impact (%)
$PM_{2.5}$	-9,800	1,500	-6,900	-15,000	-35%
NO_X	-44,000	2,600	-25,000	-66,000	-41%
VOC	-200,000	1,000	-21,000	-220,000	-50%
SO_X	-2,800	1,600	-11,000	-12,000	-42%
CO*	-1,800,000	0	0	-1,800,000	-49%

Table 4: Projected air toxic impacts from vehicles in 2055 from the proposed rule, light-duty and medium-duty (US tons)

Pollutant	Vehicle	Vehicle (%)
Acetaldehyde	-840	-49%
Acrolein	-55	-48%
Benzene	-2,900	-51%
Ethylbenzene	-3,400	-50%
Formaldehyde	-510	-49%
Naphthalene	-100	-51%
1,3-Butadiene	-340	-51%
15 Polyaromatic Hydrocarbons	-5	-78%

The GHG emission reductions would contribute toward the goal of holding the increase in the global average temperature to well below 2°C above pre-industrial levels and would subsequently reduce the probability of severe climate change related impacts including heat waves, drought, sea level rise, extreme climate and weather events, coastal flooding, and wildfires.

The decreases in vehicle emissions would reduce traffic-related pollution in close proximity to roadways. As discussed in DRIA Chapter 7, concentrations of many air pollutants are elevated near high-traffic roadways, and 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.

The changes in emissions of criteria and toxic pollutants from vehicles, EGUs, and refineries would also impact ambient levels of ozone, $PM_{2.5}$, NO_2, SO_2, CO, and air toxics over a larger geographic scale. As discussed in DRIA Chapters 8 and 9, we expect that in 2055 the proposal would result in widespread decreases in ozone, $PM_{2.5}$, NO2, CO, and some air toxics, even when accounting for the impacts of increased electricity generation. We expect that in some areas, increased electricity generation would increase ambient SO2, $PM_{2.5}$, ozone, or some air toxics. However, as the power sector becomes cleaner over time, these impacts would decrease. Although the specific locations of increased air pollution are uncertain, we expect them to be in more limited geographic areas, compared to the widespread decreases that we predict to result from the reductions in vehicle emissions.

EPA estimates the present value of net benefits lies in the range of $850 billion to $1.6 trillion, with equivalent annualized net benefits in the range of $60 billion to $85 billion. EPA estimates that the total benefits of this proposal far exceed the total costs: the present value of benefits range from $350 billion to $590 billion, with pre-tax fuel savings providing another $450 billion to $890 billion, and the present value of vehicle technology costs range from $180 billion to $280 billion, but the present value of repair and maintenance savings are estimated at $280 billion to $580 billion. The results presented here project the monetized environmental and economic impacts associated with the proposed program during each calendar year through 2055. Table 5 below summarizes EPA's estimates of total costs, savings, and benefits. Note EPA projects lower maintenance and repair costs for several advanced technologies (e.g., battery electric vehicles) and those societal maintenance and repair savings grow significantly over time, and by 2040 and later are larger than our projected new vehicle technology costs.

The benefits include climate-related economic benefits from reducing emissions of GHGs that contribute to climate change, reductions in energy security externalities caused by U.S. petroleum consumption and imports, the value of certain particulate matter-related health benefits, the value of additional driving attributed to the rebound effect, and the value of reduced refueling time needed to refuel vehicles. Between $63 and $280 billion of the present value of total benefits through 2055 (assuming a 7 percent and 3 percent discount rate, respectively, as well as different long-term PM-related mortality risk studies) are attributable to reduced emissions of criteria pollutants that contribute to ambient concentrations of smaller particulate matter ($PM_{2.5}$). $PM_{2.5}$ is associated with premature death and serious health effects such as hospital admissions due to respiratory and cardiovascular illnesses, nonfatal heart attacks, aggravated asthma, and decreased lung function. The proposed program would also have other significant social benefits including $330 billion in climate benefits (with the average SC-GHGs at a 3 percent discount rate).

The analysis also includes estimates of economic impacts stemming from additional vehicle use from increased rebound driving, such as the economic damages caused by crashes, congestion, and noise. See Chapter 10 of the DRIA for more information regarding these estimates.

Note that some non-emission costs are shown as negative values in Table 5. Those entries represent savings but are included as costs because, traditionally, things like repair and maintenance are viewed as costs of vehicle operation. Where negative values are shown, we are estimating that those costs are lower in the proposal than in the no-action case. Congestion and noise costs are attributable to increased congestion and roadway noise resulting from our assumption that people may choose to drive more under the proposal versus the no action case. Those increased miles are known as rebound miles and are discussed DRIA Chapter 4.

Similarly, some of the traditional benefits of rulemakings that result in lower fuel consumption by the transportation fleet, i.e., the non-emission benefits, are shown as negative values. Our past GHG rules have estimated that time spent refueling vehicles would be reduced due to the lower fuel consumption of new vehicles; hence, a benefit. However, in this analysis, we are estimating that refueling time would increase somewhat due to mid-trip recharging events for electric vehicles. Therefore, the increased refueling time represents a disbenefit (a negative benefit) as shown. As noted in Chapter 4 of the DRIA, we consider our refueling time estimate to be dated considering the rapid changes taking place in electric vehicle charging infrastructure, which is significantly driven by the Inflation Reduction Act.

Table 5: Monetized discounted costs, benefits, and net benefits of the proposed program for calendar years 2027 through 2055, light-duty and medium-duty (Billions of 2020 dollars).[a,b,c]

	CY 2055	PV, 3%	PV, 7%	EAV, 3%	EAV, 7%
Non-Emission Costs					
Vehicle Technology Costs	10	280	180	15	15
Repair Costs	-24	-170	-79	-8.9	-6.5
Maintenance Costs	-51	-410	-200	-21	-16
Congestion Costs	0.16	2.3	1.3	0.12	0.11
Noise Costs	0.0025	0.037	0.021	0.0019	0.0017
Sum of Non-Emission Costs	-65	-290	-96	-15	-7.8
Fueling Impacts					
Pre-tax Fuel Savings	93	890	450	46	37
EVSE Port Costs	7.1	120	68	6.2	5.6
Sum of Fuel Savings less EVSE Port Costs	86	770	380	40	31
Non-Emission Benefits					
Drive Value Benefits	0.31	4.8	2.7	0.25	0.22
Refueling Time Benefits	-8.2	-85	-45	-4.4	-3.6
Energy Security Benefits	4.4	41	21	2.2	1.7
Sum of Non-Emission Benefits	-3.6	-39	-21	-2	-1.7
Climate Benefits[a]					
5% Average	15	82	82	5.4	5.4
3% Average	38	330	330	17	17
2.5% Average	52	500	500	25	25
3% 95th Percentile	110	1,000	1,000	52	52
Criteria Air Pollutant Benefits[b]					
$PM_{2.5}$ Health Benefits – Wu et al., 2020	16 - 18	140	63	7.5	5.1
$PM_{2.5}$ Health Benefits – Pope III et al., 2019	31 - 34	280	130	15	10
Net Benefits[a,c]					
With Climate 5% Average	180 - 200	1,400	610	74	48
With Climate 3% Average	200 - 220	1,600	850	85	60
With Climate 2.5% Average	210 - 230	1,800	1,000	93	67
With Climate 3% 95th Percentile	280 - 290	2,300	1,500	120	95

[a] The same discount rate used to discount the value of damages from future emissions (SC-GHG at 5, 3, 2.5 percent) is used to calculate present and equivalent annualized values of SC-GHGs for internal consistency, while all other costs and benefits are discounted at either 3 percent or 7 percent.

[b] $PM_{2.5}$-related health benefits are presented based on two different long-term exposure studies of mortality risk: a Medicare study (Wu et al., 2020) and a National Health Interview Survey study (Pope III et al., 2019). The criteria pollutant benefits associated with the standards presented here do not include the full complement of health and environmental benefits that, if quantified and monetized, would increase the total monetized benefits.

[c] For net benefits, the range in 2055 uses the low end of the Wu range and the high end of the Pope III et al. range. The present and equivalent annualized value of net benefits for a 3 percent discount rate reflect benefits based on the Pope III et al. study while the present and equivalent annualized values of net benefits for a 7 percent discount rate reflect benefits based on the Wu et al. study.

EPA estimates the average upfront per-vehicle cost to meet the proposed standards to be approximately $1,400 in MY 2032, as shown in Table 6 below. We discuss this in more detail in DRIA Chapter 13.

Table 6: Average incremental vehicle cost by reg class, relative to the No Action scenario (2020 dollars)

	2027	2028	2029	2030	2031	2032
Cars	$249	$102	$32	$100	$527	$844
Trucks	$891	$767	$653	$821	$1,100	$1,385
Total	$633	$497	$401	$526	$866	$1,164

In addition, the proposal would result in significant savings for consumers from fuel savings and reduced vehicle repair and maintenance. These lower operating costs would offset the upfront vehicle costs. Total retail fuel savings for consumers through 2055 are estimated at $560billion to $1.1 trillion (7 percent and 3 percent discount rates). Reduced maintenance and repair costs through 2055 are estimated at $320 billion to $650 billion (7 percent and 3 percent discount rates, see Chapter 10 of the DRIA).

Analysis of Alternatives to the Proposal

EPA analyzed three alternatives to the proposed standards. Alternative 1 is more stringent than the proposal across the MY 2027-2032 time period, and Alternative 2 is less stringent. The proposal as well as Alternatives 1 and 2 all have a similar proportional ramp rate of year over year stringency, which includes a higher rate of stringency increase in the earlier years (MYs 2027-2029) than in the later years (MY 2030-3032). Alternative 3 achieves the same stringency as the proposed standards in MY 2032 but provides for a more consistent rate of stringency increase for MY 2027-2031.

The Alternative 1 projected fleet-wide CO_2 targets are 10 g/mi lower on average than the proposed targets; Alternative 2 projected fleet-wide CO_2 targets averaged 10 g/mi higher than the proposed targets. While the 20 g/mi range of stringency options may appear fairly narrow, for the MY 2032 standards the alternatives capture a range of 12 percent higher and lower than the proposed standards in the final year. Our goal in selecting the alternatives was to identify a range of stringencies that we believe are appropriate to consider for the final standards because they represent a range of standards that are anticipated to be feasible and are highly protective of human health and the environment.

While the proposed standards, Alternative 1 and Alternative 2 all have a larger increase in stringency between MY 2026 and MY 2027, Alternative 3 was constructed with the goal of evaluating roughly equal reductions in absolute g/mi targets over the duration of the program while achieving the same overall targets by MY 2032. This has the effect of less stringent year-over-year increases in the early years of the program.

Table 7, Table 8 and Table 9 compare the projected fleet average targets for cars, trucks, and the combined fleet, respectively, across the proposed standards and the three alternatives for model years 2027-2032. Table 10 compares the relative percentage year-over-year reductions of the proposed standards and the three alternatives.

Table 7: Comparison of proposed car standards to alternatives

Model Year	Proposed Stds CO_2 (g/mile)	Alternative 1 CO_2 (g/mile)	Alternative 2 CO_2 (g/mile)	Alternative 3 CO_2 (g/mile)
2026 adjusted	152	152	152	152
2027	134	124	144	139
2028	116	106	126	126
2029	99	89	108	112
2030	91	81	100	99
2031	82	72	92	86
2032 and later	73	63	83	73
% reduction vs. 2026	52%	59%	46%	52%

Table 8: Comparison of proposed truck standards to alternatives

Model Year	Proposed Stds CO_2 (g/mile)	Alternative 1 CO_2 (g/mile)	Alternative 2 CO_2 (g/mile)	Alternative 3 CO_2 (g/mile)
2026 adjusted	207	207	207	207
2027	163	153	173	183
2028	142	131	152	163
2029	120	110	130	144
2030	110	100	121	126
2031	100	90	111	107
2032 and later	89	78	99	89
% reduction vs. 2026	57%	62%	52%	57%

Table 9: Comparison of proposed combined fleet standards to alternatives

Model Year	Proposed Stds CO_2 (g/mile)	Alternative 1 CO_2 (g/mile)	Alternative 2 CO_2 (g/mile)	Alternative 3 CO_2 (g/mile)
2026 adjusted	186	186	186	186
2027	152	141	162	165
2028	131	121	141	148
2029	111	101	122	132
2030	102	92	112	115
2031	93	83	103	99
2032 and later	82	72	92	82
% reduction vs. 2026	56%	61%	50%	56%

Table 10: Combined fleet year-over-year decreases for proposed standards and alternatives

Model Year	Proposed Stds CO_2 (g/mile)	Alternative 1 CO_2 (g/mile)	Alternative 2 CO_2 (g/mile)	Alternative 3 CO_2 (g/mile)
2027	-18%	-24%	-13%	-11%
2028	-13%	-14%	-13%	-10%
2029	-15%	-16%	-14%	-11%
2030	-8%	-9%	-8%	-12%
2031	-9%	-10%	-8%	-15%
2032	-11%	-13%	-10%	-17%
Average YoY	-13%	-15%	-11%	-13%

The proposed standards will result in industry-wide average GHG emissions target for the light-duty fleet of 82 g/mi in MY 2032, representing a 56 percent reduction in average emission target levels from the existing MY 2026 standards established in 2021. Alternative 1 is projected to result in an industry-wide average target of 72 grams/mile (g/mile) of CO_2 in MY 2032, representing a 61 percent reduction in projected fleet average GHG emissions target levels from the existing MY 2026 standards. Alternative 2 is projected to result in an industry-wide average target of 92 g/mile of CO_2 in MY 2032, which corresponds to a 50 percent reduction in projected fleet average GHG emissions target levels from the existing MY 2026 standards. Like the proposed standards, Alternative 3 is projected to result in an industry-wide average target of 82 g/mile of CO_2 in MY 2032, which corresponds to a 56 percent reduction in projected fleet average GHG emissions target levels from the existing MY 2026 standards.

Table 11 gives a comparison of average incremental per-vehicle costs for the proposed standards and the alternatives. As shown, the 2032 MY industry average vehicle cost increase (compared to the No Action case) ranges from approximately $1,000 to $1,800 per vehicle for the alternatives, compared to $1,200 per vehicle for the proposed standards. These projections represent compliance costs to the industry and are not the same as the costs experienced by the consumer when purchasing a new vehicle. For example, the costs presented here do not include any state and Federal purchase incentives that are available to consumers. Also, the manufacturer decisions for the pricing of individual vehicles may not align exactly with the cost impacts for that particular vehicle.

Table 11: Comparison of projected incremental per-vehicle costs relative to the No Action scenario

Model Year	Proposed Stds $/vehicle	Alternative 1 $/vehicle	Alternative 2 $/vehicle	Alternative 3 $/vehicle
2027	$633	$668	$462	$189
2028	$497	$804	$355	$125
2029	$401	$1,120	$353	$45
2030	$526	$1,262	$337	$250
2031	$866	$1,565	$718	$800
2032	$1,164	$1,775	$1,041	$1,256

Projected emissions reductions from the alternatives are shown in Table 12 through Table 15. A summary of the costs, savings and benefits for alternatives 1, 2, and 3 are shown in Table 16, Table 17, and Table 18, respectively.

Table 12: Projected GHG emission impacts in 2055 from the proposed rule, light-duty and medium-duty (Million metric tons)

Pollutant	Vehicle	EGU	Refinery*	Net Impact	Net Impact (%)
Alternative 1					
CO_2	-480	18	0	-460	-52%
CH_4	-0.0096	0.00043	0	-0.0092	-49%
N_2O	-0.0084	0.000034	0	-0.0083	-44%
Alternative 2					
CO_2	-400	14	0	-380	-43%
CH_4	-0.0081	0.00035	0	-0.0078	-42%
N_2O	-0.0072	0.000027	0	-0.0072	-38%
Alternative 3					
CO_2	-440	16	0	-420	-47%
CH_4	-0.0088	0.00039	0	-0.0084	-45%
N_2O	-0.0078	0.00003	0	-0.0077	-41%
*GHG emission rates were not available for calculating GHG inventories from refineries.					

Table 13: Projected cumulative GHG emission impacts through 2055 from the proposed rule, light-duty and medium-duty (Million metric tons)

Pollutant	Vehicle	EGU	Refinery*	Net Impact	Net Impact (%)
Alternative 1					
CO_2	-8,900	780	0	-8,100	-29%
CH_4	-0.17	0.039	0	-0.13	-18%
N_2O	-0.15	0.005	0	-0.14	-27%
Alternative 2					
CO_2	-7,200	630	0	-6,600	-23%
CH_4	-0.14	0.032	0	-0.11	-15%
N_2O	-0.13	0.004	0	-0.12	-23%
Alternative 3					
CO_2	-7,800	670	0	-7,100	-25%
CH_4	-0.15	0.033	0	-0.12	-16%
N_2O	-0.13	0.0042	0	-0.13	-24%
*GHG emission rates were not available for calculating GHG inventories from refineries.					

Table 14: Projected criteria air pollutant impacts in 2055 from the proposed rule, light-duty and medium-duty (US tons)

Pollutant	Vehicle	EGU	Refinery	Net Impact	Net Impact (%)
Alternative 1					
$PM_{2.5}$	-9,800	1,700	-7,600	-16,000	-37%
NO_X	-47,000	2,800	-27,000	-71,000	-44%
VOC	-230,000	1,100	-23,000	-250,000	-55%
SO_X	-3,000	1,900	-12,000	-13,000	-46%
CO*	-2,000,000	0	0	-2,000,000	-55%
Alternative 2					
$PM_{2.5}$	-9,800	1,400	-6,200	-15,000	-34%
NO_X	-41,000	2,400	-22,000	-61,000	-38%
VOC	-190,000	950	-19,000	-200,000	-45%
SO_X	-2,500	1,500	-9,500	-11,000	-38%
CO*	-1,600,000	0	0	-1,600,000	-45%
Alternative 3					
$PM_{2.5}$	-9,800	1,500	-6,900	-15,000	-35%
NO_X	-44,000	2,600	-25,000	-66,000	-41%
VOC	-200,000	1,000	-21,000	-220,000	-50%
SO_X	-2,800	1,700	-11,000	-12,000	-42%
CO*	-1,800,000	0	0	-1,800,000	-50%

*EPA did not have data available to calculate CO impacts from EGUs or refineries.

Table 15: Projected air toxic impacts from vehicles in 2055 from the proposed rule, light-duty and medium-duty (US tons)

Pollutant	Vehicle	Vehicle (%)
Alternative 1		
Acetaldehyde	-920	-53%
Acrolein	-60	-52%
Benzene	-3,200	-56%
Ethylbenzene	-3,700	-55%
Formaldehyde	-550	-53%
Naphthalene	-110	-56%
1,3-Butadiene	-370	-56%
15 Polyaromatic Hydrocarbons	-5	-80%
Alternative 2		
Acetaldehyde	-780	-45%
Acrolein	-51	-44%
Benzene	-2,600	-47%
Ethylbenzene	-3,100	-46%
Formaldehyde	-470	-45%
Naphthalene	-95	-47%
1,3-Butadiene	-310	-47%
15 Polyaromatic Hydrocarbons	-5	-77%
Alternative 3		
Acetaldehyde	-850	-49%
Acrolein	-55	-48%
Benzene	-2,900	-51%
Ethylbenzene	-3,400	-50%
Formaldehyde	-510	-49%
Naphthalene	-100	-51%
1,3-Butadiene	-340	-51%
15 Polyaromatic Hydrocarbons	-5	-78%

Table 16: Monetized discounted costs, benefits, and net benefits of Alternative 1 for calendar years 2027 through 2055, light-duty and medium-duty (Billions of 2020 dollars)[a,b,c]

	CY 2055	PV, 3%	PV, 7%	EAV, 3%	EAV, 7%
Non-Emission Costs					
Vehicle Technology Costs	11	330	220	17	18
Repair Costs	-26	-180	-82	-9.3	-6.7
Maintenance Costs	-57	-450	-220	-24	-18
Congestion Costs	0.11	3.5	2.2	0.18	0.18
Noise Costs	0.0017	0.055	0.034	0.0028	0.0027
Sum of Non-Emission Costs	-71	-300	-82	-15	-6.7
Fueling Impacts					
Pre-tax Fuel Savings	100	990	510	51	41
EVSE Port Costs	7.1	120	68	6.2	5.6
Sum of Fuel Savings less EVSE Port Costs	95	870	440	45	36
Non-Emission Benefits					
Drive Value Benefits	0.22	6.5	3.9	0.34	0.32
Refueling Time Benefits	-8.8	-90	-47	-4.7	-3.8
Energy Security Benefits	4.8	46	23	2.4	1.9
Sum of Non-Emission Benefits	-3.8	-38	-20	-2	-1.6
Climate Benefits[a]					
5% Average	16	91	91	6	6
3% Average	41	360	360	19	19
2.5% Average	57	560	560	27	27
3% 95th Percentile	120	1,100	1,100	58	58
Criteria Air Pollutant Benefits[b]					
$PM_{2.5}$ Health Benefits – Wu et al., 2020	16 - 18	150	66	7.7	5.3
$PM_{2.5}$ Health Benefits – Pope III et al., 2019	32 - 35	290	130	15	11
Net Benefits[a,c]					
With Climate 5% Average	200 - 210	1,500	660	80	52
With Climate 3% Average	220 - 240	1,800	930	93	65
With Climate 2.5% Average	240 - 260	2,000	1,100	100	73
With Climate 3% 95th Percentile	300 - 320	2,500	1,700	130	100

[a] The same discount rate used to discount the value of damages from future emissions (SC-GHG at 5, 3, 2.5 percent) is used to calculate present and equivalent annualized values of SC-GHGs for internal consistency, while all other costs and benefits are discounted at either 3 percent or 7 percent.

[b] $PM_{2.5}$-related health benefits are presented based on two different long-term exposure studies of mortality risk: a Medicare study (Wu et al., 2020) and a National Health Interview Survey study (Pope III et al., 2019). The criteria pollutant benefits associated with the standards presented here do not include the full complement of health and environmental benefits that, if quantified and monetized, would increase the total monetized benefits.

[c] For net benefits, the range in 2055 uses the low end of the Wu range and the high end of the Pope III et al. range. The present and equivalent annualized values for 3 percent use the Pope III et al. values while the 7 percent values use the Wu values.

Table 17: Monetized discounted costs, benefits, and net benefits of Alternative 2 for calendar years 2027 through 2055, light-duty and medium-duty (Billions of 2020 dollars)[a,b,c]

	CY 2055	PV, 3%	PV, 7%	EAV, 3%	EAV, 7%
Non-Emission Costs					
Vehicle Technology Costs	8.8	230	140	12	12
Repair Costs	-22	-160	-74	-8.3	-6
Maintenance Costs	-47	-370	-180	-19	-14
Congestion Costs	0.064	0.74	0.48	0.039	0.039
Noise Costs	0.001	0.012	0.0078	0.00064	0.00064
Sum of Non-Emission Costs	-60	-300	-110	-16	-8.7
Fueling Impacts					
Pre-tax Fuel Savings	84	790	400	41	33
EVSE Port Costs	7.1	120	68	6.2	5.6
Sum of Fuel Savings less EVSE Port Costs	77	680	330	35	27
Non-Emission Benefits					
Drive Value Benefits	0.17	2.4	1.5	0.12	0.12
Refueling Time Benefits	-7.6	-79	-41	-4.1	-3.3
Energy Security Benefits	3.9	37	19	1.9	1.5
Sum of Non-Emission Benefits	-3.5	-39	-21	-2	-1.7
Climate Benefits[a]					
5% Average	13	74	74	4.9	4.9
3% Average	34	290	290	15	15
2.5% Average	47	450	450	22	22
3% 95th Percentile	100	900	900	47	47
Criteria Air Pollutant Benefits[b]					
$PM_{2.5}$ Health Benefits – Wu et al., 2020	15 - 17	140	61	7.2	4.9
$PM_{2.5}$ Health Benefits – Pope III et al., 2019	30 - 33	270	120	14	10
Net Benefits[a,c]					
With Climate 5% Average	160 - 180	1,300	550	68	44
With Climate 3% Average	180 - 200	1,500	780	78	54
With Climate 2.5% Average	200 - 210	1,700	930	85	61
With Climate 3% 95th Percentile	250 - 270	2,100	1,400	110	86

[a] The same discount rate used to discount the value of damages from future emissions (SC-GHG at 5, 3, 2.5 percent) is used to calculate present and equivalent annualized values of SC-GHGs for internal consistency, while all other costs and benefits are discounted at either 3 percent or 7 percent.

[b] $PM_{2.5}$-related health benefits are presented based on two different long-term exposure studies of mortality risk: a Medicare study (Wu et al., 2020) and a National Health Interview Survey study (Pope III et al., 2019). The criteria pollutant benefits associated with the standards presented here do not include the full complement of health and environmental benefits that, if quantified and monetized, would increase the total monetized benefits.

[c] For net benefits, the range in 2055 uses the low end of the Wu range and the high end of the Pope III et al. range. The present and equivalent annualized values for 3 percent use the Pope III et al. values while the 7 percent values use the Wu values.

Table 18: Monetized discounted costs, benefits, and net benefits of Alternative 3 for calendar years 2027 through 2055, light-duty and medium-duty (Billions of 2020 dollars)[a,b,c]

	CY 2055	PV, 3%	PV, 7%	EAV, 3%	EAV, 7%
Non-Emission Costs					
Vehicle Technology Costs	11	270	170	14	14
Repair Costs	-24	-170	-77	-8.6	-6.3
Maintenance Costs	-51	-390	-190	-20	-15
Congestion Costs	0.11	1.5	0.82	0.078	0.066
Noise Costs	0.0016	0.024	0.013	0.0012	0.0011
Sum of Non-Emission Costs	-64	-290	-95	-15	-7.8
Fueling Impacts					
Pre-tax Fuel Savings	93	850	430	45	35
EVSE Port Costs	7.1	120	68	6.2	5.6
Sum of Fuel Savings less EVSE Port Costs	86	740	360	38	29
Non-Emission Benefits					
Drive Value Benefits	0.21	3.2	1.8	0.17	0.15
Refueling Time Benefits	-8.2	-83	-43	-4.3	-3.5
Energy Security Benefits	4.4	40	20	2.1	1.6
Sum of Non-Emission Benefits	-3.6	-39	-21	-2.1	-1.7
Climate Benefits[a]					
5% Average	15	80	80	5.3	5.3
3% Average	38	320	320	17	17
2.5% Average	52	490	490	24	24
3% 95th Percentile	110	970	970	51	51
Criteria Air Pollutant Benefits[b]					
$PM_{2.5}$ Health Benefits – Wu et al., 2020	16 - 18	140	62	7.3	5.0
$PM_{2.5}$ Health Benefits – Pope III et al., 2019	31 - 34	280	120	14	10
Net Benefits[a,c]					
With Climate 5% Average	180 - 190	1,300	580	71	46
With Climate 3% Average	200 - 220	1,600	820	82	57
With Climate 2.5% Average	210 - 230	1,800	990	90	64
With Climate 3% 95th Percentile	270 - 290	2,200	1,500	120	91

[a] The same discount rate used to discount the value of damages from future emissions (SC-GHG at 5, 3, 2.5 percent) is used to calculate present and equivalent annualized values of SC-GHGs for internal consistency, while all other costs and benefits are discounted at either 3 percent or 7 percent.

[b] $PM_{2.5}$-related health benefits are presented based on two different long-term exposure studies of mortality risk: a Medicare study (Wu et al., 2020) and a National Health Interview Survey study (Pope III et al., 2019). The criteria pollutant benefits associated with the standards presented here do not include the full complement of health and environmental benefits that, if quantified and monetized, would increase the total monetized benefits.

[c] For net benefits, the range in 2055 uses the low end of the Wu range and the high end of the Pope III et al. range. The present and equivalent annualized values for 3 percent use the Pope III et al. values while the 7 percent values use the Wu values.

Chapter 1: Development of GHG Standards and BEV Durability Requirements

This chapter provides technical details supporting the development of the proposed greenhouse gas (GHG) standards for both Light Duty and Medium Duty Vehicles, and a separate section that provides additional background on development of EPA's proposed battery durability standards compared to those developed by the UN and California.

1.1 Development of the proposed GHG standards for Light-Duty Vehicles

As a prelude to the development of the standards for this proposal, EPA first evaluated how the market (manufacturers and consumers) responded (and the implications on emissions) since the footprint-based standards were first established for 2012 model year (MY). We have witnessed a shift in sales mix from the car regulatory class to truck class (described in 1.3.1), and an increase in average vehicle footprint. One of the issues we assessed for this proposal was potential ways to minimize potential erosion of projected GHG reductions due to changes in fleet mix that might be influenced by the program structure.

The Technical Support Document (TSD) supporting the 2017-2025 NPRM (U.S. EPA 2011) outlined EPA's rationale in its selection of footprint as the attribute for its GHG standards and provided a detailed discussion of the statistical methodology applied in fitting footprint curves to fleet data. EPA continues to believe that footprint is appropriate for attribute-based standards.

In assessing new footprint curves for this proposal, EPA wanted to a) reduce the likelihood of change to average vehicle footprint as a compliance strategy and b) to minimize the incentive to shift vehicle attributes and the resulting car/truck classification as a compliance strategy. The following steps were taken (discussed in 1.1.3):

- Establish a footprint slope for passenger vehicles (cars) that does not overly incentivize upsizing or downsizing
- Identify an appropriate CO_2 emissions offset for trucks (relative to passenger vehicles) to recognize the incremental tailpipe CO_2 due to inclusion of all-wheel drive (AWD)[1] and nominal towing capability, and incorporate it into a footprint curve for trucks
- Assess whether these slopes, of their own accord, incentivize a fleet shift towards larger or smaller vehicles
- Propose cutpoints based on observed trends in full size trucks, and reflective of equity concerns for smaller vehicles

1.1.1 <u>Analysis of fleet changes since 2012</u>

During the past rulemakings for GHG standards, several stakeholders have urged the Agency to address what they viewed as overly generous CO_2 targets for light trucks. EPA received several comments on its 2021 NPRM requesting that the nature of the footprint curves, and of

[1] We use the term AWD to include all types of four-wheel drive systems, consistent with SAE standard J1952.

the dual standards for cars and trucks, be re-examined. In collective response to these comments, and as preliminary analysis for this proposal, EPA felt that it was appropriate to assess changes in the fleet and their impact on performance of the light-duty GHG program. EPA has now gathered almost 10 years of sales data since the attribute-based GHG standards for light duty vehicles first took effect in 2012 MY. While the light-duty GHG program has achieved significant emissions reductions over the past decade, EPA witnessed underperformance of achieved tailpipe GHG emissions rates compared to those that were originally projected. This underperformance can be attributed to the market shift towards SUVs and trucks, as well as a modest increase in average vehicle size.

1.1.1.1 Car and Truck Regulatory Classes

The separate car and truck curves stem from regulatory class definitions originally established by NHTSA in its corporate average fuel economy (CAFE) program for cars and trucks, as directed by passage of Energy Policy and Conservation Act (EPCA) in 1975 (Public Law 94-163 1975). EPCA originally defined passenger automobiles ("cars") as “any automobile (other than an automobile capable of off-highway operation) which the Secretary [i.e., NHTSA] decides by rule is manufactured primarily for use in the transportation of not more than 10 individuals.” Under EPCA, there are two general groups of automobiles that qualify as non-passenger automobiles or light trucks:

1) those defined by NHTSA in its regulations as other than passenger automobiles due to their having not been manufactured “primarily” for transporting up to ten individuals; and

2) those expressly excluded from the passenger category by statute due to their capability for off-highway operation, regardless of whether they were manufactured primarily for passenger transportation. NHTSA’s classification rule directly tracks those two broad groups of non-passenger automobiles in subsections (a) and (b), respectively, of 49 CFR Part 523.5 (Title 49 CFR § 523.5 2022).

EPA stated the following reasons in its 2012 FRM (77 FR 62624 2012) as to why it adopted separate car and truck regulatory classes, and separate standards for each:

- First, some vehicles classified as trucks (such as pick-up trucks) have certain attributes not common on cars which attributes contribute to higher CO_2 emissions – notably high load carrying capability and/or high towing capability. Due to these differences, it is reasonable to separate the light-duty vehicle fleet into two groups.

- Second, EPA wished to harmonize key program design elements of the GHG standards with NHTSA’s CAFE program where it was reasonable to do so. NHTSA is required by statute to set separate standards for passenger cars and for non-passenger cars.

- Finally, most of the advantages of a single standard for all light duty vehicles are also present in the two-fleet standards. Because EPA allows unlimited credit transfer between a manufacturer’s car and truck fleets, the two fleets can essentially be viewed as a single fleet when manufacturers consider compliance strategies. Manufacturers can thus choose on which vehicles within their fleet to focus GHG reducing technology and then use credit transfers as needed to demonstrate compliance, just as they will if there was a single fleet standard.

Historically, for the same footprint vehicle, truck standards have been higher (less stringent) than their equivalent-sized car. For example, for a 50 sq. ft crossover vehicle, the AWD version (almost always classified as a truck) would be subject to a standard 40 or more g/mi higher than an equivalent 2WD version of that same model (classified as a car). Beyond MY 2021, the offset between the two curves will start to reduce but it is still significant. Table 1-1 shows a comparison of the GHG targets (and the calculated offset) for a 50-square foot car and truck crossover through the years. Certification data for MY 2019 vehicles comparing tailpipe CO_2 emissions of vehicle models which are sold as both cars and light trucks (such as crossovers), depending on their drivetrain - suggests that the empirical tailpipe CO_2 emissions offset is far less than the compliance offset which has been provided to crossover vehicles.

Table 1-1. Comparison of Car and Truck GHG Targets for 50 Square-Foot Vehicles

Model Year	Car Target g/mi	Truck Target g/mi	Offset g/mi
2012	287	331	44
2017	235	282	46
2021	197	247	50
2026	142	172	30

Since the footprint-based light duty GHG standards first took effect in MY 2012, the makeup of the fleet has changed significantly. In 2012, 64 percent of new vehicle sales were classified as passenger vehicles, with the remaining 36 percent of sales as light trucks. As of 2021, sales of sedans have declined; from 55 percent in 2012, they now represent only 26 percent of fleet sales. Sedans have largely been replaced with taller vehicles such as truck-like sport utility vehicles (SUVs) and crossover utility vehicles (CUVs). There has also been an increase in pickup truck share, from 10 percent to 16 percent in 2021. The shift in sales mix of vehicle types is shown in Figure 1-1.

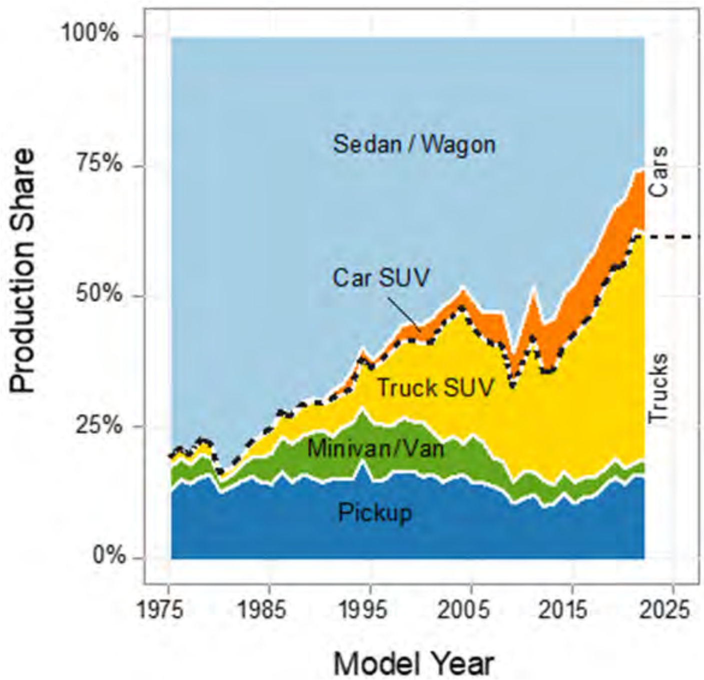

Figure 1-1. Light-Duty Sales by Vehicle Type (U.S. EPA 2022)

In total, there has been a marked increase in the number of light truck sales: as of 2021, light trucks now account for 63 percent of new sales, and passenger vehicles only account for 37 percent of sales. This is illustrated in Figure 1-2.

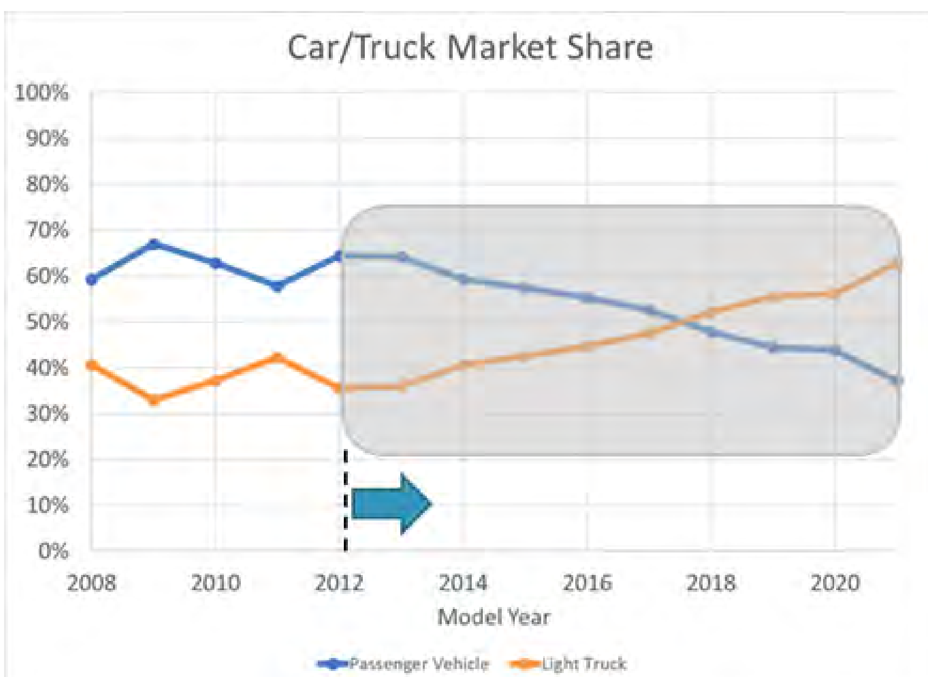

Figure 1-2. Change in Car and Truck Regulatory Class Market Share, 2012-2021 MY

The impact of this shift to light trucks on CO_2 emissions has been noteworthy. In its analysis supporting the 2012 rulemaking (which set standards for MY 2017-2025 vehicles) EPA's projected fleet mix for future years was unchanged from MY 2012 at 64 percent car and 36 percent truck[2]. For the 2021 standards, EPA projected that the MY 2021 fleet (based on the originally projected car/truck mix and average footprint) would need to meet an average CO_2 target of 217 g/mile.[3] However, the shift in actual car/truck mix to 37 percent car and 63 percent truck alone resulted in 14 g/mi higher standards by MY 2021.

Meanwhile, the fleet has increased its overall average footprint by over 5 percent (from 48.9 sq ft in 2012 to 51.5 sq ft in 2021), due to fewer small sedans, and an increase in average full-size pickup trucks. This shift has permitted compliance under higher numerical standards: the result of the increased average footprint alone resulted in an 8 g/mi increase in the MY 2021 fleet average GHG target compared to the MY 2012 average footprint.

In total, the sum of these effects has resulted in MY 2021 standards that are 22 g/mi higher on a fleetwide average than were originally projected. The effects of car/truck shift and footprint increase (combined) are illustrated in Figure 1-3. From 2012-2021, the GHG program has projected combined reductions in CO_2 emissions rates of 28 percent (or an average annual rate of 3.5 percent per year). During this period, the achieved industry CO_2 emissions performance value for new vehicles has only decreased from 287 g/mi in 2012 to 239 g/mi in 2021 - an average annual reduction of about 2 percent per year[4] (U.S. EPA 2021).

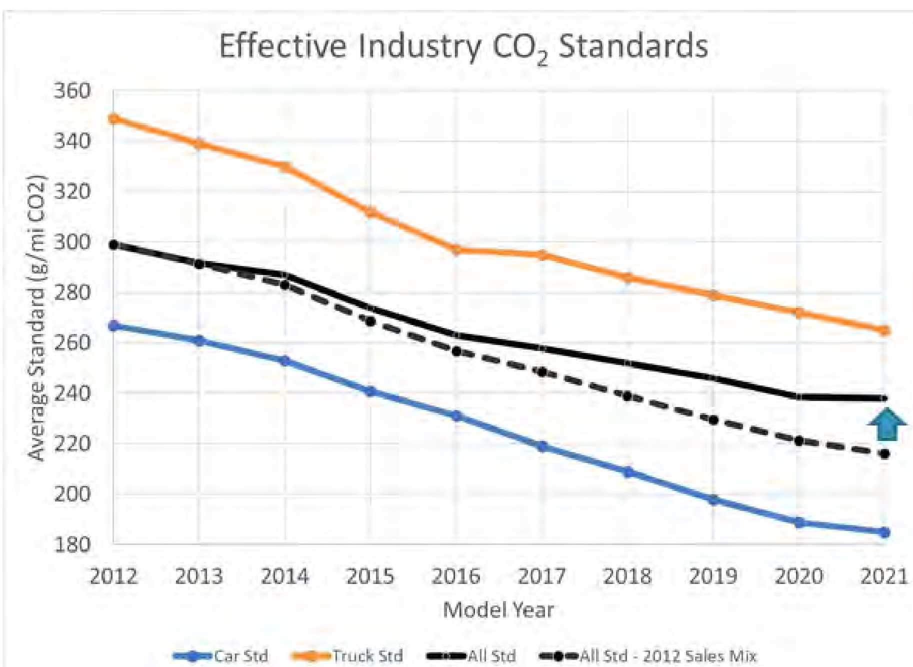

Figure 1-3. Effect of Fleet Shift on Average CO_2 Standard

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[2] For the 2020 rule the projected car/truck mix was revised to 54 percent car and 46 percent truck, but it still underestimated the market share of trucks that would be sold.
[3] This has been adjusted from the published values to reflect differences in expected lifetime VMT for trucks compared to cars.
[4] Note that the 2012 industry performance of 287 g/mi was lower than the 2012 standard of 299 g/mi (black line in Figure 3). This resulted in generation of GHG credits.

1.1.2 Relationship between GHG curve shape, stringency, and BEV share

It is important to note that for the earlier rulemakings, footprint was selected as an attribute with a fleet that was almost exclusively comprised of internal combustion engine (ICE) vehicles. In contrast, footprint does not have any relationship with tailpipe emissions from BEVs or any other zero-emission vehicle. A fleet of exclusively battery electric vehicles would all emit zero g/mi tailpipe GHG, regardless of attribute (vehicle size, weight, tow rating, etc.); mathematically, the only appropriate "footprint curve" for an all-electric fleet would have a slope of zero (flat) and be set to zero g/mi. And so, as the fleet transitions to an increasing percentage of ZEVs, the appropriate slope for the fleet will need to consider not just the current available technology of ICE vehicles, but the ratio of those ICE vehicles sold as a percentage of the entire fleet of new vehicles (including BEVs). For example, if only 50 percent of new vehicles sold were ICE vehicles, it would be reasonable to scale the slope of the curves by roughly 50 percent. In setting future fleet average standards, the anticipated decreasing level of ICE vehicles are thus factored into the setting of the car and truck slopes.

1.1.3 Development of appropriate GHG curve shape (slope and cut points)

EPA believes that footprint is still an appropriate attribute for its standards curves. However, EPA assessed ways to modify the shape of the footprint curves and the relative difference between cars and trucks to minimize the incentive for manufacturers to change vehicle size or regulatory class as a compliance strategy, which is not a goal of the program and could in turn potentially reduce the projected GHG emissions reductions.

Beginning with the premise that the primary objective of light-duty vehicles (regardless of their car/truck regulatory class designation) is to move people and their incidental cargo, EPA first determined an appropriate curve slope for passenger vehicles (cars). The distinguishing features that provide more capability for trucks and the associated increase in tailpipe emissions (for ICE vehicles) are then used to build out a separate a truck curve from the base car curve. The steps and the analysis performed are described below.

1.1.3.1 Establishing slope of car curve

EPA's OMEGA model, in addition to modeling the application of vehicle technology, also has the capability to project changes in vehicle size as a compliance response. In determining an appropriate slope for the car curve, EPA modeled a range of car slopes to evaluate the footprint response – that is, to assess the tendency of the fleet to upsize or downsize as a compliance strategy.

In theory, for ICE vehicles, a footprint-based slope that is too steep will incentivize manufacturers to increase the size of their vehicles as a compliance strategy, whereas a slope too flat may encourage some downsizing. For BEVs (or any ZEV technology), there is no relationship between footprint and tailpipe emissions, so any slope greater than zero should provide manufacturers with a compliance incentive (at some level) to upsize BEVs. For a fleet comprised of BEV and ICE vehicles subject to the same footprint curve, the best compromise for determining a "neutral" slope is one that strikes a balance between upsizing incentives for BEVs with downsizing incentives for ICE vehicles.

For any given vehicle, a manufacturer may be incentivized to increase footprint if the compliance benefit of higher GHG target values (and less potentially less costly technology needed for compliance) and consumer valuation of vehicle size exceeds the additional cost of producing a larger vehicle and higher emissions associated with greater vehicle mass. In the OMEGA model inputs, we assumed a consumer valuation, or willingness-to-pay (WTP) of $200/sq ft of vehicle footprint. While this is on the low end of the range suggested in the literature (e. a. Greene 2018), a higher WTP would create a stronger upsizing tendency, which would suggest an even flatter "size-neutral" slope than found in our analysis.

The slope that corresponded with a neutral response for ICE vehicles only (overall, no change in the average footprint of ICE vehicles) was 0.8 g/mi/square foot. This slope was then scaled down accordingly- for example, based on a nominal BEV sales penetration of around 50 percent, this 0.8 slope would be scaled down to 0.4 (based on a remaining 50 percent of ICE vehicles).

To confirm that this slope would give us a neutral response over a mixed fleet with approximately 50 percent BEVs, we reviewed the footprint response (at a consistent level of stringency which corresponds with 50 percent BEV share) for slopes ranging from 0 to 0.8 g/mi/sq ft. Figure 1-4 (for sedans) and Figure 1-5 (car SUVs) show the final fleet average footprint, compared to the base year average footprint (in orange) for each slope tested. The overall fleet-neutral slope was determined to be 0.43 g/mi/sq ft. As can be seen, the shift in the two body styles balance out (about 0.5 sq ft increase for sedans and a 0.5 sq ft decrease for car SUVs).

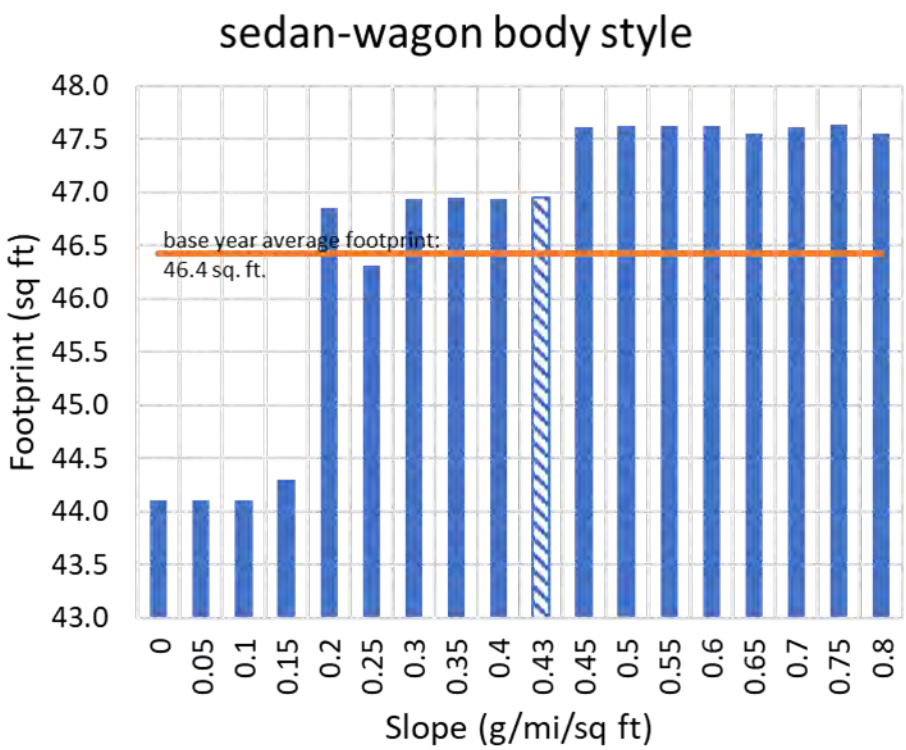

Figure 1-4. Footprint Response to Slope Sweeps, Sedan/Wagon Body Style

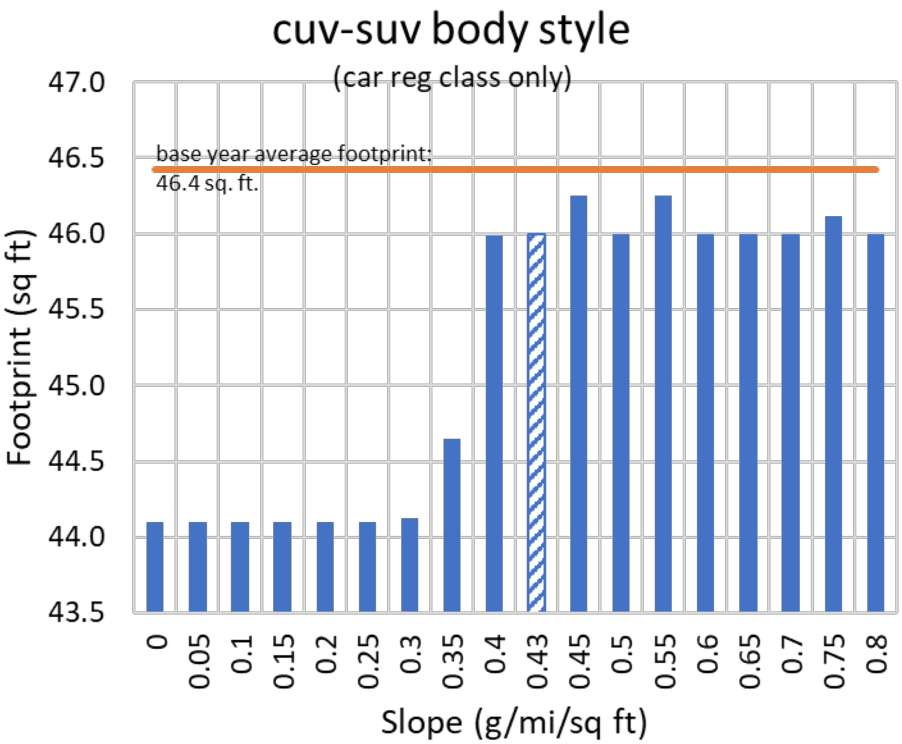

Figure 1-5. Footprint Response to Slope Sweeps, (Car Reg Class) CUV/SUV Body Style

1.1.3.2 Development of truck curve

Historically, there has been a significant increase (offset) between the car and light truck footprint-based curves to reflect the additional utility of trucks. The large shift in sales from car crossovers to truck crossovers might suggest that the size of this offset was not appropriate for vehicles with similar towing and hauling capability - for example, crossover vehicle models (trucks) equipped with AWD compared to those same models with 2WD (cars). Most of these vehicles available with both driveline options exhibit the same tow rating and nearly identical GCWR.

In redesigning the truck curve, EPA considered the "base utility" of moving people for passenger vehicles and light trucks to be similar (this is especially true for crossover vehicles and wagons, for example). However, larger trucks which are designed for more towing and hauling capability do require design changes to allow for handling of these larger loads and this is reflected in increased engine capability, body-on-frame design, and greater structural mass. EPA analyzed empirical fleet data to quantify the additional tailpipe CO_2 resulting from these required design changes and use it as a basis for a "utility offset" that is built into the slope of the proposed truck curves.

The truck curve is based on the car curve, but with additional allowances for 1) AWD and 2) towing and hauling utility. The analysis that went into the determination of each proposed offset, and the resulting truck slope, is detailed below.

3) AWD Offset

EPA analyzed certification data (Ellies 2023) from MY 2019 (the latest at the time the analysis was completed) to compare the tailpipe CO_2 emissions of crossover vehicle models with

2WD and AWD driveline configurations and identical engines. In total, 32 vehicle models were offered in both a 2WD and an AWD version and were subject to passenger vehicle and light truck CO_2 compliance targets, respectively.

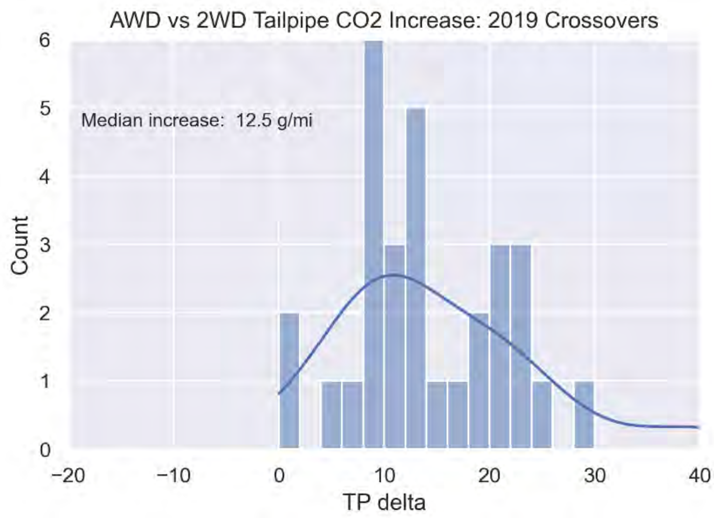

Figure 1-6. Increase in Tailpipe CO_2 Emissions: MY 2019 AWD vs. 2WD Crossovers

Figure 1-4 shows the distribution of tailpipe increase between unique 2WD and AWD vehicle models. The median increase in tailpipe CO_2 is 12.5 g/mi for these models, although several models showed increases below 10 g/mi. As this characteristic is the only attribute distinguishing a “truck” crossover from a “car” crossover that should produce measurable tailpipe CO_2 differences, it forms the basis for the proposed offset between the car and truck curves for vehicles of equivalent towing capacity. Based on this analysis, EPA's proposed footprint curves reflect an offset between the car and truck curves of 10 g/mi for ICE vehicles equipped with AWD.

4) Towing and Hauling Utility Offset

In determining an offset for truck utility, EPA reviewed vehicle specifications available in the MY 2019 fleet data. One way to quantify a vehicle's utility (or maximum output) is by its gross combined weight rating (GCWR).[5] GCWR is the value specified by the vehicle manufacturer as the maximum weight of a loaded vehicle and trailer. (Title 40 CFR § 86.1803-01 2023)

In its simplest form,

GCWR = GVWR + maximum loaded trailer weight,

where:

[5] GVWR describes the maximum load that can be carried by a vehicle, including the weight of the vehicle itself. GCWR describes the maximum load that the vehicle can haul, including the weight of a loaded trailer and the vehicle itself. For more information, please refer to the Medium and Heavy-duty GHG Phase 2 FRM (81 FR 73478 2016).

GVWR (gross vehicle weight rating) is the value specified by the manufacturer as the maximum design loaded weight of a single vehicle (Title 40 CFR § 86.1803-01 2023).

EPA first reviewed MY 2019 vehicle models and plotted GCWR vs engine performance. Of horsepower or engine torque, engine torque correlated best with a truck's utility. As shown in Figure 1-5, there is a positive correlation between a vehicle's GCWR and its rated engine torque.

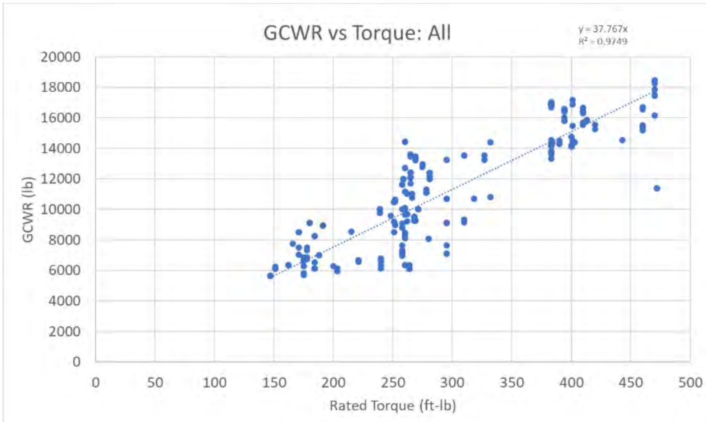

Figure 1-7. GCWR-Torque Relationship, MY 2019 Light Truck Data

As seen in the fleet data, vehicle models which are offered at a higher tow rating than the base model will be equipped with a more powerful engine (and accompanying transmission, driveline and chassis improvements). From a modeling perspective EPA focused on the increase in engine torque based on the relationship observed above.

EPA then evaluated the increase in tailpipe CO_2 for additional towing capacity using response surface equations (RSEs) from ALPHA model results as follows:

- First, we estimated the required nominal engine torque for three vehicle models with different body styles (small pickup, SUV, and full-size pickup) at various tow rating levels by calculating the GCWR and applying the relationship seen in Figure 1-7.
- Then we scaled each engine model to an appropriate displacement (to match required torque) for various modeled engine architectures[6] based on each modeled engine's BMEP. Test weight (curb + 300 pounds) was increased slightly to account for heavier powertrain, driveline, suspension and brakes that are required for greater towing capacity. Road loads were modified slightly based on this increased weight. We were then able to predict CO_2 based on the RSE results for a downsized turbocharged engine and various gasoline GDI engine models.

[6] ALPHA modeled engines include GDI with and without cylinder deactivation and Turbo Gas for pickups, and GDI and Atkinson for CUVs.

- The modeling results show the increase in CO_2 as a function of an increase in towing capacity in Figure 1-8. The data suggests that the average increase in CO_2 for a given vehicle is about 9 g/mi per additional 1000 pounds of tow capability.

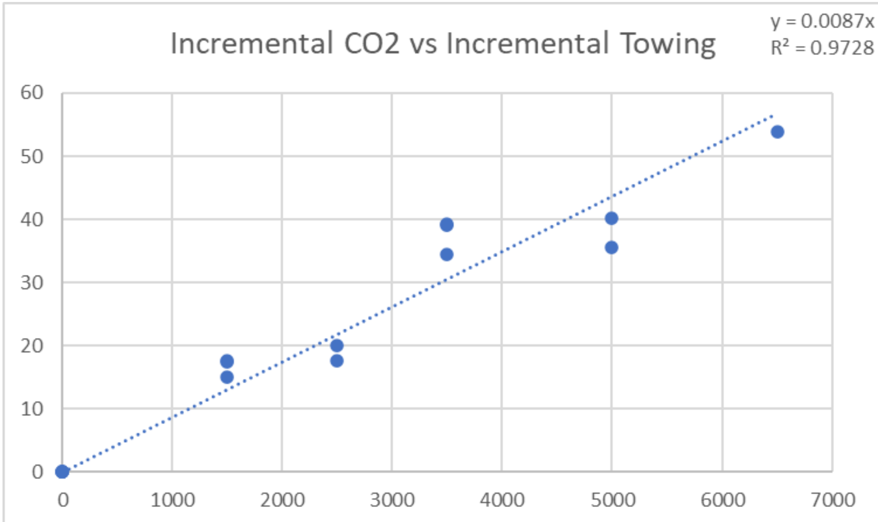

Figure 1-8. Incremental CO_2 as a Function of Increased Towing Capacity

Finally, MY 2019 data shown in Figure 1-9 indicates that tow rating is directionally proportional with footprint (as longer wheelbases are required for stability during increased towing demands). The difference in towing capacity between a 70 square foot truck (at a sales-weight average tow rating slightly over 9000 pound) and that of a 45 square foot truck (with average tow rating just over 2000 pound) is 7000 pounds. Based on the relationship derived above for CO_2 vs. towing capacity, this would correspond to an addition 63 g/mi of tailpipe CO_2 between 45 and 70 square feet[7]. EPA combined these relationships to establish an appropriate footprint-based truck slope that is based on the additional utility that trucks are designed for. This represents the full utility-based offset of the proposed truck curve for a 100 percent ICE vehicle fleet.

[7] EPA is not considering towing differences for trucks greater than 70 square feet or smaller 45 square feet

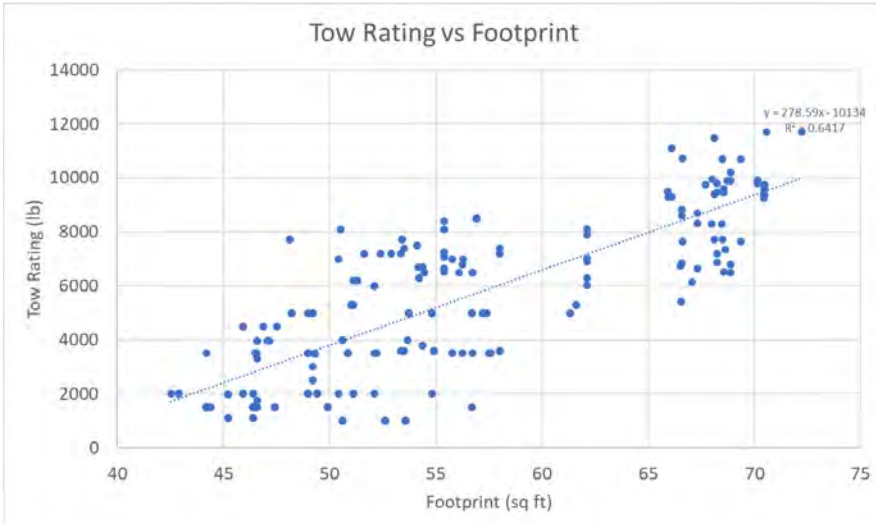

Figure 1-9. Tow Rating-Footprint Relationship, MY 2019 Trucks

For a strictly ICE vehicle fleet, the AWD and utility offset would look as shown in Figure 1-10.

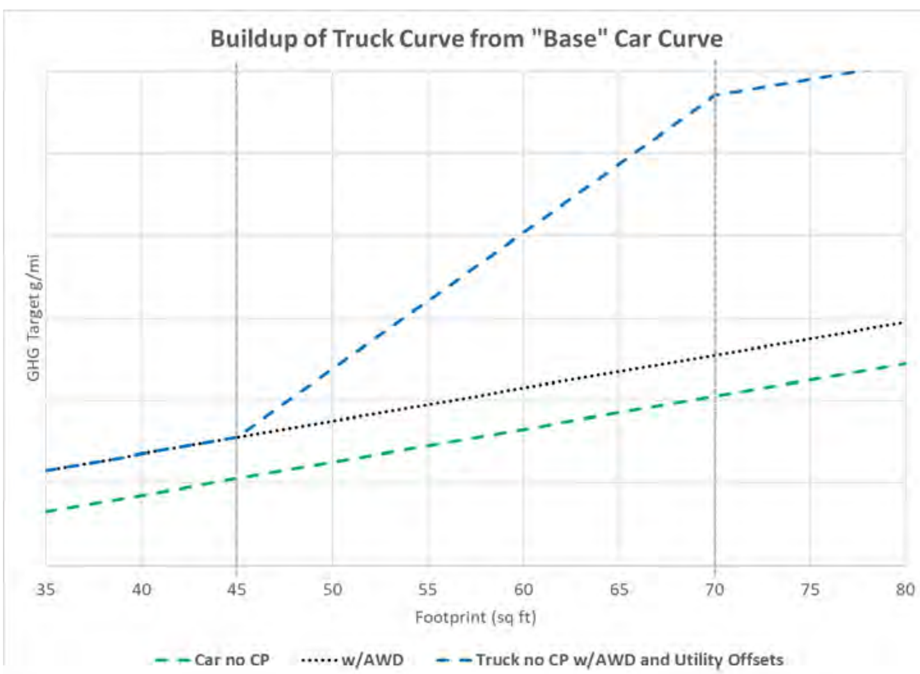

Figure 1-10. AWD and Utility Offset Applied to Establish Truck Curve (100 percent ICE)[8]

However, as described in 1.3.2, we are proposing the scaling of the car and truck curves as appropriate to reflect expected increased BEV penetration. For the 2030 fleet we are applying a

[8] For this figure and the subsequent figures, "no CP" indicates that no cutpoints were reflected in these plots.

50 percent factor to these offsets (i.e., a nominal penetration of 50 percent remaining ICE vehicles), as well as a 50 percent factor to the base car slope. We recognize BEV penetration may be higher or lower than this figure but we believe it is appropriate, as discussed above, to reflect increased BEV penetration in the curves and this is a reasonable approach. This reduces the AWD offset to 5 g/mi and the full-size truck utility offset to 31.5 g/mi as shown in Figure 1-11.

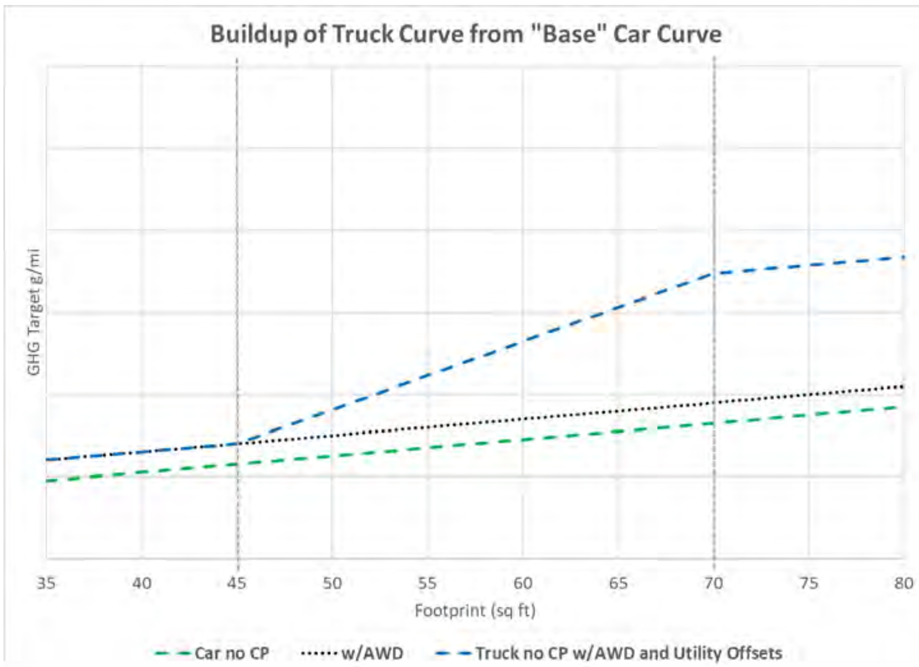

Figure 1-11. AWD and Utility Offset Applied to Establish Truck Curve (Scaled).

1.1.3.3 Analysis of Footprint Response to Proposed Standards

To confirm that the proposed slopes for car and truck curves would not incentivize a shift in vehicle size, we analyzed the projected trend in vehicle footprint for the proposed standards to confirm a minimal overall change in vehicle size for the combined fleet. Figure 1-12 shows a comparison of 2020 base year footprint (blue) compared to the MY 2032 average projected footprint (orange) for the proposed standards, for BEV and ICE vehicles, by body style. As can be seen, the BEVs increase slightly in size, while the ICE vehicles decrease slightly. These two tendencies offset each other to minimize the overall change in fleet size.

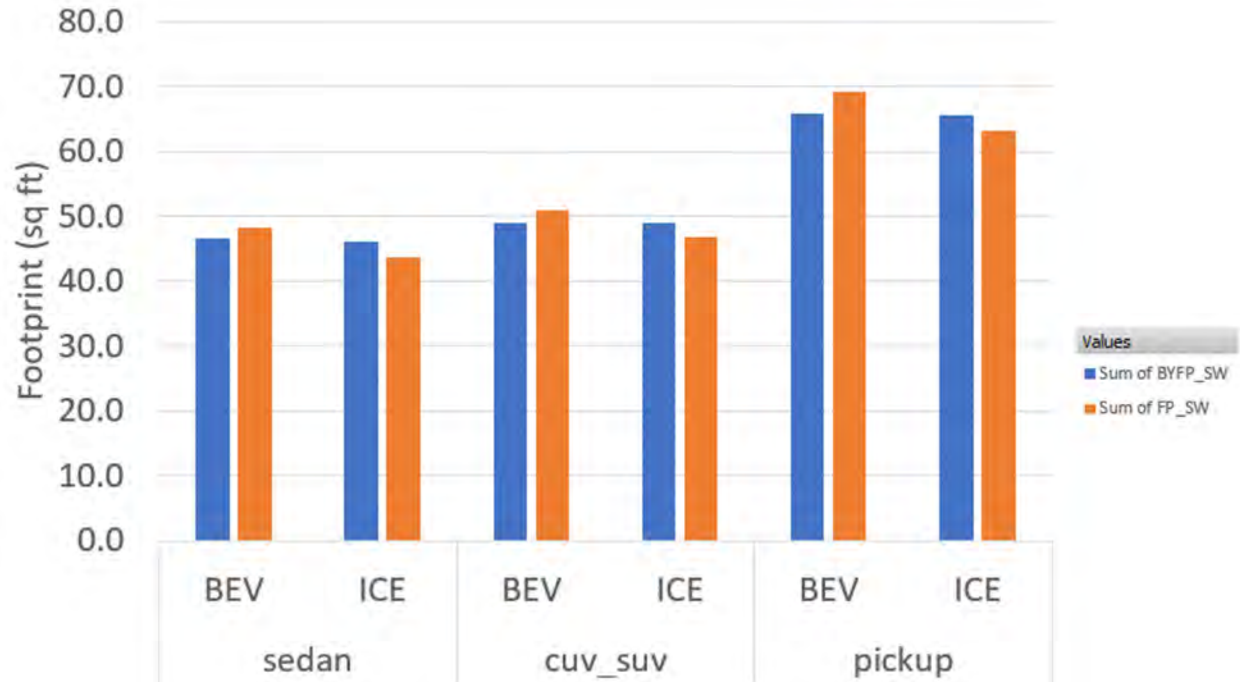

Figure 1-12. Comparison of Average Footprint to Base Year Footprint for Proposed Standards

Table 1-2 shows the numerical MY 2032 average footprint (FP) for the various body styles for BEVs and ICE vehicles, and the fleet averages, compared to base year (MY 2020) footprint for the proposed standards. The overall change in average footprint (51.3 square feet) compared to the base year footprint (50.6) is minimal (an increase of 1 percent).

Table 1-2: Comparison of MY 2032 Footprint to Base Year Footprint, Proposed Standards

	BEV		ICE		Combined	
	Base FP	MY 2032 FP	Base FP	MY 2032 FP	Base FP	MY 2032 FP
Sedan	46.5	48.1	46.0	43.7	46.4	47.1
CUV/SUV	49.0	50.9	49.0	46.7	49.0	49.7
Pickup	65.8	69.1	65.5	63.2	65.7	65.7
Total	**49.7**	**51.7**	**52.7**	**50.3**	**50.6**	**51.3**

1.1.3.4 Cut points

EPA evaluated the sales weight-average footprint for full size pickups in determining the appropriate upper truck cutpoint for this proposal. Figure 1-13 shows that the average footprint has increased for full size pickups from 67 square feet to over 69 square feet in 2021. The upper cutpoint has increased from 66 square feet in MY 2018 to 69 square feet in 2021. To avoid any incentive to further upsize the full-size pickups, EPA is proposing to phase down the long-term upper truck cutpoint to 70 square feet[9]. The upper cutpoint for cars is unchanged at 56 square feet.

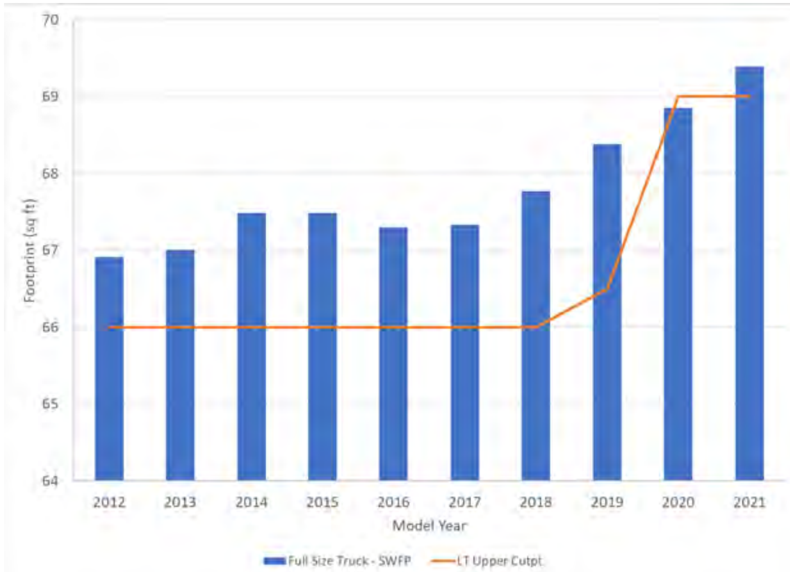

Figure 1-13. Sales-weighted Footprint of Full-Size Pickups, 2012-2021 MY

EPA proposes that vehicles smaller than 45 square feet should not necessarily be subject to more stringent standards based on an extrapolation of the utility offset approach described above. Many vehicle models smaller than 45 square feet, both cars and trucks, are offered and EPA does not want to discourage vehicles in this segment for equity and affordability concerns. These include popular vehicles such as the Subaru Crosstrek, Nissan Kicks, the Chevy Trax, and the Honda HR-V.

Applying the cutpoints to the preceding methodology yields the final curve shape that is shown in Figure 1-14.

[9] In the 2021 rule, for MYs 2023 and beyond the upper truck cutpoint was restored to the original 74 square foot value first finalized in 2012. EPA proposes to reduce the upper cutpoint beginning in MY 2027, with full phase down (from 74 in 2026) to 70 square feet by 2030.

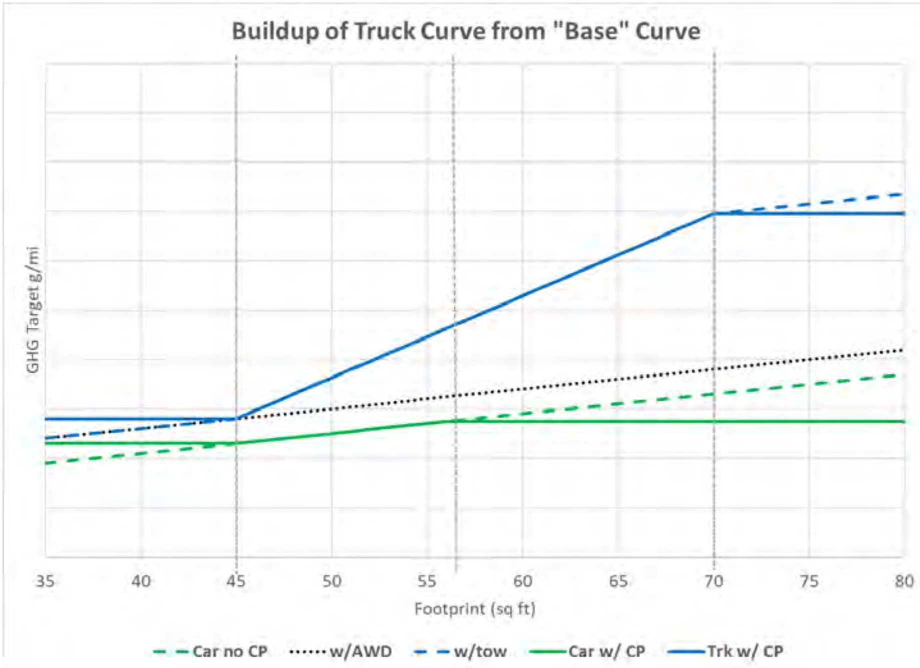

Figure 1-14. Car and Truck Curves, Scaled, with Cutpoints

1.2 Development of the proposed GHG standards for Medium-Duty Vehicles

1.2.1 History of GHG standards for Medium-Duty Vehicles

In the Phase 1 Heavy-duty rule, EPA established a GHG standards program structure for complete Class 2b and 3 heavy-duty vehicles (referred to in this rule as 'medium duty pickups and vans'') as part of a joint GHG and CAFE program with NHTSA (76 FR 57106 2011). The Phase 1 standards began to be phased-in for MY 2014 with the final Phase 1 stringency levels stabilizing in MY 2018. The Phase 1 program worked well to establish a first time GHG standards program for these work-oriented vehicles. The Phase 2 program established more stringent standards for MY 2027, phased in over MYs 2021–2027, requiring additional GHG reductions (81 FR 73478 2016). The MY 2027 standards will remain in place unless and until amended by the agency. Medium duty vehicles (previously described as heavy-duty vehicles in the Phase 1 and Phase 2 HD GHG rules) with a gross vehicle weight rating (GVWR) between 8,501 and 10,000 pounds are classified in the industry as Class 2b motor vehicles while vehicles with GVWR between 10,001 and 14,000 pounds are classified as Class 3 motor vehicles. Class 2b includes vehicles classified as medium-duty passenger vehicles (MDPVs) such as very large SUVs (Title 40 CFR § 86.1803-01 2023)[10]. Because MDPVs are designed primarily to be used as light-duty passenger vehicles, they are regulated under the light-duty vehicle rules. Thus, the requirements for MDPVs in this rulemaking are the same as the light-duty pickups with respect to both GHG and criteria emission standards.

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[10] We are proposing changes in the definition of MDPV in 40 CFR § 86.1803-01. See § III.D of the Preamble to this proposed rule.

Historically, about 90 percent of medium-duty pickups and vans have been what are often referred to as "3⁄4-ton" and "1-ton" pickup trucks[11], 12- and 15-passenger vans, and large work vans that are sold by vehicle manufacturers as complete vehicles, with no secondary manufacturer making substantial modifications prior to registration and use. Most of these vehicles are produced by companies with major light-duty markets in the United States, primarily Ford, General Motors, and Stellantis[12]. Often, the technologies available to reduce GHG emissions from this segment are similar to the technologies used for the same purpose on light-duty pickup trucks and vans, including both engine efficiency improvements (for gasoline and diesel engines) and vehicle efficiency improvements. In the Heavy-Duty Phase 1 (76 FR 57106 2011)and Phase 2 (81 FR 73478 2016) rules, EPA adopted GHG standards for medium-duty pickups and vans based on the whole vehicle (including the engine), expressed as grams of CO_2 per mile, consistent with the way these vehicles are regulated by EPA today for criteria pollutants.

Vehicle testing for both the medium-duty and light-duty vehicle programs is conducted on chassis dynamometers using the drive cycles from the EPA Federal Test Procedure (Light-duty FTP or ‘‘city’’ test) and Highway Fuel Economy Test (HFET or ‘‘highway’’ test) (Title 40 CFR § 1066.801 Subpart I 2023). For the light-duty GHG standards, EPA factored vehicle attributes into the standards by basing the GHG standards on vehicle footprint (the wheelbase times the average track width). For those standards, passenger cars and light trucks with larger footprints are assigned higher GHG targets (see Chapter 1.1.1.1). For HD pickups and vans, the agencies also set GHG standards based on vehicle attributes but used a work-based metric as the attribute rather than the footprint attribute utilized in the light-duty vehicle rulemaking. Work-based measures such as payload and towing capability are key among the parameters that characterize differences in the design of these vehicles, as well as differences in how the vehicles will be utilized. Buyers consider these utility-based attributes when purchasing a HD pickup or van. EPA therefore finalized Phase 1 and 2 standards for medium-duty pickups and vans based on a ‘‘work factor’’ attribute that combines the vehicle’s payload and towing capabilities, with an added adjustment for 4-wheel drive vehicles.

For Phase 1 and 2, the agencies adopted provisions such that each manufacturer’s fleet average standard is based on production volume-weighting of target standards for all vehicles that in turn are based on each vehicle’s work factor (76 FR 57106 2011) (81 FR 73478 2016). These target standards are taken from a set of curves (mathematical functions). The Phase 2 work factor GHG standards are shown in Figure 1-15 for reference. The agencies established separate standards for diesel and gasoline medium-duty pickups and vans. Note that this approach does not create an incentive to reduce the capabilities of these vehicles because less capable vehicles are required to have proportionally lower emissions and fuel consumption targets.

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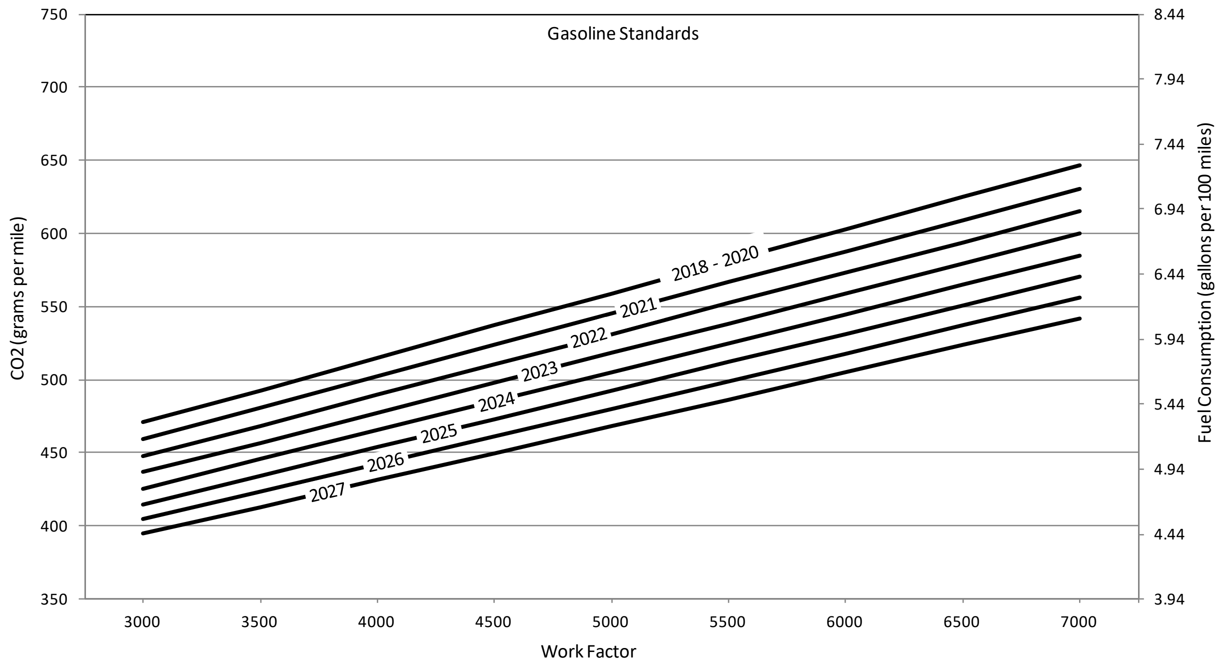
[11] "3/4-ton" and "1-ton" are common industry terms, not regulatory definitions. These terms typically refer to Class 2b and Class 3 trucks, respectively. For specific regulatory definitions for Class 2b and Class 3, please refer to 40 CFR § 86.1803-01.

[12] Formerly Fiat-Chrysler during the period when the Heavy-duty Phase 1 and 2 standards were developed.



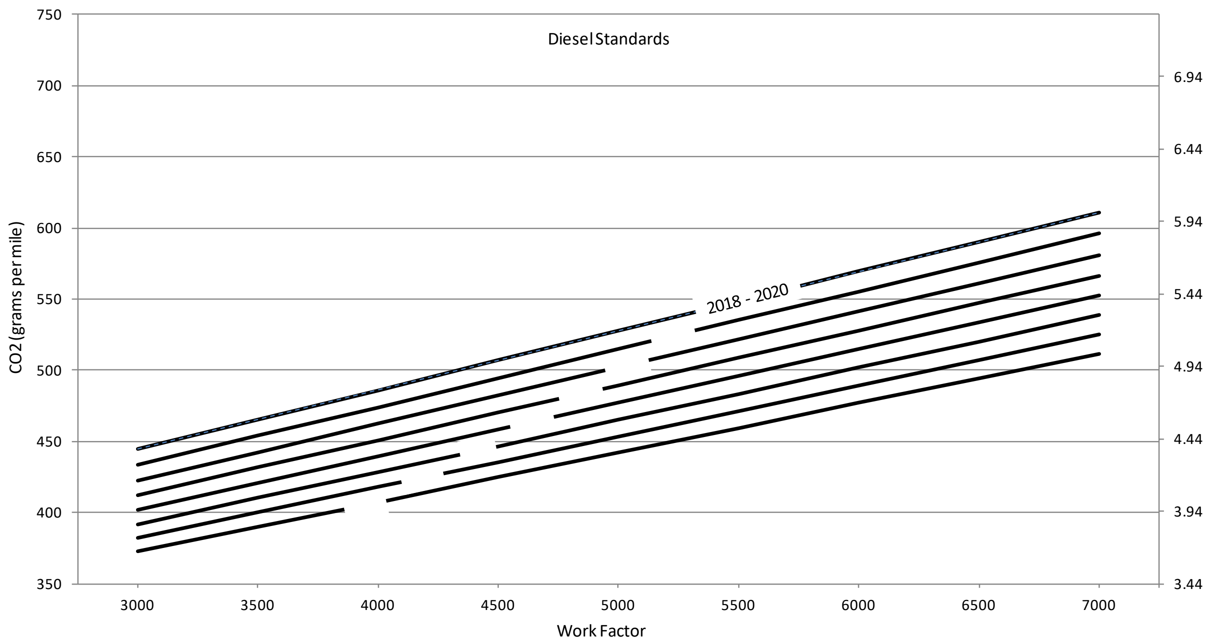


Figure 1-15: Heavy-duty Phase 2 work factor-based GHG standards for medium-duty pickups and vans (81 FR 73478 2016).

1.2.2 <u>Development of the proposed standards for Medium-Duty Vehicles</u>

Medium-duty-vehicles (MDV)[13] are similar to the light-duty trucks addressed in this program with respect to both technological opportunity for electrification as well as in terms of how they

[13] In our proposal we are defining a new MDV category that combines Class 2b and Class 3 and that excludes MDPV. For the full definition, please refer to § III.A.1 of the Preamble to this proposed rule.

are manufactured. Several light-duty manufacturers also the primary manufacturers of the majority of medium-duty pickups and vans. Medium-duty pickups and vans share close parallels to the light-duty program regarding how EPA has developed our proposed medium-duty standards and compliance structures with the penetration of new technologies such as electrification. The primary difference between the light-duty and the MDV standards is that MDV standards continue to be based on work attributes rather than vehicle footprint. MDV pickups and vans are true work vehicles that are designed for much higher towing and payload capabilities than are light-duty vehicles. The technologies applied to light-duty vehicles are not all applicable to MDVs at the same adoption rates, and the internal combustion engine technologies often produce a lower percent reduction in CO_2 emissions when used in many medium-duty vehicles. For example, electrification of a MDV pick-up designed and used solely for high towing capacity may not be appropriate or acceptable to consumers at this time. Conversely, delivery vans or payload-oriented pick-ups that operate over limited distances and daily routes present a significant opportunity for electrification. Due to this expected usage difference of MDVs, there are fewer parallels with the structure of the light-duty program. In addition, the phase-in provisions in the MDV program, although structurally different from those of the light-duty program due to CAA requirements, serve the same purpose, which is to allow manufacturers to achieve large reductions in emissions while providing a broad mix of products to their customers.

The form and stringency of the original Phase 1 and 2 standards curves were based on the performance of a set of vehicle, engine, and transmission technologies expected (although not required) to be used to meet the GHG emissions standards with full consideration of how these technologies were likely to perform in medium-duty vehicle specific testing and use. The technologies included:

- Advanced engine improvements for friction reduction and low friction lubricants
- Improved engine parasitics, including fuel pumps, oil pumps, and coolant pumps
- Valvetrain variable lift and timing • cylinder deactivation
- Direct gasoline injection
- Cooled exhaust gas recirculation
- Turbo downsizing of gasoline engines
- Diesel engine efficiency improvements
- Downsizing of diesel engines
- Electric power steering
- High efficiency transmission gear boxes and driveline
- Further improvements in accessory loads
- Additional improvements in aerodynamics and tire rolling resistance
- Low drag brakes

- Mass reduction
- Mild hybridization
- Strong hybridization
- Advanced 8 and higher speed automatic transmissions
- Diesel aftertreatment optimization
- BEV

Substantial opportunity still exists to further implement and make improvements to most of these technologies to achieve further reductions in GHG emissions beyond those achieved in the initial implementation of the Heavy-duty Phase 2 program as it applies to Class 2b and Class 3 vehicles (81 FR 73478 2016). Many of these technologies have not yet been implemented since the Phase 2 standards are still within a phase-in period continuing through MY 2027. The agency still expects to see additional penetration of many of these technologies.

The electrification of MDVs in the form of BEVs, particularly in delivery vans some pick-ups, has the highest potential for GHG reductions of all technologies investigated by the agency. However, mild and strong hybridization and targeted PHEV implementation, particularly PHEV Class 2b pickup trucks, may also provide substantial GHG emission reductions as well as potential improvements in internal combustion engines, transmissions and vehicle technologies.

1.2.2.1 Proposed MDV GHG Standards

Our proposed GHG standards for all MDVs[14] are entirely chassis-dynamometer based and continue to be work-factor-based as with the previous heavy-duty Phase 2 standards. The standards also continue to use the same work factor (WF) and GHG target definitions (81 FR 73478 2016). However, for MDVs with high towing capability at or above 22,000 pounds GCWR, we are proposing to limit the GCWR input into the work factor equation to 22,000 pounds GCWR in order to prevent increases in the GHG emissions target standards that are not fully captured within the loads and operation reflected during chassis dynamometer GHG emissions testing. The chassis dynamometer testing methodology for MDVs does not directly incorporate any GCWR related direct load or weight increases (e.g., trailer towing) however, they would be reflected in the higher target standards when calculating the GHG targets using GCWR values above 22,000 pounds. Without some limiting “cap”, the resulting high target standards relative to actual measured performance would be unsupported within the test data used to demonstrate compliance and would generate windfall compliance credits for higher GCWR ratings. The equations for MDV compliance with the proposed GHG standards are:

CO_{2e} Target (g/mi) = [a × WF] + b

WF = Work Factor = [0.75 × [Payload Capacity + xwd] + [0.25 × Towing Capacity]

Payload Capacity = GVWR (pounds) - Curb Weight (pounds)

[14] Pickup trucks, vans, incomplete vehicles and other vehicles having GVWR between 8,501 and 14,000 pounds, excluding MDPVs. See § III.A.1 of the Preamble to this proposed rule.

xwd = 500 pounds if equipped with 4-wheel-drive, otherwise 0 pounds

Towing Capacity = GCWR (pounds) - GVWR (pounds); with GCWR capped within the calculation at 22,000 pounds for GCWR > 22,000 pounds

and with coefficients "a" and "b" as defined in Table 1-3:

Table 1-3: Proposed Coefficients for MDV Target GHG Standards

Model Year	a	b
2027	0.0348	268
2028	0.0339	261
2029	0.0310	239
2030	0.0280	216
2031	0.0251	193
2032	0.0221	170

The feasibility of the–2027 - 2032 GHG standards is based primarily upon an assessment of the potential for a steady increase in MDV electrification, primarily within the van segment. The feasibility of the initial year of compliance (2027) is from continued introduction of technologies phasing into use for compliance with HD GHG Phase 2 as described in DRIA Chapter 1.2.2. Note that the proposed fuel neutral standard in 2027 is a revision that would replace the last year of phase-in into the HD Phase 2 GHG program and applies solely to MDVs within that program.

The primary assumptions within the work factor based GHG standards for MDV from 2028 to 2032 include an approximately 8 percent year over year improvement, to a large degree from electrification of MDV vans and to a lesser degree electrification of a small fraction (<25 percent) of MDV pickups and adoption of other technologies. The MDV target GHG standards are compared to the current HD Phase 2 gasoline standards in Figure 1-13. Note that the GHG standards continue beyond the data markers shown in Figure 1-13. The data markers within the figure reflect the approximate transition from light-duty trucks and MDPVs to MDVs at a WF of approximately 3,000 pounds and the approximate location of 22,000 pounds GCWR in work factor space (e.g., a WF of approximately 5,500 pounds). Beginning in 2027, the MDV GHG program moves gasoline, diesel, and PEV MDVs to fuel-neutral standards, i.e., identical standards regardless of the fuel or energy source used.

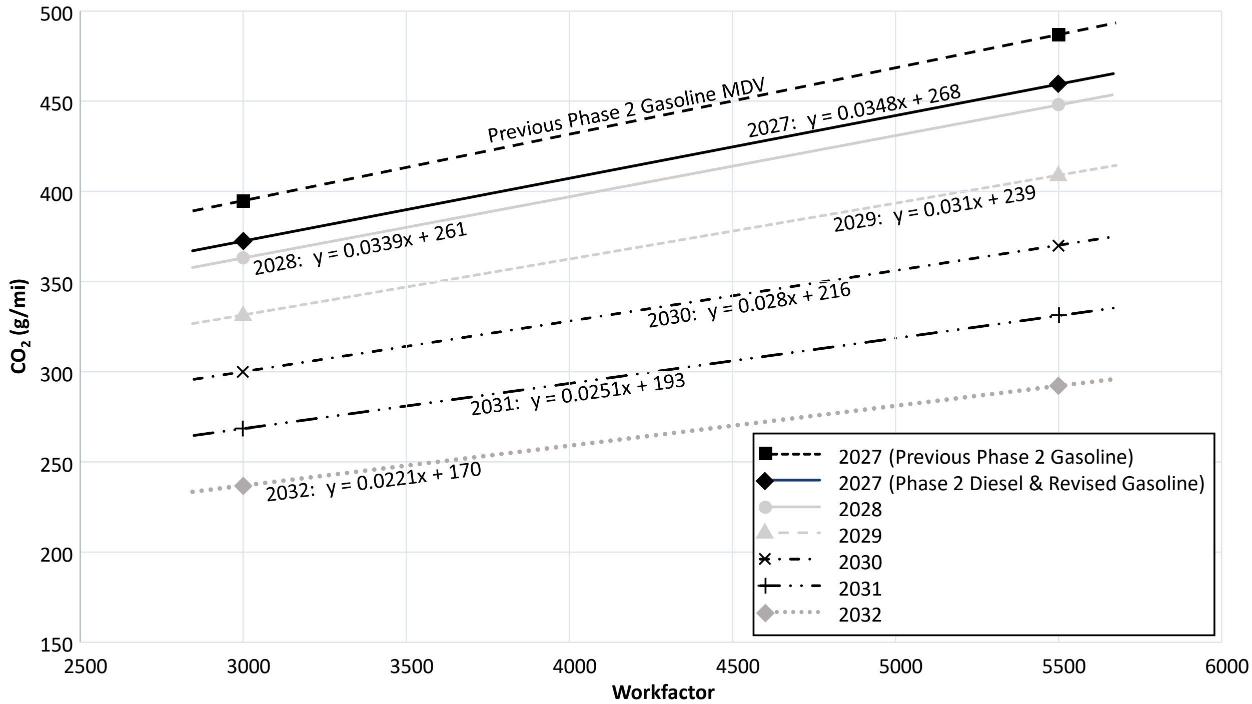


Figure 1-16: Proposed MDV GHG Target Standards

1.3 Development of the proposed battery durability standards

As described in sections III.F.2 and III.F.3 of the Preamble, EPA is proposing new battery durability and warranty standards for PEVs.

In developing the proposed standards, EPA took into consideration the provisions established in United Nations Global Technical Regulation No. 22, as well as the California Air Resources Board battery durability and warranty requirements under the Advanced Clean Cars II program.

Although EPA is not proposing provisions that are identical to either program, we recognize the fact that automakers may be subject to GTR No. 22 in markets outside the U.S., and that many may also be subject to the durability and warranty requirements under the State of California ACC II program. In considering the design and feasibility of the proposed standards, EPA has considered the specific features and purposes of both programs and has considered opportunities for harmonization.

The following discussion provides background on GTR No. 22, and on the California Air Resources Board ACC II durability and warranty requirements. For a complete discussion of the proposed requirements under this proposal and their relation to these other programs, please refer to Preamble III.F.2 and III.F.3.

1.3.1 United Nations Global Technical Regulation No. 22 on In-Vehicle Battery Durability

For several years, EPA has worked closely with the United Nations Economic Commission for Europe (UNECE) Working Party on Pollution and Energy (GRPE) to develop a world harmonized Global Technical Regulation (GTR) for In-vehicle Battery Durability for Electrified

Vehicles, or GTR No. 22 (UN ECE 2022). This GTR was created within a GRPE Informal Working Group (IWG) known as Electric Vehicles and the Environment (EVE).

The EPA proposal for the BEV and PHEV battery durability program is described primarily in Section III.F.2 of the Preamble. The proposed program largely adopts the general framework and requirements described in GTR No. 22, with minor adaptations to incorporate established EPA test procedures and to achieve specific program objectives. In addition to the reference published GTR, the EVE also produced a document which outlines the technical justification and the development process of the GTR requirements (UN ECE 2021).

In 2015 the UNECE began studying the need for a GTR governing battery durability in light-duty vehicles. In 2021 it finalized GTR No. 22, which provides a regulatory structure for contracting parties to set standards for battery durability in light-duty BEVs and PHEVs. The European Commission and other contracting parties are currently working to adopt this standard in their local regulatory structures. EPA representatives chaired the informal working group that developed this GTR and worked closely with global regulatory agencies and industry partners to complete its development in a form that could be adopted in various regions of the world, including potentially the United States.

GTR No. 22 establishes a framework for regulating battery durability of BEVs and PHEVs by establishing durability metrics, durability performance monitoring requirements, minimum performance requirements, and procedures for determining monitor accuracy and determining compliance. It does not include battery warranty requirements. To monitor durability performance, it requires that manufacturers implement two ways of monitoring battery state-of-health (SOH): State of Certified Energy (SOCE) and State of Certified Range (SOCR). SOCE (and potentially in the future, SOCR) is then used to determine compliance with a Minimum Performance Requirement (MPR) at two points during the vehicle's life, as described below. In the current version of the GTR, the monitor requirements apply to Category 1-1, 1-2, and Category 2 vehicles. The MPR applies only to Category 1-1 and Category 1-2 vehicles. The IWG chose not to set an MPR for Category 2 vehicles at this time, largely because the early stage of adoption of these vehicles meant that in-use data regarding battery performance of these vehicles was difficult to obtain, and because these vehicles are more likely to have auxiliary work-related features that use power from the battery for non-propulsion purposes, and the impact of these features on battery life was not currently well characterized. MPR requirements for category 2 vehicles were therefore reserved for possible inclusion in a future amendment to the GTR.

SOCE is an estimate of remaining usable battery energy (UBE) capacity at a point in the vehicle's life, expressed as a percentage of the original UBE capacity when the vehicle was new. In most jurisdictions, including the U.S. and those that have adopted the WLTP, original UBE is already measured as part of the vehicle certification or range labeling process when the vehicle is new. The GTR requires the SOCE monitor estimate of remaining UBE capacity to be readable by the customer and by regulatory authorities. The algorithm for estimating and updating SOCE during the lifetime of the vehicle is left to the manufacturer. The SOCE monitor value is required to be on average no more than 5 percent higher than the actual value that would be obtained if the true remaining UBE capacity were to instead be determined by the test procedure that was used at certification. Accuracy is determined by a test program in which a statistical test is applied to test results from a sample of test vehicles within a defined test group.

SOCR is an estimate of the total electric driving range that the vehicle battery remains capable of providing at a point in the vehicle's life, expressed as a percentage of the original electric driving range when the vehicle was new. As with UBE, electric driving range is already measured and collected under applicable regional certification or type approval procedures when the vehicle is new. The GTR requires SOCR to be readable by regulatory authorities but not necessarily by the consumer. The SOCR monitor is also subject to the requirements for determination and reporting of monitor accuracy but is not currently subject to the accuracy requirement.

The GTR establishes a Minimum Performance Requirement (MPR) that specifies a minimum percentage retention of SOCE and SOCR at two points in the vehicle's life. During the first phase of implementation of the GTR, only the SOCE MPR will be enforced, although SOCR will be collected for information purposes. As shown in Table 1-2, the MPRs established by GTR No. 22 require retention of at least 80 percent SOCE at 5 years or 100,000 km (about 62,000 mi), and 70 percent SOCE at 8 years or 160,000 km (about 100,000 miles).

Table 1-4. Battery durability performance requirements of UN GTR No. 22

Percent retention	of	at	Mileage	Percent of sample must pass
80%	SOH (UBE)	5 years	100,000 km	90%
70%		8 years	160,000 km	

In the GTR, compliance with the SOCE MPR is determined for the vehicles within a given durability test group by collecting a large sample of SOCE monitor values from in-use vehicles at appropriate points in their life. The test group is compliant if at least 90 percent of the vehicles monitored meet the applicable SOCE MPR.

This section has outlined the requirements and framework of GTR No. 22. For a description of the specifics of the proposed EPA battery durability program and how they compare to the provisions of the GTR, please refer to Section III.F.2 of the Preamble and to the regulatory text.

1.3.2 California Air Resources Board battery durability and warranty provisions under the ACC II program

In 2022, the California Air Resources Board (CARB), as part of its Advanced Clean Cars II (ACC II) program, established battery durability and battery warranty requirements as part of a suite of customer assurance provisions designed to ensure that zero-emission vehicles maintain similar standards for usability, useful life, and maintenance as conventional vehicles. The performance requirements under the initial proposed version of the CARB durability standard were significantly more stringent than those of UN GTR No. 22. After taking public comment and consulting with the Board, the performance requirements were modified to a level closer to that of GTR No. 22, while certain aspects of the program remain more stringent than those of the GTR.

In contrast to GTR No. 22, the CARB battery durability requirement applies to electric driving range instead of capacity, and phases in according to model year (MY). As shown in Table 1-5, for MYs 2026 through 2029, a vehicle test group is compliant if at least 70 percent of the vehicles in the group maintain 70 percent of certified range after 10 years or 150,000 miles (240,000 km). For MYs 2030 and later, a test group is compliant if, on average, the vehicles in the group maintain 80 percent of certified range after 10 years or 150,000 miles (240,000 km). Details on monitor accuracy requirements, thresholds for determination of non-conformance, and specific data reporting requirements are outlined in the regulations (California, California Code of Regulations, title 13, section 1962.4. 2022a), (California 2022b).

The CARB warranty requirement also phases in by model year, but instead of range it refers to a state of health as expressed by usable battery energy (UBE). As shown in Table 1-6, for MYs 2026 to 2030, the battery must maintain 70 percent state of health after 8 years or 100,000 miles (160,000 km). For MYs 2031 and later, it increases to 75 percent state of health. The warranty requirement applies to the first purchaser and each subsequent purchaser. The warranty requirements are further outlined in the regulation (Title 13, California Code of Regulations 2022).

Table 1-5. CARB ACC II battery durability requirements

Model years	Percent retention	of	at	Mileage	Percent of sample must pass
2026-2029	70%	Range	10 years	150,000 mi	70%
2030+	80%				On average

Table 1-6. CARB battery warranty requirements

Model years	Percent retention	of	at	Mileage
2026-2030	70%	SOH (UBE)	8 years	100,000 mi
2031+	75%			

As described in the Preamble sections III.F.2 and III.F.3, EPA is proposing battery durability and warranty standards that would differ to some degree from those of the CARB program, but we have taken California's approach into consideration because we recognize that a substantial number of vehicles sold in the United States will be subject to California's requirements. The proposed battery warranty requirements would be implemented under the existing regulatory structure that establishes a minimum warranty for major emission control components, and would thus retain similarities to the requirements under that program. The proposed durability requirements are less stringent than the CARB program and have a greater similarity to those of GTR No. 22. For a complete discussion of the proposed requirements under this proposal and their relation to these other programs, please refer to Preamble III.F.2 and III.F.3.

Chapter 1 References

76 FR 57106. 2011. (September 15). https://www.govinfo.gov/content/pkg/FR-2011-09-15/pdf/2011-20740.pdf.

77 FR 62624. 2012.

81 FR 73478. 2016. (October 25). https://www.govinfo.gov/content/pkg/FR-2016-10-25/pdf/2016-21203.pdf.

California, State of. 2022a. "California Code of Regulations, title 13, section 1962.4."

—. 2022b. "California Code of Regulations, title 13, section 1962.7."

Ellies, B. 2023. "Docket CUV Compliance Data Memo (Docket EPA-HQ-OAR-2022-0829)."

Greene, et al. 2018. "Consumer willingness to pay for vehicle attributes: What do we know?" Transportation Research Part A.

Public Law 94-163. 1975. (December 22). Accessed 1 8, 2023. https://www.govinfo.gov/content/pkg/STATUTE-89/pdf/STATUTE-89-Pg871.pdf.

Title 13, California Code of Regulations. 2022. Section 1962.7

Title 40 CFR § 1066.801 Subpart I. 2023. (March 6). https://www.ecfr.gov/current/title-40/chapter-I/subchapter-U/part-1066/subpart-I.

Title 40 CFR § 86.1803-01. 2023.

Title 49 CFR § 523.5. 2022. https://www.ecfr.gov/current/title-49/subtitle-B/chapter-V/part-523/section-523.5.

U.S. EPA. 2011. "Draft Joint Technical Support Document: Proposed Rulemaking for 2017-2025 Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards."

U.S. EPA. 2021. The 2021 EPA Automotive Trends Report: Greenhouse Gas Emissions, Fuel Economy, and Technology since 1975. U.S. EPA.

U.S. EPA. 2022. "The EPA Automotive Trends Report: Greenhouse Gas Emissions, Fuel Economy, and Technology since 1975."

UN ECE. 2021. "Proposal for a technical report on the development of a new UN Global Technical Regulation on In-Vehicle Battery Durability for Electrified Vehicles." November. https://unece.org/sites/default/files/2021-10/GRPE-84-02e_0.pdf.

—. 2022. "United Nations Global Technical Regulation on In-vehicle Battery Durability for Electrified Vehicles." April. https://unece.org/transport/documents/2022/04/standards/un-gtr-no22-vehicle-battery-durability-electrified-vehicles.

Chapter 2: Tools and Inputs Used for Modeling Technologies and Adoption Towards Compliance

This chapter summarizes the tools and inputs used for modeling technologies, adoption of technologies, and vehicle compliance with the proposed standards. This includes details regarding the OMEGA model, ALPHA vehicle simulation tools, and the Agency's approach to analyzing vehicle manufacturing costs, consumer demand, vehicle operational costs. The chapter also includes a summary of modeling inputs that reflect our assessment of impacts due to the implementation of the Inflation Reduction Act of 2022.

2.1 Overview of EPA's Compliance Modeling Approach

EPA's technical analysis supporting the proposed emissions standards, at its highest level, is based on the following major tools that are used in the assessment of emissions reduction technologies and costs. These are, in order of execution: ALPHA, response surface modeling, and OMEGA. They are used in an integrated fashion as follows:

- EPA's ALPHA model is our vehicle simulation tool used to predict tailpipe CO_2 emissions and energy consumption for advanced technologies. ALPHA is detailed in 2.4.

- Response surface methodology (RSM) incorporates ALPHA results for various vehicle technologies over thousands of vehicle combinations into response surface equations (RSE) which can be quickly referenced to characterize any future vehicle's GHG emissions based on its size, weight, power and road loads. This approach is described in 2.4.10.

- EPA's manufacturer compliance model, OMEGA, incorporates RSEs, technology costs and other inputs into its algorithms for finding cost-efficient pathways for manufacturers to achieve compliance with desired emissions standards. The compliance modeling produces a fleet of new light- and medium-duty vehicles for each analyzed model year, which OMEGA integrates into projections of the on-road vehicle stock and VMT. Finally, OMEGA tabulates the emissions inventories, physical effects, and costs and benefits that arise from the usage of vehicles over their lifetimes. A schematic of the overall analytical workflow is provided in Figure 2-1.

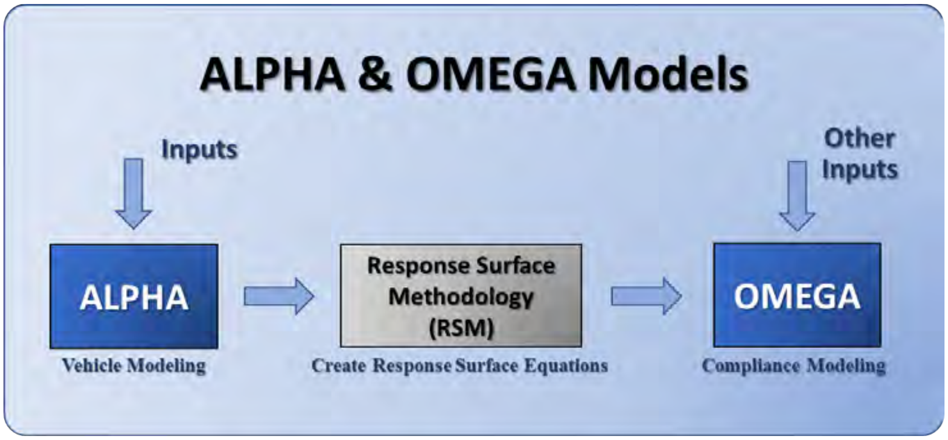


Figure 2-1. Compliance modeling workflow.

Finally, the results from OMEGA are used to inform its fleet onroad vehicle emissions model (MOVES) to generate fleet vehicle emissions and project benefits due to the proposed standards. A discussion of MOVES is provided in 8.2.1.

2.1.1 OMEGA Compliance and Model Overview

The OMEGA model has been developed by EPA to evaluate policies for reducing greenhouse gas (GHG) emissions from light duty vehicles. Like the prior releases, this latest version is intended primarily to be used as a tool to support regulatory development by providing estimates of the effects of policy alternatives under consideration. These effects include the costs associated with emissions-reducing technologies and the monetized effects normally included in a societal benefit-cost analysis, as well as physical effects that include emissions quantities, fuel consumption, and vehicle stock and usage. In developing OMEGA version 2.0 (OMEGA2), the goal was to improve modularity, transparency, and flexibility so that stakeholders can more easily review the model, conduct independent analyses, and potentially adapt the model to meet their own needs.

2.1.2 OMEGA Updates

EPA created OMEGA version 1.0 (OMEGA1) to analyze new GHG standards for light-duty vehicles proposed in 2011. The 'core' model performed the function of identifying manufacturers' cost-minimizing compliance pathways to meet a footprint-based fleet emissions standard specified by the user. A preprocessing step involved ranking the technology packages to be considered by the model based on cost-effectiveness. Postprocessing of outputs was performed separately using a spreadsheet tool, and later a scripted process which generated table summaries of modeled effects. An overview of OMEGA1 is shown on the left of Figure 2-2.

In the period since the release of OMEGA1, there have been significant changes in the light duty vehicle market including technological advancements and the introduction of new mobility services. Advancements in battery electric vehicles (BEVs) with greater range, faster charging capability, and expanded model availability, as well as potential synergies between BEVs, ride-hailing services and autonomous driving are particularly relevant when considering pathways for greater levels of emissions reduction in the future. OMEGA2 has been developed with these trends in mind. The model's interaction between consumer and producer decisions allows a user to represent consumer responses to these new vehicles and services. The model now also has been designed to have expanded capability to model a wider range of GHG program options, which is especially important for the assessment of policies that are designed to address future GHG reduction goals. In general, with the release of OMEGA2, the goal is to improve usability and flexibility while retaining the primary functions of OMEGA1. The right side of Figure 2-2 shows the overall model flow for OMEGA2 and highlights the main areas that have been revised and updated.

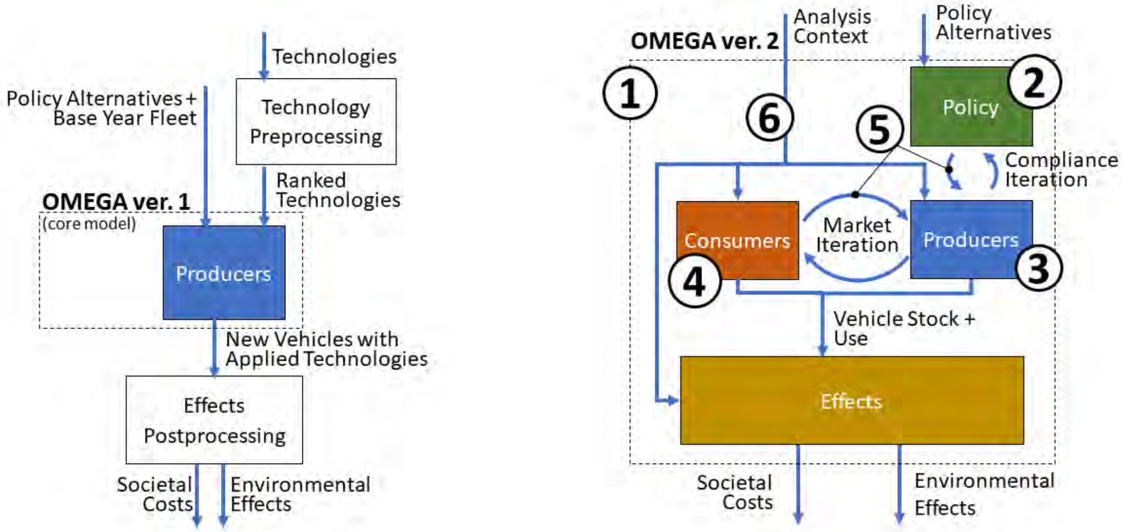


Figure 2-2 - Comparison of OMEGA1 and OMEGA2.

Update #1: Expanded model boundaries. In defining the scope of this model version, EPA has attempted to simplify the process of conducting a run by incorporating into the model some of the pre- and post-processing steps that had previously been performed manually. At the same time, EPA recognizes that an overly expansive model boundary can result in requirements for inputs that are difficult to specify. To avoid this, the input boundary has been set only so large as to capture the elements of the system assumed are responsive to policy. This approach helps to ensure that model inputs such as technology costs and emissions rates can be quantified using data for observable, real-world, characteristics and phenomena, and in that way enable transparency by allowing the user to maintain the connection to the underlying data. For the assumptions and algorithms within the model boundary, the aim is transparency through well-organized model code and complete documentation.

Update #2: Independent Policy Module. OMEGA1 was designed to analyze a very specific GHG policy structure in which the vehicle attributes and regulatory classes used to determine emissions targets were incorporated into the code throughout the model. To make it easier to define and analyze other policy structures, the details regarding how GHG emissions targets are determined and how compliance credits are treated over time are now included in an independent Policy Module and associated policy inputs. This allows the user to incorporate new policy structures without requiring revisions to other code modules. Specifically, the producer decision module no longer contains any details specific to a GHG program structure, and instead functions only on very general program features such as fleet averaging of absolute GHG credits and required technology shares.

Update #3: Modeling of multi-year strategic producer decisions. As a policy analysis tool, OMEGA is intended to model the effect of policies that may extend well into the future, beyond the timeframe of individual product cycles. OMEGA2 is structured to consider a producer objective function to be optimized over the entire analysis period. Year-by-year compliance decisions account for management of credits which can carry across years in the context of projections for technology cost and market conditions which change over time. The timeframe of a given analysis can be specified anywhere from near-term to long-term, with the length limited only by inputs and assumptions provided by the user.

Update #4: Addition of a consumer response component. The light-duty vehicle market has evolved significantly in the time since the initial release of OMEGA1. As the range of available technologies and services has grown wider, so has the range of possible responses to policy alternatives. The model structure for this version includes a Consumer Module that can be used to project how the light-duty vehicle market would respond to policy-driven changes in new vehicle prices, fuel operating costs, trip fees for ride hailing services, and other consumer-facing elements. The Consumer Module outputs the estimated consumer responses, such as overall vehicle sales and sales shares, as well as vehicle re-registration and use, which together determine the stock of new and used vehicles and the associated allocation of total VMT.

Update #5: Addition of feedback loops for producer decisions. OMEGA2 is structured around modeling the interactions between vehicle producers responding to a policy and consumers who own and use vehicles affected by the policy. These interactions are bi-directional, in that the producer's compliance planning and vehicle design decisions will both influence, and be influenced by, the sales and shares of vehicles demanded and the GHG credits assigned under the policy. Iterative feedback loops have now been incorporated; between the Producer and Consumer modules to ensure that modeled vehicles would be accepted by the market at the quantities and prices offered by the producer, and between the Producer and Policy modules to account for the compliance implications of each successive vehicle design and production option considered by the producer. This update has been peer reviewed as detailed in Section 2.3.

Update #6: Use of absolute vehicle costs and emissions rates. OMEGA1 modeled the producer application of technologies to a fleet of vehicles that was otherwise held fixed across policy alternatives. With the addition of a consumer response component that models market share shifts, OMEGA2 utilizes absolute costs and emissions rates to compare vehicle design and purchase decisions across vehicle types and market classes.

2.2 OMEGA2 Model Structure and Operation

2.2.1 <u>Inputs and Outputs</u>

Like other models, OMEGA relies on the user to specify appropriate inputs and assumptions. Some of these may be provided by direct empirical observations, for example the number of currently registered vehicles. Others might be generated by modeling tools outside of OMEGA, such as physics-based vehicle simulation results produced by EPA's ALPHA model, or transportation demand forecasts from DOE's NEMS model. OMEGA has adopted data elements and structures that are generic, wherever possible, so that inputs can be provided from whichever sources the user deems most appropriate.

The inputs and assumptions are categorized according to whether they define the policies under consideration or define the context within which the analysis occurs. Policy alternative inputs describe the standards themselves, including the program elements and methodologies for determining compliance as would be defined for an EPA rule in the Federal Register and Code of Federal Regulations. Analysis context inputs and assumptions cover the range of factors that the user assumes are independent of the policy alternatives. The context inputs may include fuel costs, costs and emissions rates for a particular vehicle technology package, attributes of the existing vehicle stock, consumer demand parameters, existing GHG credit balances, producer decision parameters, and many more. The user may project changes in the context inputs over the analysis timeframe based on other sources, but for a given analysis year the context definition requires that these inputs are common across the policy alternatives being compared.

The primary outputs are the environmental effects, societal costs and benefits, and producer compliance status for a set of policy alternatives within a given analysis context. These outputs are expressed in absolute values, so that incremental effects, costs, and benefits can be evaluated by comparing two policy alternatives for a given analysis context. For example, comparing a No Action scenario to an Action (or Policy) Alternative. Those same policy alternatives can also be compared using other analysis context inputs to evaluate the sensitivity of results to uncertainty in particular assumptions. For example, comparing the incremental effects of a new policy in high fuel price and low fuel price analysis contexts.

2.2.2 Model Structure and Key Modules

OMEGA2 has been set up so that primary components of the model are clearly delineated in such a way that changing one component of the model will not require code changes throughout the model. The four main modules — Producer, Consumer, Policy, and Effects — are each defined along the lines of their real-world analogs. Producers and consumers are represented as distinct decision-making agents, which each exist apart from the regulations defined in the Policy Module. Similarly, the effects, both environmental and societal, exist apart from producer and consumer decision-making agents and the policy. This structure allows a user to analyze policy alternatives with consistently defined producer and consumer behavior. It also provides users the option of interchanging any of OMEGA's default modules with their own, while preserving the consistency and functionality of the larger model.

Producer Module: This module projects the decisions of the regulated entities (producers) in response to policy alternatives, while accounting for consumer demand. The regulated entities can be specified as individual companies, or considered in aggregate as a collection of companies, depending on the assumptions made by the user regarding how GHG credits are averaged or transferred between entities.

Consumer Module: This module projects demand for vehicle sales, ownership and use in response to changes in vehicle characteristics such as price, ownership cost, and other key attributes.

Policy Module: This module determines the compliance status for a producer's possible fleet of new vehicles based on the characteristics of those vehicles and the policy defined by the user.

Policies may be defined as performance-based standards using fleet averaging (for example, determining compliance status by the accounting of fungible GHG credits), as a fixed requirement without averaging (for example, a minimum required share of BEVs), or as a combination of performance-based standards and fixed requirements.

Effects Module: This module projects the physical and cost effects that result from the modeling of producers, consumers, and policy within a given analysis context. Examples of physical effects include the stock and use of registered vehicles, electricity, and gasoline consumption, and the GHG and criteria pollutant emissions from tailpipe and upstream sources. Examples of cost effects include vehicle production costs, ownership and operation costs, societal costs associated with GHG and criteria pollutants, and other societal costs associated with vehicle use.

2.2.3 Iteration and Convergence

OMEGA2 is intended to find a solution which simultaneously satisfies producer, consumer, and policy requirements while minimizing the producer generalized costs. OMEGA2's Producer and Consumer modules represent distinct decision-making entities, with behaviors defined separately by the user. Without some type of interaction between these modules, the model would likely not arrive at an equilibrium of vehicles supplied and demanded. For example, a compliance solution which only minimizes producer generalized costs without consideration of consumer demand may not satisfy the market requirements at the fleet mix and level of sales preferred by the consumer. Similarly, the interaction between Producer and Policy modules ensures that that with each subsequent iteration, the compliance status for the new vehicle fleet under consideration is correctly accounted for by the producer. Since there is no general analytical solution to this problem of alignment between producers, consumers, and policy which also allows model users to independently define producer and consumer behavior and the policy alternatives, OMEGA2 uses an iterative search approach.

2.2.4 Analysis Resolution

The policy response projections generated by OMEGA2 are centered around the modeled production, ownership, and use of light-duty vehicles. It would not be computationally feasible (nor would it be necessary) to distinguish between the nearly 20 million light-duty vehicles produced for sale each year in the US, and hundreds of millions of vehicles registered for use at any given time. Therefore, OMEGA is designed to operate using 'vehicles' which are aggregate representations of individual vehicles, while still retaining sufficient detail for modeling producer and consumer decisions, and the policy response. The resolution of vehicles can be set for a given analysis and will depend on the user's consideration of factors such as the availability of detailed inputs, the requirements of the analysis, and the priority of reducing model run time.

2.3 OMEGA2 Peer Review

In parallel to the OMEGA2 development process, an early version of the model and documentation was submitted to peer review. This process was intended to gain additional insights for the updated structure, new modules, processing methods, and reporting methodology of OMEGA2.

2.3.1 Charge Questions for the Peer Review:

- The overall approach to the specified modeling purposes, the specific approaches chosen for modeling individual modules, and the methodologies chosen to achieve that purpose.
- The appropriateness and completeness of the contents of the input files.
- The types of information which can be input to the model point to both the flexibilities and constraints of the model.
- The accuracy and appropriateness of the model's conceptual algorithms and equations for technology application, market impacts, and calculation of compliance.
- The congruence between the conceptual methodologies and the program execution.
- Clarity, completeness, and accuracy of the model's visualization output, in which the technology application is displayed.
- Recommendations for any functionalities beyond what EPA has described as "future work."

2.3.2 Information Received from Peer Review

EPA's charge to the peer reviewers requested their expert opinions on the concepts and methodologies upon which the model relies and whether the OMEGA2 model correctly executes the associated algorithms. EPA's charge also asked the peer reviewers to comment on specific aspects of the model's design, execution, outputs, and documentation.

All peer reviewers commented favorably that they appreciated the increased capability and complexity of OMEGA2 over the previous OMEGA1 version. In general, the peer reviewers provided numerous specific detailed, complex, and nuanced comments and recommendations that indicated a good understanding of the model's design. The most common category of comments consisted of recommendations for improving the model's documentation by adding further explanations or specifics to enhance the user's understanding.

The second most common category of peer reviewer comments concerned the model's overall approach, including the functions of each module. Reviewers commented on specific details, recommended improvements, and noted inputs and results that would benefit from further explanation. Many peer reviewer recommendations for new or additional functionality focused on specific enhancements of the existing modules. Reviewers did not recommend additions that deviated significantly from the current model's scope. EPA has addressed the recommendations significant to the current application of the OMEGA2 model.

Certain topics were raised by multiple peer reviewers. For example, all peer reviewers commented on some aspect of the model's handling of greenhouse gas (GHG) emissions credits, especially as it relates to manufacturers banking these credits from one year to the next and, in some cases, how credit banking would interact with manufacturers' multi-year model development cycle.

Peer reviewers indicated that it was likely that wide-scale implementation of the technologies available in OMEGA2 could cause a significant change to overall fuel prices that should be considered. Also, peer reviewers indicated the OMEGA2 model would benefit from further consideration of VMT rebound due to increased vehicle fuel economy. The peer reviewers also requested further explanation of how the OMEGA2 model processes hauling/non-hauling vehicles and all-wheel drive (AWD).

Finally, all reviewers commented on some aspect of the OMEGA2 model algorithm's treatment of iterative convergence on a final result and how additional documentation of this process would be helpful.

In addition to the key themes and most common comments summarized here, reviewers provided numerous other specific observations and recommendations for the OMEGA2 model in response to EPA's individual charge questions, as documented in the peer review report.

2.4 ALPHA Full Vehicle Simulation and Response Surface Equations

ALPHA is a physics-based, forward-looking, full vehicle computer simulation capable of analyzing various vehicle types with different powertrain technologies, showing realistic vehicle behavior. The software tool is a MATLAB/Simulink based simulation.

ALPHA is capable of estimating CO_2 emission values for many different vehicle types and technology packages. OMEGA needs to quickly estimate the CO_2 emission values for each future vehicle considered along with estimates for future fleets. Because operating ALPHA in real time to conduct full vehicle simulations is time prohibitive, EPA developed a methodology of reproducing ALPHA model CO_2 values using an industry standard statistical technique known as response surface methodology (RSM). (Kleijnen 2015) This methodology is used to computationally access CO_2 results from a complete set of ALPHA model results by generating a collection of response surface equations (RSEs) that represent those simulation results. In 2018, EPA commissioned RTI International to conduct an independent peer review of an earlier version of the RSE methodology. (RTI International 2018)

ALPHA simulates a single combination of technologies (known as a technology package) across different combinations of vehicle parameters. Each set of ALPHA simulation outputs are processed to create the RSEs needed for each technology package addressed. These RSEs are subsequently used within OMEGA to quickly reproduce the ALPHA model estimates for CO_2 in real time for the various vehicle technologies. ALPHA's role in the creation of the RSEs for use within OMEGA is shown in Figure 2-3 and described in detail in Section 2.4.10.

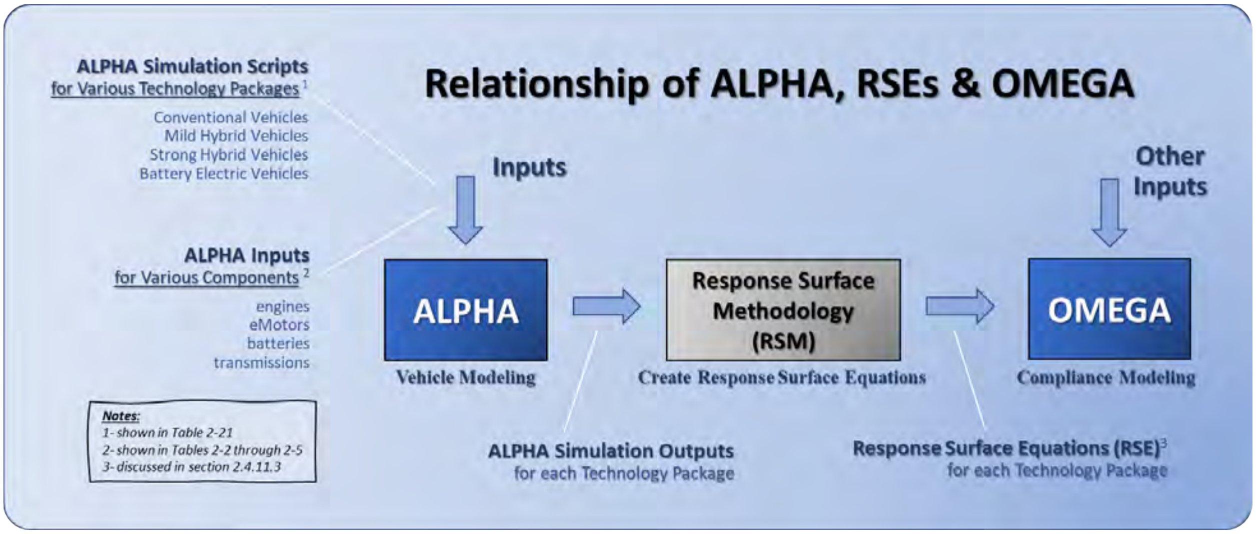


Figure 2-3. Relationship of ALPHA, RSEs and OMEGA.

2.4.1 General Description of ALPHA

Within ALPHA, an individual vehicle is defined by specifying the appropriate vehicle road loads (inertia weight and coast-down coefficients) and specifications of the powertrain components. Powertrain components (e.g., engines, transmissions, e-motors) are individually parameterized and can be exchanged within the model draft.

Vehicle control strategies are also modeled, including engine accessory loading, deceleration fuel cut off (DFCO), hybrid behavior, torque converter lockup, and transmission shift strategy. Transmission shifting is parameterized and controlled by ALPHAshift, (Newman, K., Kargul, J., and Barba, D. 2015a) a shifting strategy algorithm that ensures an appropriate shifting strategy when engine size or vehicle loading changes. The control strategies used in ALPHA are modeled after strategies observed during actual vehicle testing.

The performance of vehicle packages defined within ALPHA can be modeled over any pre-determined vehicle drive cycle. To determine fuel consumption values used to calculate LD GHG rule CO_2 values, the FTP and HWFET cycles are simulated, separated by a HWFET prep cycle as normally run during certification testing. ALPHA does not include a temperature model, so the FTP is simulated assuming warm component efficiencies for all bags. Additional fuel consumption due to the FTP cold start is calculated in post-processing by applying a fuel consumption penalty to bags 1 and 2, depending on the assumed warmup strategy (refer to Section 5.3.3.2.5 of the *2016 Draft Technical Assessment Report* (U.S. EPA; U.S. DOT-NHTSA; CARB 2016)). In addition, supporting vehicle drive cycles are defined and fuel economy simulated in ALPHA. For example, the results from the US06, NEDC, and WLTP cycles (among others) are used to tune vehicle control strategy parameters to match simulation results to measured vehicle test results across a variety of conditions. In addition, performance cycles have been defined, which are used to determine acceleration performance metrics.

2.4.2 <u>Overview of Previous Versions of ALPHA</u>

The Advanced Light-Duty Powertrain and Hybrid Analysis (ALPHA) tool was created by EPA to evaluate the Greenhouse Gas (GHG) emissions of Light-Duty (LD) vehicles. In addition, to provide additional flexibilities and transparency, EPA developed this in-house full vehicle simulation model that could freely be released to the public. Model development, along with the data collection and benchmarking that comes along with model calibration, is an extremely effective means of developing expertise and deeper understanding of technologies and their interactions. Better understanding of technologies makes for more robust regulatory analysis. Having a model available in-house allows EPA to make rapid modifications as new data is collected.

EPA began developing both light-and heavy-duty vehicle models simultaneously as these vehicles share many of the same basic components. The light-duty vehicle model (ALPHA), and the heavy-duty model (GEM), share much of the same basic underlying architecture.[15] ALPHA 2.1 and 2.2 were developed and used previously under the *EPA's 2016 Draft Technical Assessment Report* (U.S. EPA; U.S. DOT-NHTSA; CARB 2016), the *2016 Proposed Determination* (U.S. EPA 2016a) (U.S. EPA 2016b), and the *2017 Final Determination* (U.S. EPA 2017a) (U.S. EPA 2017b).

As part of the Midterm Evaluation, EPA validated the ALPHA model using several sources including vehicle benchmarking, stakeholder data, and industry literature. To further enhance transparency, in May 2016, EPA completed an external peer review of ALPHA 2.0 (U.S. EPA 2023a). This peer review package included runnable MatLab Simulink source code along with the input data provided as part of the review.

2.4.3 <u>Current version of ALPHA</u>

ALPHA 3.0 is the current version of the simulation tool used for this proposal. The two primary changes in ALPHA 3.0 compared to the previous version of ALPHA (ALPHA 2.2) are the addition of electrified vehicle architectures (including hybrid, plug-in hybrid, and battery electric vehicles) and the addition of a robust structure to allow large numbers of simulations to characterize current and future fleets. A basic description of how ALPHA 3.0 works can be found online (U.S. EPA 2022c).

While ALPHA 3.0 continues to be refined and calibrated, the new electrified vehicle models of the version in use as of October 9, 2022, were externally peer-reviewed (U.S. EPA 2023a). The concepts and methodologies upon which the model relies were examined by peer reviewers to determine if these algorithms can deliver sufficiently accurate results. The results of the peer review are discussed in section 2.4.9.

Throughout this section, details are provided on the major technology assumptions built into ALPHA 3.0. EPA has also provided technical details in Section 3.5 which summarizes the ALPHA inputs used for this proposal. In the time since ALPHA development began, EPA has

[15] The GEM model has also been peer reviewed multiple times and was the subject of comment during the rulemaking adopting the second phase of GHG standards for heavy duty vehicles and engines. See 81 FR 73530-531, 538-549. (U.S. EPA 2022b)

published over twenty peer-reviewed papers describing ALPHA and the results of key testing, validation, and analyses (U.S. EPA 2023a) (U.S. EPA 2022b).

2.4.4 ALPHA Models for Conventional and Electrified Vehicle Architectures

One of the most significant changes in ALPHA 3.0 is the addition of new electrified vehicle architecture models. Early in the development phase of ALPHA 3.0, EPA conducted research to determine which electrified vehicle architectures should be included in ALPHA's suite of models (W. Zhuanga, S. Li (Eben), X. Zhangc, D. Kum, Z. Song, G. Yin, F. Ju, 2020). Based on trends of the various hybrid and electric vehicles available for sale in the US in recent years, the conclusion was the electrified vehicle market could be modeled with the addition of three hybrid vehicle architectures and one battery electric vehicle architecture to the base conventional vehicle architecture.

Figure 2-4 summarizes the five vehicle models used to simulate vehicle efficiency for this proposal, including the conventional model used in previous versions of ALPHA, the three new hybrid models, and the one new battery electric vehicle model added for ALPHA 3.0. A summary of these five vehicle architectures used in ALPHA 3.0 is provided in the sections below.

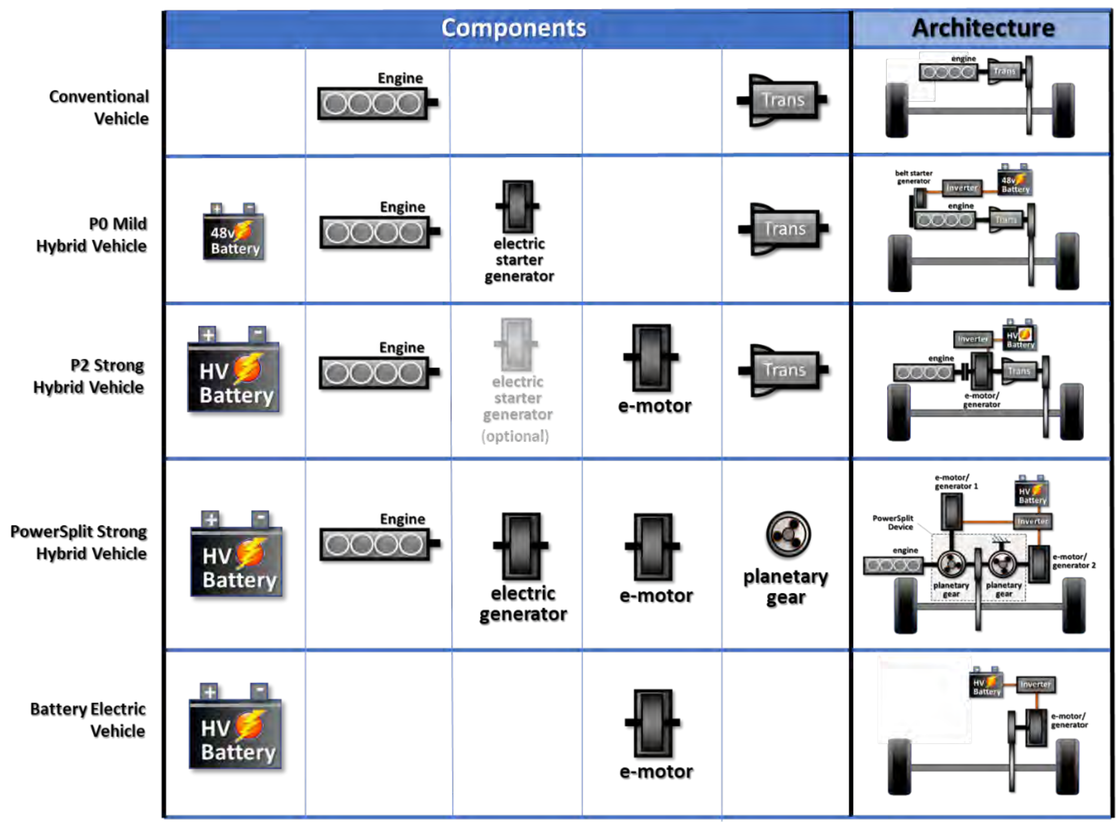


Figure 2-4: Summary of components and architectures used in ALPHA's modeling for this proposal.

2.4.4.1 Conventional Vehicle Architecture

The CO_2 performance for all conventional vehicles is modeled using the basic engine plus transmission architecture shown in Figure 2-5. Different types of engines and transmissions (including their many operational strategies such as cylinder deactivation, engine stop/start control, engine deceleration fuel cut off) can be scaled to suit the different vehicle models. For this proposal, conventional vehicles are modeled using the same model described in section 2.3.3.3 of the Proposed Determination on the Appropriateness of the Model Year 2022-2025 Light-Duty Vehicle Greenhouse Gas Emissions Standards under the Midterm Evaluation: Technical Support Document (U.S. EPA 2016b).

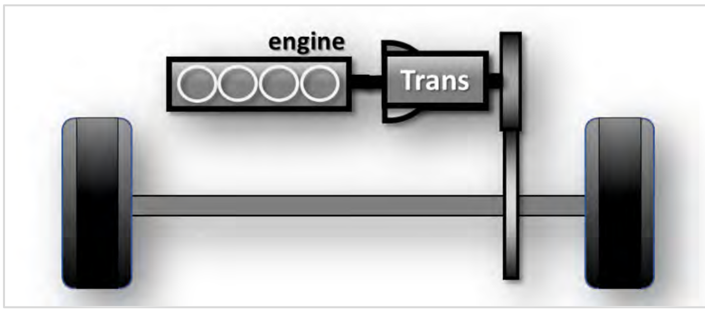


Figure 2-5: Conventional vehicle architecture.

2.4.4.2 Hybrid Electric Vehicle (HEV) Architectures

There are a wide variety of possible hybrid-electric vehicle architectures, many of which are or have been represented in the fleet. To assess the scope of this variety, EPA used a recent hybrid architecture survey paper (W. Zhuanga, S. Li (Eben), X. Zhangc, D. Kum, Z. Song, G. Yin, F. Ju, 2020). Although other researchers may use a different terminology for specific architectures, in the interest of consistency EPA adopted the categorization and nomenclature of the authors in this survey paper for further discussion of hybrid-electric vehicle architectures.

The CO_2 performance of hybrid vehicles in ALPHA is modeled using one mild and two strong hybrid architectures. The mild hybrid architecture chosen was a parallel P0 configuration (referred to later as simply "P0"). The two strong hybrid architectures chosen were a parallel P2 configuration (referred to later as simply "P2") and a PowerSplit configuration patterned after the Toyota Prius (referred to later as simply "PowerSplit").

While other mild and strong hybrid architectures also exist in the fleet, for example parallel P1 configurations (referred to later as "P1"), series configurations, and series-parallel multi-mode configurations (referred to later as "series-parallel"), EPA's analysis in section 2.4.8.5 and 2.4.8.6 shows that these hybrid variations can be adequately modeled using the three core hybrid architectures chosen for incorporation into ALPHA 3.0.

An analysis of the MY 2019 vehicle fleet revealed that nearly 30 percent of all hybrid vehicles in the MY 2019 fleet were mild hybrids, and the remaining 70 percent were strong hybrids (Table 2-1). Of the strong hybrids, 68 percent were based on PowerSplit architecture, 16 percent were based on P2 hybrid technology, and the remaining 16 percent were based on other architectures such as series-parallel and pure series architectures. The following will discuss the different hybrid models incorporated into ALPHA 3.0 to simulate these different types of hybrid vehicles.

Table 2-1: Percentage breakdown of mild and strong hybrids in the MY 2019 vehicle fleet

ALPHA's Mild Hybrid Model	% of Mild Hybrids	% of all Hybrid Vehicles
P0 Mild Hybrids	94.9%	28.0%
P1 Mild Hybrids	5.1%	1.5%

ALPHA's Strong Hybrid Model	% of Strong Hybrids	% of all Hybrid Vehicles
PowerSplit Strong Hybrids	67.8%	47.8%
PowerSplit PHEVs		
P2 Strong Hybrids	16.3%	11.5%
P2 PHEVs		
Other Hybrids	16.0%	11.2%
Other PHEVs		

2.4.4.2.1 Mild Hybrid Architectures

Mild hybrids are modeled within ALPHA using a 48V P0 architecture, which includes a conventional engine and transmission along with a starter/generator mounted on the front of the engine and connected through a belt and pulley, as shown in Figure 2-6. The battery energy capacity of a typical mid-sized mild hybrid vehicle is around 0.25 kWh.

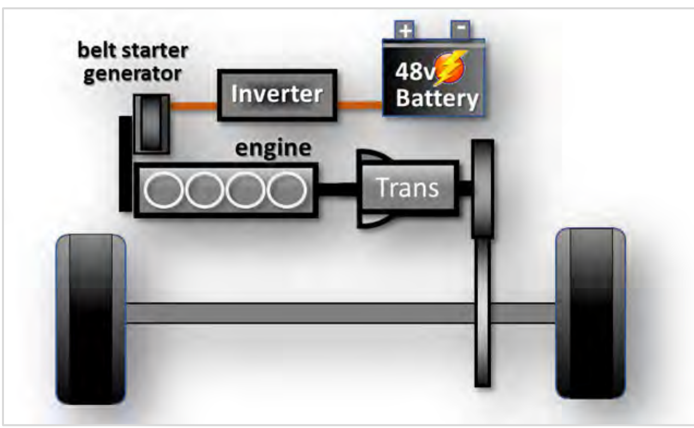


Figure 2-6: P0 Mild hybrid-electric vehicle architecture.

Table 2-1 shows that 95 percent of the mild hybrids in the MY 2019 LD fleet are based on a P0 design. FCA/Ram and Volkswagen were the two biggest producers of P0 mild hybrids vehicles in the fleet. The other 5 percent of mild hybrids were based on a P1 design, where the starter generator is directly mounted on the backside of the engine without the use of a belt. Mercedes was the only manufacturer of P1 mild hybrids in 2019.

Analysis of P0 and P1 hybrids in the MY 2019 fleet presented later in this chapter (section 2.4.8.5) indicates the P1 variant of mild hybrids, although more efficient than the P0 architecture, can be reasonably represented by ALPHA's P0 mild hybrid model. Consequently, the ALPHA P0 model was chosen to simulate all the mild hybrids associated with this proposal.

2.4.4.2.2 Strong Hybrid Architectures

ALPHA 3.0 uses two distinct models to simulate strong hybrid-electric vehicles in the U.S. vehicle fleet.

The PowerSplit hybrid architecture is shown in Figure 2-7. This architecture includes a dedicated hybrid engine specifically designed to provide higher efficiency at the more stable engine loads possible with a PowerSplit powertrain. ALPHA 3.0 models the PowerSplit device using a planetary arrangement like that in the third-generation Prius, with the engine mated to the planetary's carrier gear, Motor/Generator 1 (MG1) connected the sun gear, and Motor/Generator 2 (and its associated planetary gear) connected to both the ring gear and drive axle (through the final drive gear). The PowerSplit device balances the torque between the engine, MG1 and MG2/drive axle to provide the needed torque to the wheels while optimizing efficiency of the powertrain components. The battery for a typical mid-sized PowerSplit hybrid electric vehicle is around 1.6 kWh. The battery capacity of a similar sized plug-in hybrid version of PowerSplit hybrid is around 10 kWh.

Table 2-1 illustrates that 68 percent of the strong hybrid vehicles in the MY 2019 fleet are the PowerSplit architecture. The biggest producer of PowerSplit hybrids in MY 2019 by far (both by number of vehicle models and total sales) was Toyota. Ford, FCA, and Subaru also offered a plug-in version of the PowerSplit architecture on at least one vehicle model, and GM sold a multi-mode version of the PowerSplit design.

The PowerSplit model also delivered suitable CO_2 predictions for other strong hybrids design (e.g., series-parallel and pure series architecture), which represent 16 percent[16] of the remaining MY 2019 hybrid fleet. In total, ALPHA's PowerSplit strong hybrid model was used to simulate 84 percent of the MY 2019 strong hybrid fleet.

[16] Slightly more than half of these remaining vehicles are based on a series-parallel hybrid design like the Honda Accord hybrid. While the CO_2 performance of a series-parallel hybrid can be estimated using a PowerSplit hybrid architecture, EPA is developing a dedicated series-parallel model for future use in ALPHA.

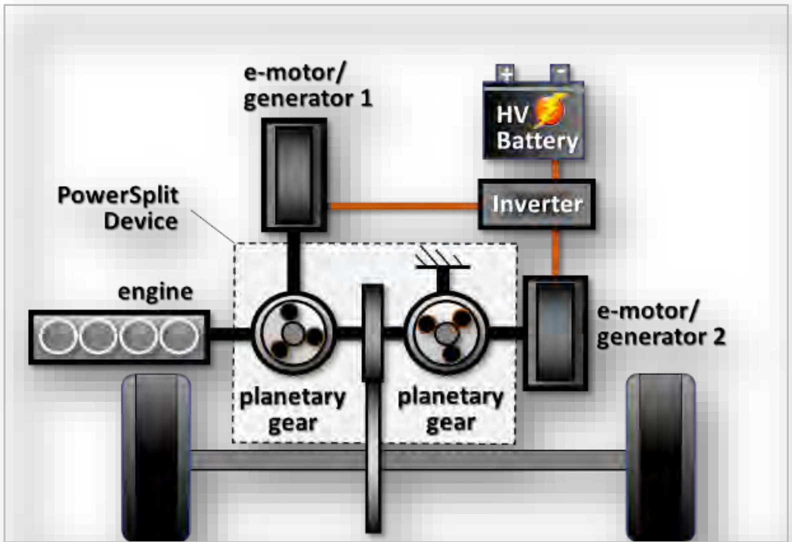


Figure 2-7: PowerSplit strong hybrid-electric architecture (& planetary gear arrangement).

The P2 hybrid architecture illustrated in Figure 2-8 is the second strong hybrid-electric model used within ALPHA. This hybrid architecture uses a conventional or a dedicated hybrid engine and a conventional 6 speed (or higher) automatic transmission with a clutch and electric motor/generator in place of the standard torque converter for a conventional vehicle. The P2 architecture has higher power and torque capability due to the full power engine and transmission and is suitable for truck and large SUV applications with towing capability. The battery energy capacity of a typical P2 strong hybrid vehicle is around 1.6 kWh (same as the PowerSplit strong hybrid). The battery capacity of a similar sized plug-in hybrid version of P2 hybrid is around 10 kWh. Table 2-1 shows that 16 percent of the strong hybrids in the MY 2019 fleet are based on a P2 design. Leading manufacturers of P2 hybrid and plug-in hybrid vehicles include Hyundai/Kia, BMW, Mercedes, and Porsche AG.

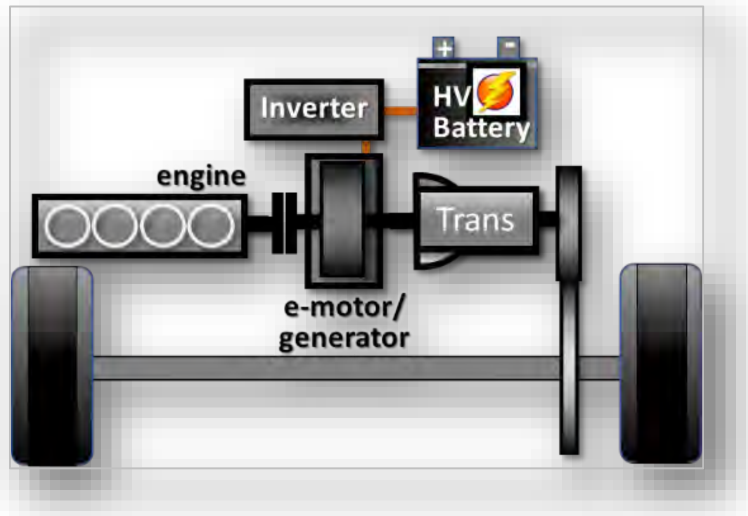


Figure 2-8: P2 strong hybrid-electric architecture.

2.4.4.3 Battery Electric Vehicle Architecture (BEV)

The energy consumption performance of battery electric vehicles (BEVs) is modeled using a battery and an electric drive unit (EDU) consisting of inverter, motor/generator, and gearing assembly as shown in Figure 2-9. The battery capacity for a typical mid-sized vehicle with a 300-mile range is around 80 kWh.

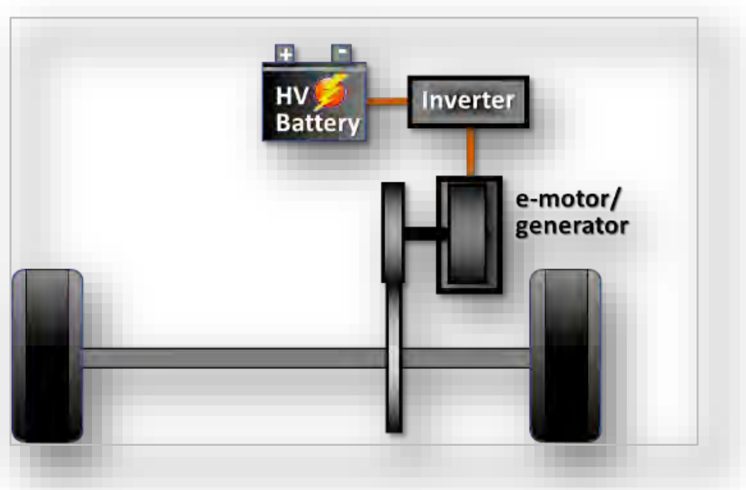


Figure 2-9: Battery electric vehicle architecture.

2.4.5 Engine, E-motor, Transmission and Battery Components

ALPHA stores engine, transmission, e-motor and battery component data in ALPHA input files. The data included in each of the ALPHA inputs comes from various sources including EPA and other national laboratory benchmark testing, GT-Power modeling, contracted benchmark testing, and technical papers. Each input dataset receives extensive quality analysis from EPA's benchmarking and engineering team to identify and remove any errors, document primary sources of data, apply best practices when extrapolating to very low or high speeds/torques, and ensure consistency between similar ALPHA input files.

This rest of this section discusses the various ALPHA input files for the internal combustion engines, electric inverters/motors, batteries, and transmissions used for this proposal. These ALPHA inputs are listed in Table 2-2 through Table 2-5 and described in detail in section 3.5.

2.4.5.1 Light-Duty Engines

Table 2-2 identifies the internal combustion engines that ALPHA uses for this proposal. The details of each engine ALPHA input listed are described in the section 3.5.1 of the RIA. Detailed information about the engines (engine efficiency map, inertia, DFCO, fuel penalties, cylinder deactivation features, fuel used, etc.) can be found in the data packet associated with each engine (U.S. EPA 2023a) (U.S. EPA 2023c).

Table 2-2: Engine ALPHA input maps used to create ALPHA outputs for RSEs

Type	ALPHA Component Name	Data Source
PFI Large Bore	GT Power Baseline 2020 Ford 7.3L Engine from Argonne Report Tier 3 Fuel[17]	Technical Report (Argonne/SwRI)
GDI	2013 Chevrolet 2.5L Ecotec LCV Engine Reg E10 Fuel	Contracted Testing (FEV)
GDI	2014 Chevrolet 4.3L EcoTec3 LV3 Engine LEVIII Fuel	EPA-NCAT Testing
Turbo Gas	2013 Ford 1.6L EcoBoost Engine LEV III Fuel[17]	EPA-NCAT Testing
Turbo Gas	2015 Ford 2.7L EcoBoost Engine Tier 3 Fuel	EPA-NCAT Testing
Turbo Gas	2016 Honda 1.5L L15B7 Engine Tier 3 Fuel	EPA-NCAT Testing
Turbo Gas Miller	Volvo 2.0L VEP LP Gen3 Miller Engine from 2020 Aachen Paper Octane Modified for Tier 3 Fuel	Technical Paper (2020 Aachen)
Turbo Gas Miller Dedicated Hybrid	Geely 1.5L Miller GHE from 2020 Aachen Paper Octane Modified for Tier 3 Fuel	Technical Paper (2020 Aachen)
Atkinson	2018 Toyota 2.5L A25A-FKS Engine Tier 3 Fuel	EPA-NCAT Testing
Atkinson Dedicated Hybrid	Toyota 2.5L TNGA Prototype Hybrid Engine from 2017 Vienna Paper Octane Modified for Tier 3 Fuel	Technical Paper (2017 Vienna)

2.4.5.2 Electric Drive Components

Table 2-3 shows the three types of electric drive components that ALPHA uses for this proposal.

- **BISG** - Belt Integrated Starter Generator consisting of an inverter, an **electric motor**, and the engine's front-end pulley/belt drive.
- **EDU** - Electric Drive Unit consisting of an inverter, an **electric motor**, and the drive gearing.
- **EMOT -** Electric Motor consisting of an inverter and an electric motor (the gear losses are not accounted for within this device).

The details of each electric motor ALPHA input listed are described in the section 3.5.2 of the RIA. Detailed information about the electric component (efficiency map, losses, gear ratios, etc.) can be found in the data package associated with each component (U.S. EPA 2023a) (U.S. EPA 2023b).

Table 2-3: Electric motor/related ALPHA input maps for electrified vehicles used to create ALPHA outputs for RSEs

[17] Not included in the draft but are likely to be added to the analysis for the FRM.

Type	ALPHA Component Name	Data Source
E-motor	2010 Toyota Prius 60kW 650V MG2 EMOT	ORNL
E-motor	Est 2010 Toyota Prius 60kW 650V MG1 EMOT	ORNL / NCAT
E-motor	2011 Hyundai Sonata 30kW 270V EMOT	ORNL
Belt Integrated Starter Generator	2012 Hyundai Sonata 8.5kW 270V BISG	ORNL
Electric Drive Unit	Generic IPM 150kW EDU	NCAT

2.4.5.3 Transmissions

Table 2-4 identifies the automatic transmissions used for this proposal. These transmission models are all traditional step automatic transmissions and are used to represent all drivetrains in conventional and electrified vehicles (except for PowerSplit vehicles and BEVs). Transmission losses as a function of load and gear number are built into the ALPHA input. The torque converter efficiency and lockup logic are also programmed into each ALPHA input. The shifting logic for each transmission is built into a function called ALPHA-shift. The TRX_ECVT_FWD transmission supplies the planetary gear ratios and the gear mesh efficiency for the PowerSplit drivetrain. EPA did not perform any additional transmission testing for this rulemaking.

For more information on most of these transmissions, please refer to the description of ALPHA in the *2016 Final Determination* (U.S. EPA 2017b).

Table 2-4: Transmission ALPHA inputs used to create ALPHA outputs for RSEs

Type	ALPHA Component Name
5-spd FWD AT	TRX10_FWD
5-spd RWD AT	TRX10_RWD
6-spd FWD AT	TRX11_FWD
6-spd RWD AT	TRX11_RWD
Adv 6-spd FWD AT (no torque converter)	TRX12_FWD_P2_Hybrid
Adv 6-spd FWD AT	TRX12_FWD
Adv 6-spd RWD AT	TRX12_RWD
8-spd FWD AT	TRX21_FWD
8-spd RWD AT	TRX21_RWD
Adv 8-spd FWD AT (no torque converter)	TRX22_FWD_P2_Hybrid
Adv 8-spd FWD AT	TRX22_FWD
Adv 8-spd RWD AT	TRX22_RWD
PS Planetary Gear	TRX_ECVT_FWD
Surrogate for BEV Transmission	BEV transmission

2.4.5.4 Batteries

Table 2-5 lists the drive battery packs used in electrified vehicles. EPA did not test any battery packs for this rulemaking. We relied on battery RC data provided by Southwest Research Institute and other sources.

Table 2-5: Battery ALPHA inputs used to create ALPHA outputs for RSEs

Type	ALPHA Component Name	Used For
48-Volt Battery	battery_base_A123_48V_8Ah	P0
High-Voltage Battery	battery_base_Samsung_LI_Power_mod2	PowerSplit
High-Voltage Battery	battery_base_9p8_kWh_NCM	P2
High-Voltage Battery	battery_pack_NMC_58kWh	BEV

An equivalent circuit model, as shown in Figure 2-10 is used for the battery cells in the ALPHA. The following parameters are used to define the high voltage battery model:

- Open circuit voltage (OCV_V)
- Series resistance (RS) to model ohmic effects
- Short time constant resistor and capacitor (RP_ST and CP_ST) to model charge transfer dynamics
- Long time constant resistor and capacitor (RP_LT and CP_LT) to model diffusion dynamics

The ALPHA framework allows for these parameters to be a function of multiple variables such as SoC, temperature, etc. The state of charge (SoC) is estimated based on coulomb counting. Additionally, the model also contains a basic thermal model that estimates battery temperature based on the losses.

Specifically, for the HEV and BEV models validated for the program, the propulsion battery parameters are a function of SoC (at minimum) and temperature (when data was available). Further, it was decided that using a series resistance (RS) was sufficient based on the performance of the model compared to the vehicle test data, so the short and long-time constants are disabled in such scenarios but can be enabled if data is available.

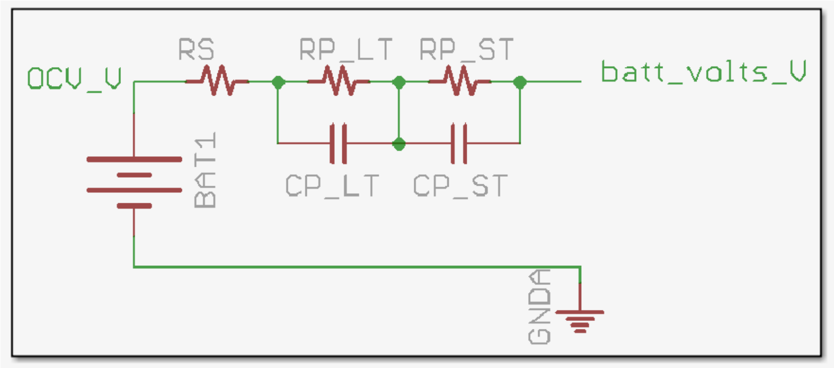


Figure 2-10: Schematic of equivalent circuit battery model used in ALPHA.

2.4.6 <u>Scaling rules for ALPHA input maps</u>

As described in the previous section, subcomponents (engines, transmissions, e-motors, and/or batteries) are included in the ALPHA input component library for use in conventional, hybrid, or battery electric architecture models described in Section 2.4.4. The specific inputs are chosen to best estimate the performance of the various vehicle technology packages within the vehicle architecture modeled. To appropriately simulate the CO_2 performance of a specific vehicle (with its particular mass, engine power, transmission torque capacity, road load, etc), ALPHA engine, transmission and e-motor inputs need to be scaled up or down in size to match the size of the simulated vehicles.

EPA scales its engine maps based on cylinder count, surface to volume ratio of the cylinders, and total displacement. For engines and transmissions, the scaling and sizing methodology is the same as previously used in the Proposed Determination on the Appropriateness of the Model Year 2022-2025 Light-duty Vehicle Greenhouse Gas Emissions Standards under the Midterm Evaluation (described in section 2.3.3.3. of the Technical Support Document (U.S. EPA 2016b).

The scaling methodology used in ALPHA for e-motors and electric drive units is simpler than for engines and is accomplished solely by adjusting the y-axes (torque and power) of the input map while maintaining the same maximum speed, as shown in Figure 2-11.The scaling methodology used in ALPHA for e-motors and electric drive units is simpler than for engines and is accomplished solely by adjusting the y-axis (torque and power) of the input map while maintaining the same maximum speed, as shown in Figure 2-11.

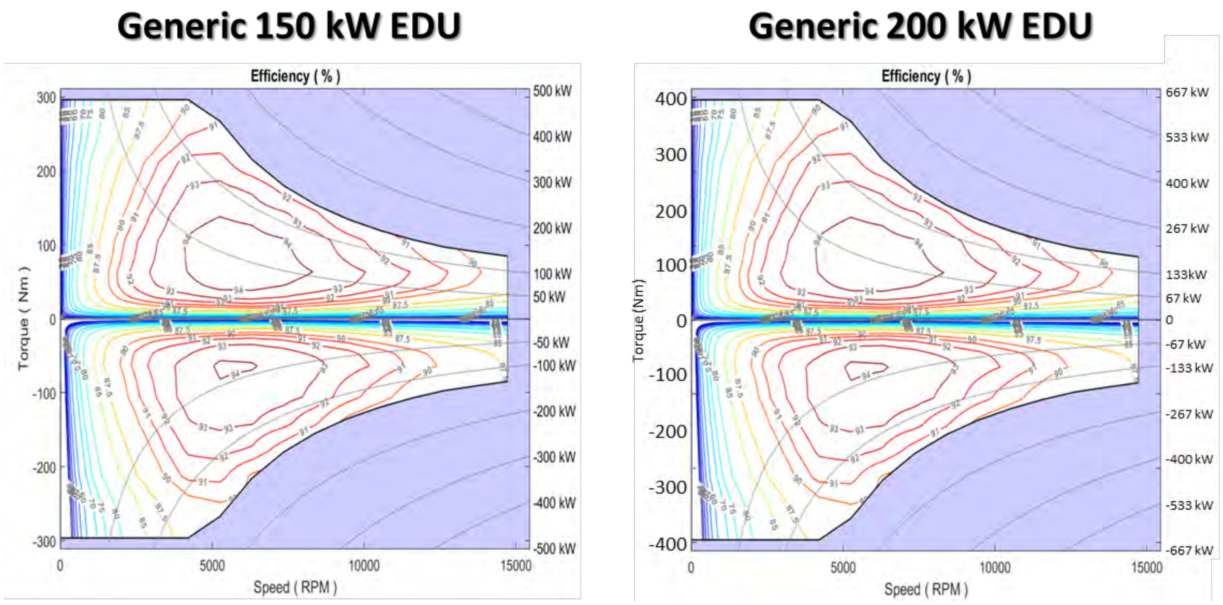


Figure 2-11: Power scaling example - Electric drive unit.

2.4.7 Tuning ALPHA's Electrified Vehicle Models Using Vehicle Validations

Using the architectures and ALPHA component input data described above, the P0, P2, PowerSplit, and BEV models were developed, calibrated, tuned, and validated using detailed test data measured in a laboratory from specific vehicles listed in Table 2-6 while driven over the EPA city, highway and US06 regulatory drive cycles.

Table 2-6: Table of test data vehicles used to validate ALPHA

Model	Validation Vehicle	Notes
P0 Mild Hybrid	2013 Chevrolet Malibu Eco	-Validation of ALPHA's P0 mild hybrid model was previously completed during the Midterm Evaluation. [9] - Slight updates have been made since then based on data from chassis testing done on 2018 Jeep Wrangler eTorque and 2020 Dodge Ram eTorque vehicles.
PowerSplit Strong Hybrid	2017 Toyota Prius Prime PHEV	- While this vehicle is a PHEV, the ALPHA validation of ALPHA's PowerSplit model primarily focused on "charge sustaining" operation.
P2 Strong Hybrid	2016 Hyundai Sonata PHEV	- While this vehicle is a PHEV, the ALPHA validation of ALPHA's P2 hybrid model primarily focused on "charge sustaining" operation.
Battery Electric Vehicle (BEV)	2018 Tesla Model 3	

Each electrified vehicle model was tuned to achieve similar operational behavior for the engine, transmission, electric motors, and battery, as observed in actual vehicle test data. For example, Figure 2-12 compares data from the PowerSplit model against the corresponding measured test data on a 2016 Toyota Prius Prime. This validation process similar to what was done in previously for conventional vehicles. (Newman, K., Kargul, J., and Barba, D. 2015b)

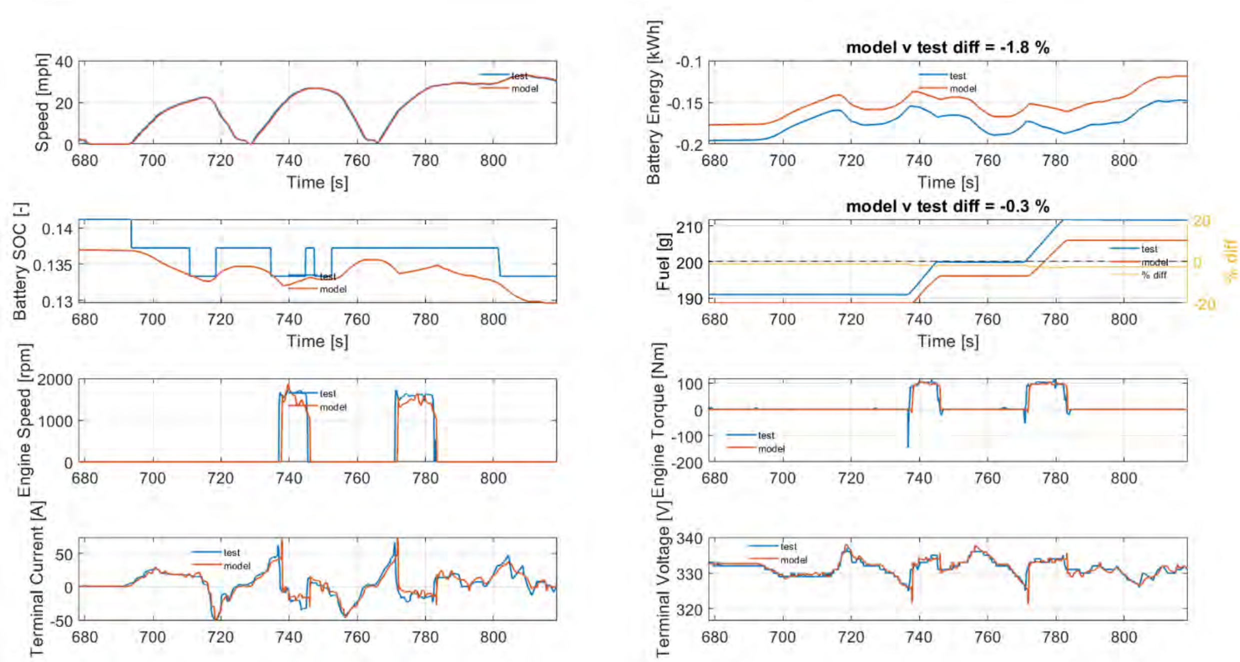


Figure 2-12: Sample validation comparison of modeled versus measured data from a 2016 Toyota Prius Prime operating on the drive schedule between 680 to 820 seconds.

Table 2-7 summarizes the final results of the strong hybrid and BEV models. For the PowerSplit strong hybrid model, the ALPHA simulated combined city-highway CO_2 grams per mile was 3.5 percent higher than that of the 2017 Toyota Prius Prime driven on the dynamometer. For the P2 strong hybrid model, the combined city-highway simulation results were -4.4 percent lower than the 2016 Hyundai Sonata PHEV tested on the chassis dyno. Finally, the combined results from the BEV model were 1.1 percent higher than the test data from the 2018 Tesla Model 3.

Table 2-7: Percent difference of ALPHA vehicle validation simulation versus benchmarking test data

Model: Validation Vehicle	Hot UDDS	HW	US06	Combined (hot-UDDS & HW)	Units
Power Split Strong Hybrid: 2017 Toyota Prius Prime PHEV	3.2%	3.9%	-2.5%	**3.5%**	% Diff CO_2 g/mi
P2 Strong Hybrid: 2016 Hyundai Sonata PHEV	-8.3%	0.4%	-6.6%	**-4.4%**	% Diff CO_2 g/mi
Battery Electric Vehicle: 2018 Tesla Model 3	-0.8%	3.4%	1.6%	**1.1%**	% Diff kWh/mi

Comments regarding the P2 validation results: Normally EPA targets +/- 4 percent difference between the simulation and the test vehicle for each drive cycle in its validation efforts. In case of the P2 model, Table 2-7 shows a -8.3 percent difference for the hot UDDS cycle and a -6.6 percent difference for the US06 cycle. While the combined UDDS/HW result is close to 4 percent difference, there could be two reasons for this wider difference of the values for the individual cycles.

The Toyota A25A-FKS engine was used as a surrogate for the 2016 Hyundai Sonata engine, which was not available as an ALPHA input. Without the actual Hyundai engine map, it would be expected the simulation results would be slightly different than the test vehicle data.

It is possible that coastdown coefficient adjustments for P2 strong hybrids do not adequately account for the losses that occur when the electric motor is always connected to the input of the transmission. (Moskalik 2020)

Typical test-to-test variation of chassis dynamometer testing can be +/-3 percent due to a variety of factors such as different drivers, measurement equipment, fuel, and facilities. Since the test vehicle test data used in the P2 model came from several different laboratories, and other differences between the dynamometer results and simulation results (as noted above) would lead to even greater variation, the combined vehicle validation differences are reasonable when considering the factors listed. However, EPA intends to continue working to refine ALPHA's P2 strong hybrid model for the final rulemaking.

2.4.7.1 Verifying the Validated Strong Hybrid and BEVs Models against Variant Vehicles

Since ALPHA architecture models are intended to simulate a range of vehicles, it is helpful to compare ALPHA results to data from multiple tests on multiple vehicles. Therefore, the next step in the validation process was to verify the ALPHA model against a number of similar, but different, vehicles (think of these other vehicles as "sibling" or "cousin" vehicles). These variant vehicles were selected because they have very similar powertrain designs and control strategies to the initial validation vehicle, yet they may of different size and make. Additionally, the Certification data originates from different vehicles, drivers, equipment, and laboratories, all of which increases the variability of the comparisons, and can yield a measure of how well the validated model can simulate other vehicles.

Once each vehicle model was developed and tuned to provide similar behavior as its test vehicle, CO_2 (for hybrid operation) and energy consumption (for BEVs and PHEVs running in charge depleting mode) results were compared for other "variant" vehicles from the same manufacturer with very similar powertrain designs as the original validation vehicle. Since there were no dynamometer test data for these variant vehicles, the ALPHA simulation results were checked to see how close they agreed with available vehicle Certification data. These results of the ALPHA model validations and their variant verifications for the strong hybrids and BEVs are summarized in Table 2-8.

- **The top row of** Table 2-8 summarizes the average difference between ALPHA estimated CO_2 gpm and Certification CO_2 gpm for four Toyota variants of the Prius Prime PowerSplit design operating in charge sustaining mode. The comparison shows the average CO_2 percent difference over the three drive cycles (FTP, HW and US06) to be 1.7 percent, -1.1 percent and -3.3 percent, respectively. The average percent difference of the combined (FTP-HW) CO_2 values is shown to be -0.1 percent. The standard deviation of these combined averages is shown to be 2.2 percent.

- **The center row of** Table 2-8 summarizes the average difference between a P2 strong hybrid vehicle's ALPHA estimated CO_2 gpm and its Certification CO_2 gpm for five Hyundai/Kia variants of the Sonata P2 Hybrid design operating in charge sustaining mode. This comparison shows the average CO_2 percent difference over the three drive cycles (FTP, HW and US06) to -6.1 percent, 2.2 percent and -10.1 percent, respectively. Again, as mentioned in the discussion of the P2 validation, the primary reasons this lower FTP and US06 differences is because the Toyota A25A-FKS engine was used as a surrogate for the 2016 Hyundai Sonata engine. Without the actual Hyundai engine map, it would be expected the simulation results would be slightly different than the certification data. The average percent difference of the combined (cold FTP-HW) CO_2 values is shown to be -2.6 percent. The standard deviation of these combined averages is shown to be 3.6 percent.

- **The bottom row of** Table 2-8 summarizes the average difference between a Tesla BEV's ALPHA estimated energy consumption (kWh/mi) and its Certification energy consumption (kWh/mi) for 14 variants of the Tesla Model 3 design. This comparison shows the average kWh/mi percent difference over the three drive cycles (FTP and HW) to 4.1 percent, 2.6 percent, respectively. No US06 Certification data were available for this comparison. The average percent difference of the combined (FTP-HW) CO_2 values is shown to be 3.4 percent. The standard deviation of these combined averages is shown to be 4.3 percent.

Comparing the combined city-highway averages of the variant vehicle simulations in Table 2-8 to the vehicle validation combined averages in Table 2-7 shows a slight increase in variability, which was expected given the validated model was tuned using a specific vehicle, yet it being asked to estimate results for slightly different vehicles. Consequently, the results in Table 2-8 are considered quite good.

Table 2-8: Percent difference of variant vehicle ALPHA simulations versus certification data

Verification of Variant Vehicles	City	HW	US06	Combined (City & HW)	units	# vehs.
Power Split Strong Hybrid Variants: 2017 Toyota Prius Prime PHEV	0.7%*	-1.1%	-3.3%	-0.1%	Avg % diff CO_2 g/mi	4
	1.9%*	2.6%	2.7%	2.2%	Std-dev of % diff CO_2 g/mi	
P2 Strong Hybrid variants: 2016 Hyundai Sonata PHEV	-6.1%*	2.2%	-10.1%	-2.6%	Avg % diff CO_2 g/mi	5
	3.8%*	3.4%	1.6%	3.6%	Std-dev of % diff CO_2 g/mi	
Battery Electric Vehicle: 2018 Tesla Model 3	4.1%**	2.6%	n/a	3.4%	Avg % diff kWh/mi	14
	5.6%**	3.2%	n/a	4.3%	Std-dev of % diff kWh/mi	

* cold-start FTP ** warm-UDDS

2.4.7.2 P0 Mild Hybrid Validation Efforts

The ALPHA validation for P0 mild hybrid vehicles was done during the Midterm Evaluation (Lee, SoDuk; Cherry, Jeff; Safoutin, Michael; Neam, Anthony; McDonald, Joseph; Newman, Kevin; 2018), consequently there is no recent P0 vehicle validation data shown in Table 2-9. Instead, a different approach to validating the accuracy of the P0 model. The first part of Table 2-9 summarizes the differences between comparisons of 24 ALPHA CO_2 simulations of P0 mild hybrids with engine start-stop applied against the ALPHA CO_2 simulations of the same vehicles without P0 and start-stop technology. The ALPHA simulation data shows an average combined (FTP-HW) CO_2 reduction of 9.3 percent when applying P0 and start-stop technology to a conventional vehicle.

The second part of Table 2-9 documents the differences between five comparisons of EPA certification results of P0 mild hybrids with engine start-stop applied against the EPA certification results of similar conventional vehicles without P0 and start-stop. The EPA certification data shows an average combined (FTP-HW) CO_2 reduction of 10.9 percent when applying P0 with start-stop technology to a conventional vehicle. These results verify that ALPHA simulates a P0 with start-stop technology within -1.6 percent.

Table 2-9 Estimated CO_2 reductions with P0 mild hybrid & start-stop technology applied to the comparable conventional vehicle

MY 2019 P0 Mild Hybrids	Cold-Start FTP	HW	US06	Combined (cold-FTP & HW)	units	# vehs.
ALPHA of P0 vs ALPHA sim of conv vehicles	13.3%	2.1%	n/a	**9.3%**	avg % diff CO2 for all pairs of sims.	24
	2.4%	0.5%	n/a	**1.8%**	std-dev of $diff CO2 for all pairs of sims.	
Cert of P0 vs Cert of conv vehicles	13.8%	5.1%	n/a	**10.9%**	avg % diff CO2 for all pairs of Cert data	5
	2.7%	2.0%	n/a	**1.5%**	std-dev of $diff CO2 for all pairs of Cert data	
Difference of CO2 averages	-0.5%	-3.0%	n/a	**-1.6%**	difference of avg % diff CO2	-

2.4.8 Verifying ALPHA's Ability to Simulate Entire Fleets

With the validated conventional and electrified models, ALPHA3 was used to simulate the entire MY 2019 base year fleet. To model the performance of these vehicles, data collected by EPA for compliance purposes, together with information from other sources including laboratory vehicle benchmarking, were used to calculate various metrics for vehicle and technology characteristics that are related to fuel economy and GHG emissions. The process used was similar to that used by the EPA in 2018. (Kevin Bolon, Andrew Moskalik, Kevin Newman, Aaron Hula, Anthony Neam, and Brandon Mikkelsen 2018)

2.4.8.1 Data Sources to Determine 2019 Fleet Parameters

Vehicle specification data that is relevant to characterizing emissions-reducing technologies are available from multiple sources. Because these data sources were generally not originally developed for this particular use, any single source will often provide only partial coverage of vehicle models over the years of interest, and production volume data necessary for generating aggregate statistics is often lacking. This section describes a methodology for consolidating data from multiple sources, while maintaining the integrity of the original data.

The most basic obstacle to consolidating data sets is variation in how vehicles are classified in different data sources. This might include variation in the level of detail as well as variation in the particular dimensions along which vehicles are characterized. Even when various data sets share a common categorization method, merging multiple sources may still be complicated when one or more of the data sets does not include the entire range of vehicles.

The primary data source used by EPA to characterize the GHG performance of the existing fleet is the certification data submitted by manufacturers to EPA's VERIFY database. The data pertain mainly to vehicle emissions performance collected in dynamometer testing, and include a general classification of engines, transmissions, and drive systems. Also included are vehicle characteristics related to road loads: dynamometer target and set coefficients, road load horsepower, and test weights. Additional data is obtained from EPA's Test Car database, which is publicly available.

In addition to the information in datasets maintained by EPA, additional vehicle specifications and technology details can be obtained through other public and commercially available sources of vehicle data such as Edmunds.com©, Wards Automotive (Penton©) and AllData Repair (AllData LLC©).

For the MY 2019 base year fleet, there were a total of 1341 distinct vehicle model types.

2.4.8.2 Vehicle Parameters

Using these data sources, for each vehicle model type the powertrain components were categorized and vehicle parameters were determined. The categories of powertrain components used are shown in Table 2-10.

Table 2-10: Powertrain components and categories

Component Category	Applicable to	Values
Level of electrification	All vehicles	Conventional, mild hybrid, strong hybrid, strong PHEV, or battery electric vehicle
Start-stop	Conventional vehicles	Y or N
Type of hybridization	Mild hybrids	P0 or P1
	Strong hybrids/PHEVs	PowerSplit, P2, series-parallel, or series
Engine type	Non-BEVs	diesel, PFI naturally aspirated, GDI naturally aspirated, turbocharged, supercharged, none
Transmission type	Conventional and mild hybrids	AT, CVT, DCT, manual
	Strong hybrids/PHEVs	specialty
	BEVs	none
Number of gears	Step transmissions	Number
Cylinder deactivation		Discrete, continuous, or none
Engine power	Non-BEVs	Power (HP)
Engine displacement	Non-BEVs	Displacement (liters)
Engine number of cylinders	Non-BEVs	3/4/6/8
Electric motor power	BEVs and hybrids	Power (kW)

In addition, other vehicle parameters were defined for each vehicle model type. The parameters defined are shown in Table 2-11.

Table 2-11: Vehicle parameters

Parameter	Values / Units
Equivalent test weight (ETW)	Pounds
Drive type	FWD, RWD, or AWD

Vehicle coastdown target values (A, B, C)	A (pounds), B (pounds/mph), C (pounds/mph2)
n/v ratio	rpm/mph
Footprint	Square feet
Production volume	Number of units
Frame style	Unibody v. body on frame

2.4.8.3 Electrified Powertrain Model Assignments

Based on the level of electrification and the type of hybridization, vehicle model types in the fleet were separated into individual groups to which to apply the appropriate ALPHA model. These groups are shown in Table 2-12.

Table 2-12: Electrified model assignments

Vehicle architecture groups	ALPHA model	Number of vehicle model types
Conventional vehicles, with or without stop-start	Conventional vehicle model	1199
Mild hybrids (P0 and P1)	P0 model	24
PowerSplit and other strong hybrids (series and series-parallel)	PowerSplit model	46
P2 hybrids	P2 model	31
BEVs	BEV model	41

2.4.8.4 Modeling Conventional Vehicles in the Fleet

To model conventional vehicles, available ALPHA maps for powertrain components were assigned to each vehicle, depending on which map had attributes closest to the specific vehicle being modeled. Engines in conventional vehicles were mapped to the ALPHA input engine maps given in Table 2-2. For some engine categories, different engines were specified depending on whether the modeled vehicle was categorized as a “truck” or not. For this purpose, all body-on-frame SUVs and pickup trucks, as well as large vans, were classified as "trucks," while the remaining vehicles were categorized as "cars." The assignment of ALPHA engines to conventional base year fleet vehicles is given in Table 2-13.

For each vehicle model type, the engine model was scaled to match either the given power of the engine (power scaling), or to match the engine displacement (displacement scaling) as described in section 2.4.6 (Paul Dekraker, John Kargul, Andrew Moskalik, Kevin Newman, Mark Doorlag, and Daniel Barba 2017).

Table 2-13: Assignments of engines used to simulate MY 2019 base year fleet conventional vehicle model types, based on engines in Table 2-2

Engine Categories	Modeled As	Scaling	ALPHA engine input
Diesel engines	Miller cycle engine	power	Volvo 4-cyl 2.0L 2020 paper
PFI and GDI NA engines (cars)	GDI engine	power	2013 Chevrolet 2.5L Ecotec LCV
PFI and GDI NA engines (trucks)	GDI engine	displacement	GTPower 2020 Ford 7.3L
Atkinson engines	Atkinson	power	2018 Toyota 2.5L A25A-FKS
Turbocharged engines (cars)	TDS engine	power	2013 Ford Ecoboost 1.6L
Turbocharged engines (trucks)	TDS engine	power	2015 Ford EcoBoost 2.7L
Supercharged engines	TDS engine	displacement	2013 Ford Ecoboost 1.6L
Advanced turbocharged engines	Adv. TDS	power	2016 Honda 1.5L L15B7

Transmissions in conventional vehicle model types were mapped to one of five automatic step transmissions given in Table 2-4. Losses in the transmission and differential were modified depending on whether the vehicle was a front or rear wheel drive. This mapping is very similar to the process used by EPA in earlier rulemakings (U.S. EPA 2016b). Losses in the transmission were scaled to the peak torque of the engine.

Table 2-14: Transmissions used to simulate MY 2019 base year fleet conventional vehicles, based on transmissions given in Table 2-4

Transmission Categories	Modeled As	Source / Notes
4- and 5-spd ATs, 5- and 6-spd manuals	TRX10	Five-speed from 2007 Toyota Camry
6-spd ATs	TRX11	Six-speed GM 6T40
All DCTs, 7-spd manuals	TRX12	Six-speed with advanced loss reduction
7-spd and above ATs, older CVTs	TRX21	Eight-speed FCA 845RE
Newer CVTs	TRX22	Eight-speed with advanced loss reduction

With the appropriate powertrain assigned, each vehicle was simulated in ALPHA over the FTP and HWFET cycles, using the vehicle parameters in Table 2-11.

The grams/mile CO_2 values from the ALPHA simulation were compared to certification values; the sales-weighted average of the difference is given in Table 2-15. A scatter plot of the ALPHA versus certification values is shown in Figure 2-13. The sizes of the bubbles in the plot reflect sales volumes for each vehicle.

Table 2-15 Conventional vehicle model type ALPHA CO_2 grams/mile values versus certification CO_2 gpm (2019 fleet)

	FTP	HW	Combined
Sales-weighted average	-3.8%	+4.8%	-0.8%
Sales-weighted std. dev.	6.1%	6.2%	5.2%

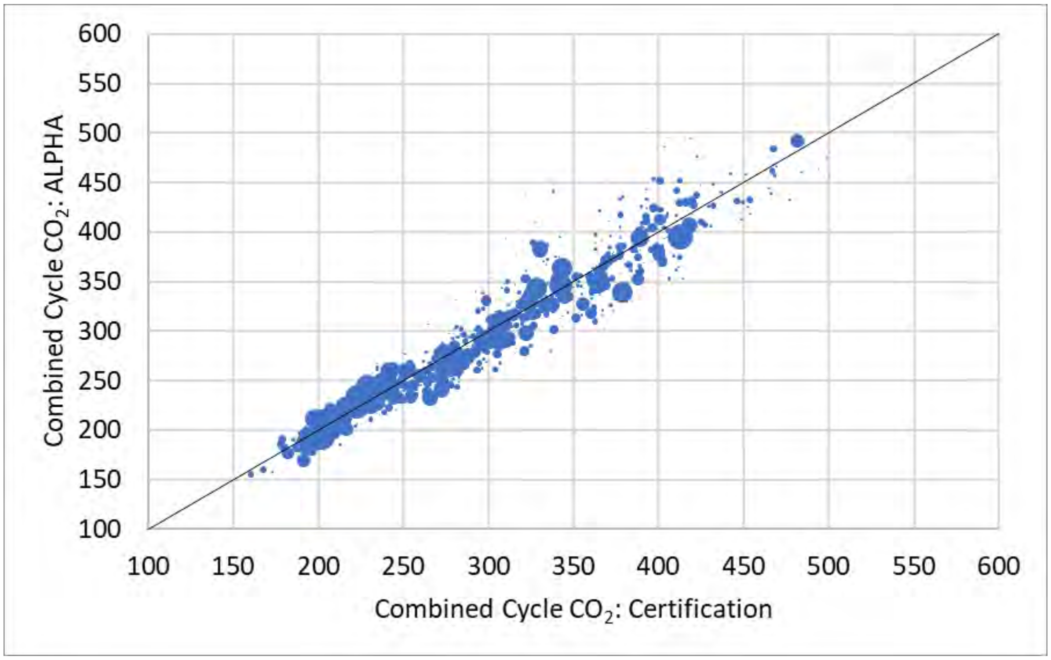


Figure 2-13: Conventional vehicle ALPHA combined cycle CO_2 grams/mile values versus certification CO_2 grams/mile (2019 fleet). Bubble sizes reflect sales volumes.

2.4.8.5 Modeling Mild Hybrids in the Fleet

All mild hybrids were modeled using a P0 BISG model, (Lee, SoDuk; Cherry, Jeff; Safoutin, Michael; Neam, Anthony; McDonald, Joseph; Newman, Kevin; 2018) using the BISG motor from Table 2-3 and the 48V battery from Table 2-5. All mild hybrids in the fleet have 48V, however, these vehicles are from multiple manufacturers with different operational strategies and configurations (some mild hybrids have a P0 configuration, and some have a P1 configuration). However, a single P0 model was judged to be reasonably representative of all mild hybrid vehicles.

The engines and transmissions for mild hybrids were assigned and sized in the same way as for conventional vehicles. Both electric motor and battery components were sized as a function of the rated engine power to keep the power values proportional. Each vehicle was simulated in ALPHA over the FTP and HWFET cycles, using the parameters in Table 2-11.

Each vehicle was simulated in ALPHA over the FTP and HWFET cycles, using the parameters in Table 2-11. The grams/mile CO_2 values from the ALPHA simulation were compared to certification values; the sales-weighted average of the difference is given in Table 2-16. A scatter plot of the ALPHA versus certification values is shown in Figure 2-14.

Table 2-16 P0 ALPHA CO_2 grams/mile values versus certification CO_2 grams/mile (2019 fleet)

	FTP	HW	Combined
Sales-weighted average	-5.0%	+8.5%	-0.1%
Sales-weighted std. dev.	6.3%	5.3%	5.5%

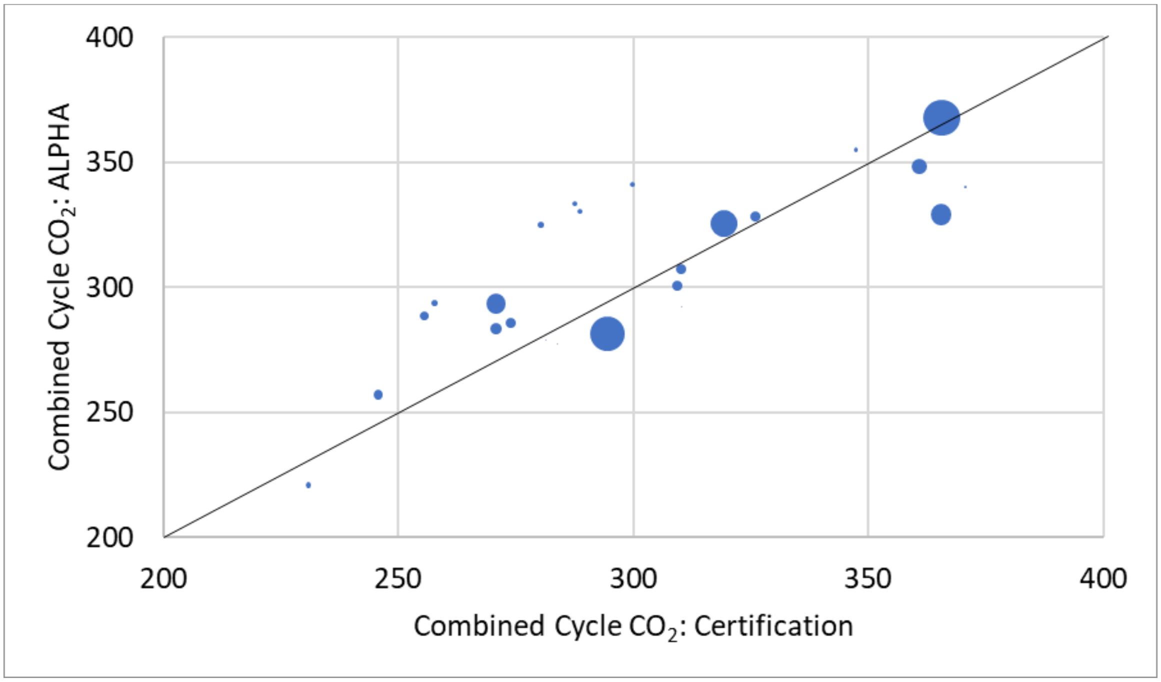


Figure 2-14: P0 ALPHA Combined Cycle CO_2 grams/mile values versus Certification CO_2 grams/mile (2019 fleet). Bubble sizes reflect sales volumes.

2.4.8.6 Modeling Strong Hybrids in the Fleet

As shown in Table 2-12, strong hybrids were divided into parallel P2 hybrids (modeled as P2s) and the remainder of the strong hybrid fleet (modeled as PowerSplits). For these strong hybrids, it was assumed that the engine was a dedicated hybrid engine (DHE), utilizing either an Atkinson cycle or (in the case of turbocharged engines) a Miller cycle, based on the two dedicated hybrid engines given in Table 2-2. Likewise, the electric motors for strong hybrids are based on the motors shown in Table 2-3, and the batteries are based on the batteries from Table 2-5.

The range of strong hybrids in the fleet covers multiple manufacturers, vehicle applications, hybrid configurations and operational strategies. Additionally, not all strong hybrids have a dedicated hybrid engine as modeled in ALPHA. However, it was judged that using these two strong hybrid models would be reasonably representative of the fleet.

In a similar way to conventional vehicles, the engine model in each hybrid vehicle was resized to match the given power of the vehicle engine as discussed above. For the vehicles modeled as a P2, the chosen engine was coupled to a six-speed transmission, based on the TRX12. PowerSplit vehicles used a planetary gearset based on the Toyota Prius. The electric motors were sized using the values reported by the manufacturers. PowerSplit generators were sized as a function of the rated engine power to keep the power values proportional. Additionally, the motor sizes for the series-parallel vehicles (modeled as PowerSplits) were also sized as a function of the rated engine power, to maintain reasonable motor sizes for that configuration. Battery sizes were assigned either according to the given value for the vehicle from EPA's 2019 fleet parameter file (described in section 2.4.8.1) or assigned a default value (1.62 kWh for HEVs and 9.18 kWh for PHEVs).

Each vehicle was simulated in ALPHA over the FTP and HWFET cycles, using the vehicle parameters in Table 2-11. The grams/mile CO_2 values from the ALPHA simulation were compared to certification values; the sales-weighted average of the difference is given in Table 2-17. A scatter plot of the ALPHA versus certification values for vehicles modeled as PowerSplit hybrids in the 2019 fleet is shown in Figure 2-15.

Table 2-17 PowerSplit ALPHA CO_2 grams/mile values versus certification CO_2 grams/mile (2019 fleet)

	FTP	HW	Combined
Sales-weighted average	+0.5%	+1.6%	+1.0%
Sales-weighted std. dev.	5.0%	4.1%	4.2%

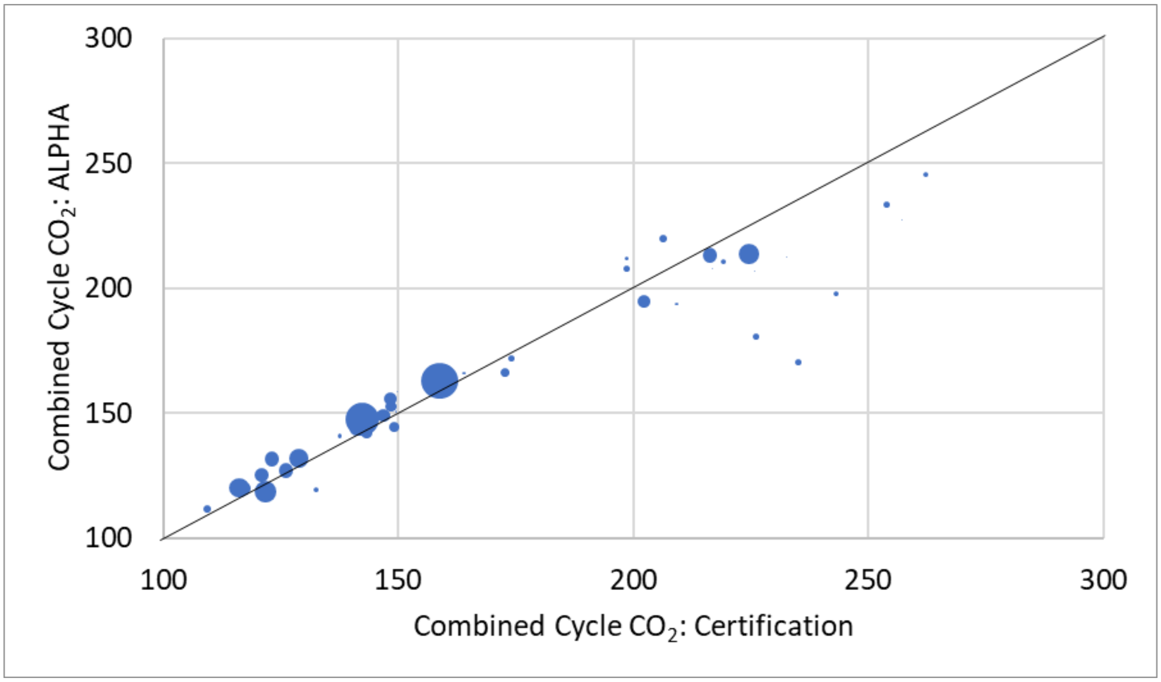


Figure 2-15: PowerSplit ALPHA combined cycle CO_2 grams/mile values versus certification CO_2 grams/mile (2019 Fleet). Bubble sizes reflect sales volumes.

For those vehicles modeled as P2s, each vehicle was simulated in ALPHA over the UDDS and HWFET cycles, using the parameters in Table 2-11. The grams/mile CO_2 values from the ALPHA simulation were compared to certification values; the sales-weighted average of the difference is given in Table 2-18. A scatter plot of the ALPHA versus certification values for P2 hybrid vehicles in the 2019 fleet is shown in Figure 2-16. Note that many of the P2 vehicles in the fleet are performance-oriented vehicles with engines that are not optimized for hybrid applications and performance-oriented operational strategies. Thus, it should be expected that ALPHA will underpredict the CO_2 emissions of these vehicles, as reflected in the figure.

Table 2-18 P2 ALPHA CO_2 grams/mile values versus certification CO_2 grams/mile (2019 Fleet)

	FTP	HW	Combined
Sales-weighted average	-13.5%	-0.2%	-7.7%
Sales-weighted std. dev.	10.1%	8.2%	9.3%

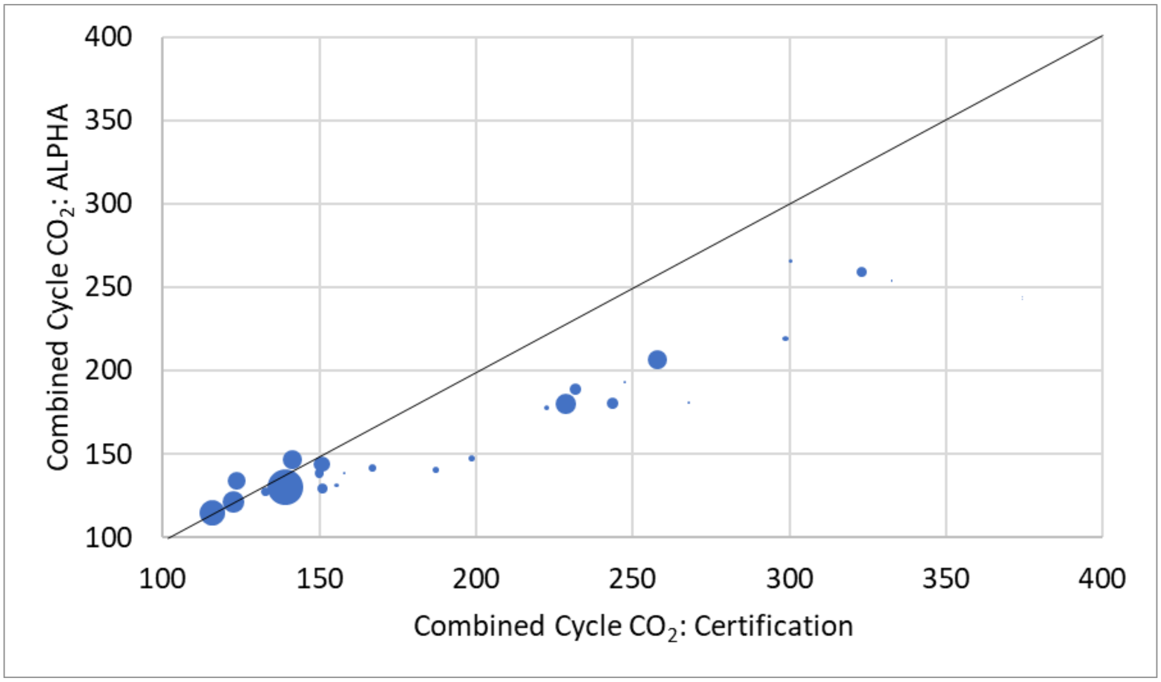


Figure 2-16: P2 ALPHA combined cycle CO_2 grams/mile values versus certification CO_2 grams/mile (2019 fleet). Bubbles sizes reflect sales volumes.

2.4.8.7 Modeling Battery Electric Vehicles in the Fleet

A single model was used to represent all battery electric vehicles. This model used an electric drive unit, as shown in Table 2-3, which was resized to match the rated power of each BEV. The ratio of DC electric energy used to AC energy used to charge the vehicle was assumed to be 0.87, based on an average of available vehicle data.

The kWh/100 mi values from the ALPHA simulation were compared to certification values; the sales-weighted average of the difference is given in Table 2-19. A scatter plot of the ALPHA versus certification values is shown in Figure 2-17.

Table 2-19 BEV ALPHA kWh/100 mi values versus certification kWh/100 mi

	UDDS	HW	Combined
Sales-weighted average	+4.2%	+1.7%	+3.0%
Sales-weighted std. dev.	9.3%	7.4%	8.3%

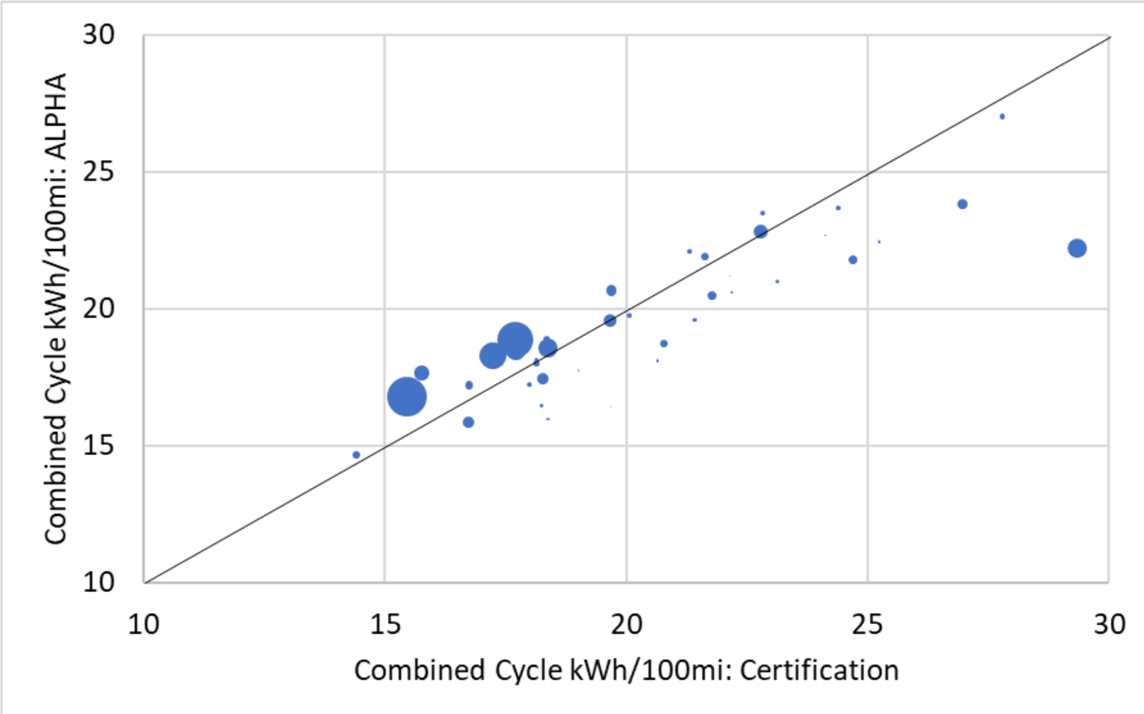


Figure 2-17: BEV ALPHA combined cycle kWh/100 mi values versus certification kWh/100 mi (2019 fleet). Bubble sizes reflect sales volumes.

2.4.9 Peer-Reviewing ALPHA Electrified Models

After preparing ALPHA 3.0 to correctly simulate electrified vehicles, it was submitted to a peer review process to examine its structure, operation, and simulation results to determine the effectiveness of various vehicle technologies via simulation. The scope of the peer-review was limited to the concepts and methodologies upon which the model relies and whether or not the model can be expected to execute these algorithms correctly for the new electrified vehicle architectures added to ALPHA. (ICF International 2022)

The peer review is centered on the five vehicle models detailed in Table 2-20. The table summarizes the configuration of each model provided for the peer review. The ETW and road loads provided in the peer review were for a generalized mid-sized car and do not correspond to any particular vehicle in the fleet. The Toyota Atkinson 2.5L engine was chosen based on the base conventional vehicle and maintained for the electrified models to allow the CO_2 performance of each model to be directly compared without the confounding factor of changing engines. The transmission selected was a 6-speed automatic transmission (TRX12) and again maintained for the P0 and P2 models. The PowerSplit, P2, and BEV models (including engine and e-motor scaling) used for the peer review was the same as that described in the sections above.

Table 2-20: Details of ALPHA 3.0 models peer reviewed

Model	ETW	Road Load (A, B, C terms)	Engine Component Name	Trans	E-motor/EDU Component Name	Engine and E-motor scaling for peer review vehicle
Conv.	3500	30, 0, 0.02	engine_2018_Toyota_A25AFKS_2L5_Tier2.m (scaled to 150kw)	TRX12	NA	Engine: power scale
P0	3500	30, 0, 0.02	engine_2018_Toyota_A25AFKS_2L5_Tier2.m (scaled to 150kw)	TRX12	emachine_2012_Hyundai_Sonata_8p5kW_270V_BISG.m	Engine: power scale E-motor: power scaling based on engine size (11kw for peer review)
PS PHEV	3500	30, 0, 0.02	engine_2018_Toyota_A25AFKS_2L5_Tier2.m (scaled to 150kw)	Internal to PS model	MG1 and MG2: emachine_2010_Toyota_Prius_60kW_650V_MG2_EMOT.m	Engine: Displacement scaling E-motor: Power scaling based on engine size (MG1 86kw MG2 106kw)
P2 PHEV	3500	30, 0, 0.02	engine_2018_Toyota_A25AFKS_2L5_Tier2.m (scaled to 150kw)	TRX12	emachine_2011_Hyundai_Sonata_30kW_270V_EMOT.m	Engine: power scale E-motor: power scaling based on engine size (65kw)
EV	4250	30, 0, 0.02	NA	9.5:1 single speed	emachine_IPM_150kW_350V_EDU.m	E-motor: Power scaling based on road load 150kw

Each sub-model provided to the peer reviewers was validated against a combination of internally and externally collected vehicle operational data while running the vehicle on a vehicle dynamometer over the USEPA city, highway and US06 regulatory cycles (as described above in section 2.4.7). EPA's approach for validations was to use detailed 10hz CAN and discrete sensor vehicle benchmarking data to set up the model structure and tune it based on e-motor and battery current and voltage, engine speed and load, battery SOH, etc. to generally achieve within 2- 4 percent agreement with the CO_2 measured over the city, highway and US06 EPA regulatory cycles as shown in Table 2-7. Once the benchmarking test vehicle validation target was achieved (generally after 3-6 months of work), the validated model was applied to variant vehicles with the same powertrain design from the same manufacturer to achieve within 3-6 percent agreement on CO_2 with EPA certification data over the combined FTP/Highway cycle. Then the validated model was applied to the broader fleet of similar technology hybrid/BEV vehicles to understand the variation in the hybrid/BEV performance (CO_2 g/mile or kWh/mile) across manufacturers.

Highlights of the peer reviewer comments were not ready at the time of this draft. However, the peer review of the added electrified models in ALPHA can be found on EPA ALPHA webpage (U.S. EPA 2023a).

2.4.10 Estimating CO_2 emissions of Future Fleets

To estimate CO_2 emissions in future fleets, OMEGA uses a set of response surface equations (RSEs) based on ALPHA simulation outputs (results). To define each RSE, technology packages (consisting of specific combinations of components) were identified. Then, an ALPHA simulation matrix run was created, sweeping vehicle parameters over a defined range so that the RSE could be applied to any vehicle. A unique ALPHA simulation output is created for each vehicle parameter setting of the sweep.

2.4.10.1 Technology Packages used to create RSEs for OMEGA

ALPHA simulation outputs used to create the RSEs consisted of CO_2 emissions or electric energy consumption over each bag of the standard dynamometer cycles (FTP, HWFET, and

US06), as well as acceleration times. Each RSE represents the results from simulating a single combination of technologies known as a technology package across different combinations of vehicle parameters.

The components used to create each technology package are shown below in Table 2-21.

Table 2-21: Technology packages for LDV/LDT RSEs

Configuration	Engine Name	Transmission	Drive	Electrification	Electric motor	RSEs
Conventional	**11**	**5**	**1.09**	**3**		**180**
GDI-car	2013 Chevrolet 2.5L Ecotec LCV Engine Reg E10 Fuel					
GDI+fixed CDA-car	2013 Chevrolet 2.5L Ecotec LCV Engine Reg E10 Fuel + fixed CDA modifier					
GDI+dyn CDA-car	2013 Chevrolet 2.5L Ecotec LCV Engine Reg E10 Fuel + dyn CDA modifier			No stop-start		
ATK-car	2018 Toyota 2.5L A25A-FKS Engine Tier 3 Fuel	TRX10 (5-spd)				
ATK+dyn CDA-car	2018 Toyota 2.5L A25A-FKS Engine Tier 3 Fuel + dyn CDA modifier	TRX11 (6-spd)				
GDI-truck	2014 Chevrolet 4.3L EcoTec3 LV3 Engine LEVIII Fuel	TRX12 (6-spd adv)	FWD			
GDI+fixed CDA-truck	2014 Chevrolet 4.3L EcoTec3 LV3 Engine LEVIII Fuel + fixed CDA	TRX21 (8-spd)	RWD	Stop-start P0 MHEV (48V) [2012 Hyundai BISG]		
GDI+dyn CDA-truck	2014 Chevrolet 4.3L EcoTec3 LV3 Engine LEVIII Fuel + dyn CDA modifier	TRX22 (8-spd adv)				
TDS12:car	2016 Honda 1.5L L15B7 Engine Tier 3 Fuel					
TDS11:truck	2015 Ford EcoBoost 2.7L Engine Tier 3 Fuel					
Miller: car + truck	Volvo 2.0L VEP LP Gen3 Miller Engine from 2020 Aachen Paper Octane Modified for Tier 3 Fuel					
Strong Hybrids	**2**				**1**	**2**
Atkinson Dedicated Hybrid	Toyota 2.5L TNGA Prototype Hybrid Engine from 2017 Vienna Paper Tier 3 Fuel				2010 Prius MG1 + MG2 EMOT	
Miller Dedicated Hybrid	Geely 1.5L GHE Miller from 2020 Aachen Paper Tier 3 Fuel					
Battery Electric Vehicles					**1**	**1**
LDV/LDT BEV EDU					IPM 150 kW EDU	

For conventional and mild hybrid (P0) vehicles, powertrain technology packages were created for each combination of engine and transmission shown under the "conventional" heading in Table 2-21. For the combinations that were not exclusively cars or trucks, separate packages were created for both front- and rear-wheel drive (truck RSEs were rear-wheel-drive only and car RSEs were front-wheel-drive only). Finally, for each combination, different packages were created (a) without stop-start technology, (b) with stop-start technology, and (c) with a mild hybrid P0 technology.

Two technology packages were created for the strong hybrid, using each of the two dedicated hybrid engines in Table 2-21. For this proposal, the strong hybrid packages created were modeled as regular (non-plug-in) hybrids only using the PowerSplit model. A single additional technology package was created for battery electric vehicles (BEVs).

2.4.10.2 Vehicle Parameter Sweeps for each Technology Package

For each technology package, ALPHA 3.0 was used to provide data with which to construct an RSE. To construct each RSE, a series of ALPHA simulations were performed using the same technology package, but with different combinations of vehicle parameters, so that a single RSE could be used to accurately characterize the performance of a range of different vehicles.

2.4.10.2.1 Swept Vehicle Parameters and Their Values

The vehicle parameters chosen for RSE development directly relate to vehicle parameters used in certification dynamometer testing. These parameters were:

- Equivalent test weight (ETW).
- Road load horsepower at 20 mph, calculated from the target coefficients (this value is substantially dominated by rolling resistance losses).
- Road load horsepower at 60 mph, calculated from the target coefficients (this value is substantially dominated by aerodynamic losses).
- Rated power of primary power source (engine or electric motor).

The calculated road loads at 20 mph and 60 mph were chosen to characterize vehicle losses rather than the coefficient of rolling resistance and drag coefficient. The choice of road loads to characterize losses ensures that all road load losses in base year vehicles are correctly accounted for, while the choice of two widely separated speeds gives parameters combinations where road loads dominated by rolling resistance (at low speed) and aero resistance (at high speed) can be separately altered.

In choosing which combinations of parameters to simulate, combinations of parameters that would not appear in the real fleet were avoided. For example, vehicles with very high ETW would not also have low road loads, as both weight and road load are correlated to vehicle size. With that in mind, rather than independently setting the value of each parameter, values of road loads and engine/motor power were chosen to be proportional to ETW. In other words, the parameters set were:

- Equivalent test weight (ETW)
- Road load horsepower at 20 mph / ETW (RLHP@20/ETW)
- Road load horsepower at 60 mph / ETW (RLHP@60/ETW)
- ETW / rated power (ETW/HP)

To determine the ranges of these parameters for light-duty RSEs, the values of ETW, target coefficients, and rated power from the EPA’s publicly available "Data on Cars used for Testing Fuel Economy from MY 2021" were used. (U.S. EPA 2022e) As shown in Figure 2-18, ETW values range from 2500 pounds to 7000 pounds, and the values of RLHP@20/ETW, RLHP@60/ETW, and ETW/HP are roughly consistent across the span of ETW.

Additionally, the road loads at 20 mph and 60 mph are related, and thus so are the values of RLHP@20/ETW and RLHP@60/ETW. When choosing parameters to simulate, only combinations of RLHP@20/ETW and RLHP@60/ETW that were near the envelope of points shown in Figure 2-18 were chosen.

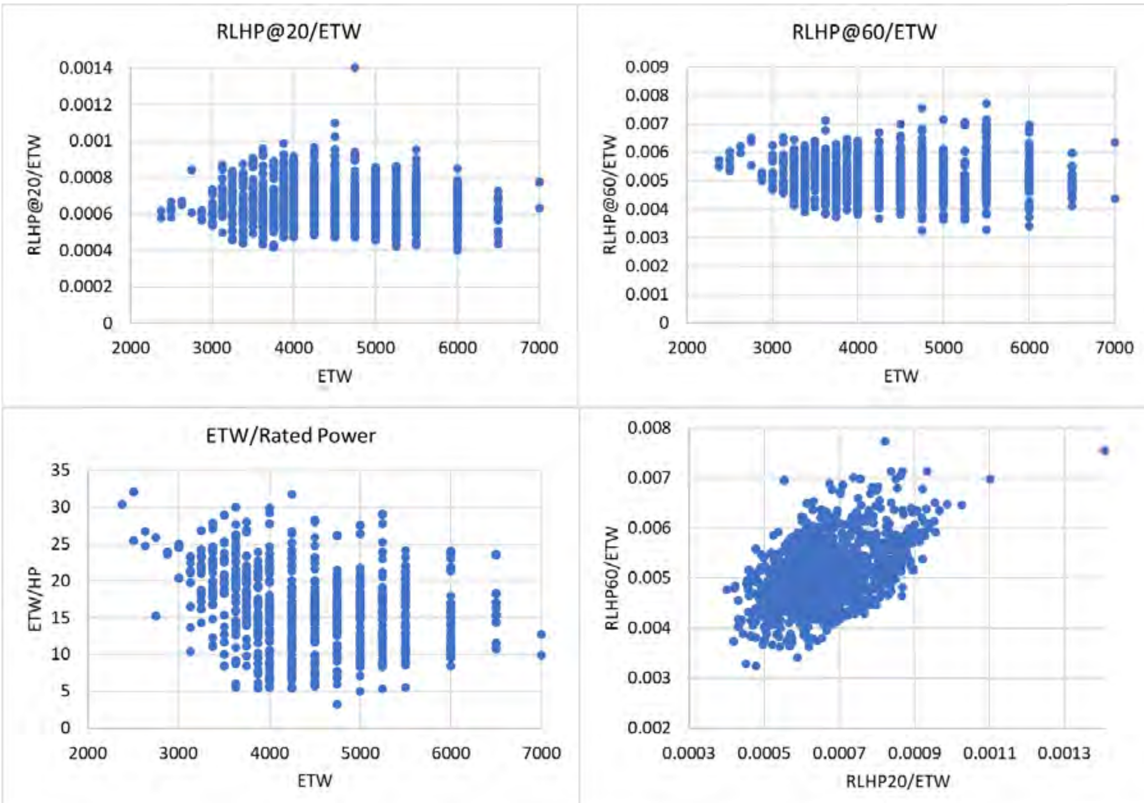


Figure 2-18: Relationships between vehicle parameters for the MY 2021 fleet.

For each RSE, discrete values of ETW, corresponding to test weight bins, were chosen spanning from 3000 pounds to 10,000 pounds. Four values of RLHP@20/ETW were chosen (0.0003, 0.0005, 0.00075, and 0.001 HP/lb), and for each value of RLHP@20/ETW, three values of RLHP@60/ETW were chosen which spanned the point cloud shown in Figure 2-18.

Finally, for conventional vehicles, engine sizes were assigned so that the ETW/HP spanned the values shown in Figure 2-18. The engines sizes were chosen from the displacements listed in Table 2-22. For hybrid vehicles, the same set of engine sizes were used. For BEVs, electric motor sizes were chosen in 50kW increments from 100 kW to 400 kW.

Table 2-22 Engine displacements used in RSE construction

Engine configuration	Displacements
I3	1.0L, 1.4L, 1.8L
I4	1.6L, 2.2L, 2.8L
V6	2.5L, 3.4L, 4.3L
V8	4.0L, 5.5L, 7.0L

2.4.10.2.2 Values of Parameters Used for ALPHA Simulations

The ALPHA simulation uses various input parameters to set up the vehicle simulation. A batch run was created for each RSE, using the powertrain configuration for that RSE. For each combination of swept vehicle parameters, the powertrain was sized according to the engine displacement or BEV EDU power specified.

The quadratic target coefficients (designated "A," "B," and "C" for the constant, linear, and quadratic term, respectively) were determined using the values of RLHP@20 and RLHP@60. To do so, the linear (B) coefficient was assumed to be 0.22 pounds/mph, representing the average value for that coefficient in the MY 2021 fleet. The constant (A) and quadratic (C) coefficients were then calculated to give the correct values for RLHP@20 and RLHP@60. Although this method does constrain the range of coefficients generated (as the linear term is always 0.22 lbs/mph), the resulting quadratic target force curve accurately reflects a wide range of target curves. For example, recalculating the target coefficients of the MY 2021 fleet with this methodology results in a difference between the original and recalculated curves at 40 mph (midway between 20 and 60) of less than 4 percent for over 97 percent of the vehicles.

For hybrid vehicles, the electric machines and batteries used in the RSE ALPHA runs were also scaled. For each hybrid configuration, the electric machine power was maintained as a constant percentage of the engine power.

2.4.10.2.3 ALPHA Simulation Outputs for RSEs

The ALPHA runs for each RSE consisted of a series of simulations using a single powertrain, but with different combinations of swept parameters. Each run simulated vehicle performance on the FTP, HWFET, and US06 cycles, as well as a "performance cycle" which was used to determine acceleration times.

For conventional and hybrid vehicles, the ALPHA 3.0 outputs consisted of CO_2 emissions for each bag of each simulated cycle, and acceleration times. For electric vehicles, the ALPHA3 outputs consisted of energy usage for each bag of each simulated cycle, and acceleration times.

2.4.10.3 Transforming ALPHA Simulation Outputs into RSEs for OMEGA

The OMEGA model requires a complete set of full-vehicle efficiency simulations for the entire vehicle fleet represented in this proposal. To create this full set of simulations using a tool such as the ALPHA model alone would require an unrealistic number of resources as millions of simulation runs would be required to generate the resolution required to satisfy the requirements of the OMEGA model.

To provide the necessary resolution for the OMEGA model while maintaining a realistic number of ALPHA simulations, EPA implemented a peer reviewed (RTI International 2018) Response Surface Methodology (RSM) (Kleijnen 2015). As described above, the inputs to the RSM are a controlled set of ALPHA simulation outputs. The output from the RSM is a set of Response Surface Equations (RSEs) suitable for the OMEGA model.

2.4.10.3.1 Steps to Create a RSE from the RSM

For this example, 157 ALPHA model results were generated from CO_2 Bag 1 representing cars with GDI engine, Continuous DEAC, TRX21 Transmission, FWD, and Start-Stop.

Step 1: Compile the ALPHA model results. Table 2-23 contains a sample of the 157 results from Bag 1 CO_2 showing the 4 inputs and the CO_2 output:

Table 2-23 - Sample results

RLHP20	**RLHP60**	**HP_ETW**	**ETW**	**CO_2**
0.0005	0.003	0.032258	3250	204.8645
0.0005	0.0065	0.032258	3250	248.2313
0.00075	0.004	0.032258	4250	293.0054
0.00075	0.006	0.032258	3250	254.2941
0.00075	0.006	0.032258	4250	326.5969
0.001	0.005	0.032258	3250	252.8225

Step 2: Generate the RSE from a commercial or open-source product. EPA utilized the popular open-source R language (Foundation 2022) including the RSM library (Lenth 2021) to generate the RSE:

CO_2-RSE = (11.6954329620654 + RLHP20 * -19931.541254933 + RLHP60 * -3972.87047794276 + HP_ETW * 491.637862683 + ETW * 3.59189981164081E-02 + RLHP20 * RLHP60 * -605147.450118866 + RLHP20 * HP_ETW * -114528.849261411 + RLHP20 * ETW * 16.4326074843966 + RLHP60 * HP_ETW * -14364.8208136198 + RLHP60 * ETW * 3.88487044872695 + HP_ETW * ETW * 9.75218337820661E-02 + RLHP20 * RLHP20 * 19630639.3025487 + RLHP60 * RLHP60 * 495588.873797923 + HP_ETW * HP_ETW * 700.465061662175 + ETW * ETW * -7.38489713757848E-09)

Step 3: Verify the output. Table 2-24 adds an additional column containing the results from the RSE and Figure 2-19 shows all 157 ALPHA results vs 157 RSE results.

Table 2-24 - Tabular results

RLHP20	RLHP60	HP_ETW	ETW	CO_2	CO_2-RSE
0.0005	0.003	0.032258	3250	204.8645	203.0853
0.0005	0.0065	0.032258	3250	248.2313	247.1682
0.00075	0.004	0.032258	4250	293.0054	294.2893
0.00075	0.006	0.032258	3250	254.2941	252.7991
0.00075	0.006	0.032258	4250	326.5969	327.4422
0.001	0.005	0.032258	3250	252.8225	254.8888

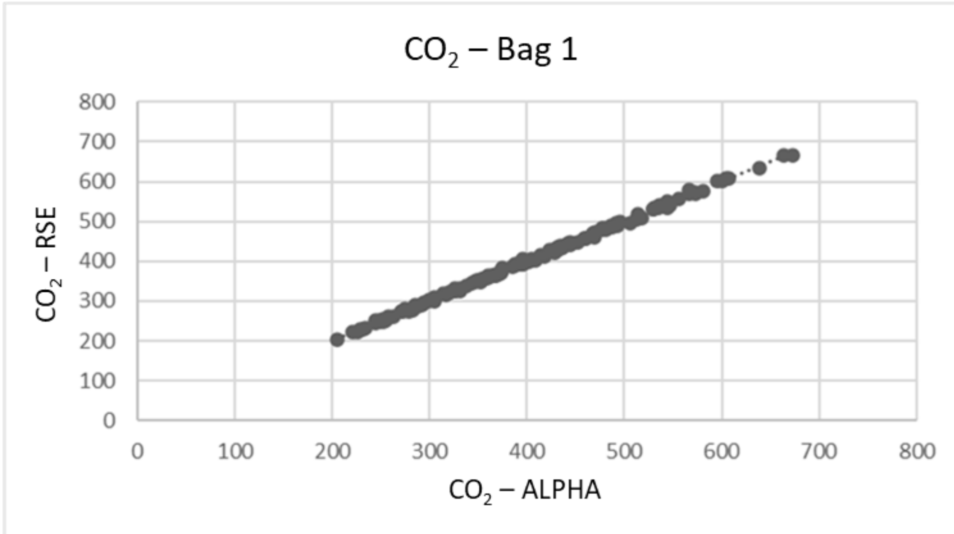


Figure 2-19: Graphical results.

The validated RSE can now be used by the OMEGA model to generate a CO_2 value (or energy consumption rate, for BEVs) for any vehicle within the range of the controlled set of ALPHA model simulation results. Utilizing the RSM results in a reduction of simulation and storage resources by approximately a factor of 100.

2.5 Cost Methodology

EPA has developed several new approaches to estimating technology costs relative to our past GHG and criteria emission analyses. We describe those new approaches here. Despite our new approaches, we continue to first estimate direct manufacturing costs and apply to those costs the well understood learning-by-doing methodology to estimate how those costs are expected to change going forward (U.S. EPA 2016). We then apply established markups to those direct manufacturing costs to estimate the indirect costs (e.g., research, development, etc.) associated with the technology. We provide more detail here in Chapter 2.5 and in Chapter 2.6.

2.5.1 Absolute vs. incremental cost approach

Powertrain costs used in OMEGA are based on a combination of prior GHG and/or criteria air pollutant rulemaking analyses (e.g., EPA's LD Tier 3 rule), and on new work. However, in contrast to previous rulemaking analyses, all costs used in this analysis are expressed as cost curves rather than as discrete costs for specific pieces of technology. More importantly, costs are now determined as absolute costs rather than incremental costs and geared toward generating full vehicle costs rather than the incremental costs considered in previous analyses. That is, when the cost of a new piece of technology or package of technologies is assigned, it is in terms of its absolute cost instead of the incremental cost relative to the older or less capable piece of technology or package of technologies that it replaces. This is an important aspect of the OMEGA technology costs because OMEGA now incorporates a consumer choice element. This means that the impacts of, for example, a $40,000 BEV versus a $35,000 ICE vehicle of similar utility (i.e., a 14 percent increase for the BEV) is a much different consideration than a $6,000 incremental BEV cost versus a $1,000 incremental ICE cost (a 500 percent increase for the BEV).

2.5.2 <u>Direct manufacturing costs</u>

2.5.2.1 Battery cost modeling methodology

In the 2012 rule, the 2016 Draft TAR, and the 2017 Proposed and Final Determinations, EPA estimated battery costs by specifying batteries for a large set of modeled BEVs, PHEVs, and HEVs across a variety of vehicle sizes and driving ranges. This involved first determining the battery power and gross energy capacity needed by each, and then using ANL BatPaC to determine the direct manufacturing cost (DMC) for each battery, in dollars per pack. These costs were assigned to a base year, and costs in future years were estimated by applying a learning curve to the base year costs.

Later, in the 2021 rule, NHTSA estimated battery costs by means of lookup tables derived from ANL BatPaC, in which energy capacity (kWh) and battery power (kW) were the primary variables. Future costs again were estimated by applying a learning curve.

For this proposal, EPA used ANL BatPaC 5.0 to develop base year (MY 2022) battery costs, expressed as a cost per kWh as a function of battery gross energy capacity (kWh). To assign costs for future years, we applied a cost reduction due to learning, based on cumulative Gigawatt-hours (GWh) of battery production necessary to supply the number of BEVs that OMEGA has placed in the analysis fleet up to that analysis year. Finally, we applied additional manufacturing cost reductions based on our assessment of the future impact of the Inflation Reduction Act.

2.5.2.1.1 Battery sizing

The compliance analysis for the current proposal, which uses battery cost as an input, was performed using the updated version of the OMEGA model. One difference from previous versions of OMEGA is that the new version directly calculates and assigns the gross battery capacity of PEVs. When the updated version of OMEGA generates a BEV, it determines the necessary gross battery capacity (kWh) for that vehicle given its estimate of the vehicle's energy consumption as a BEV, its target driving range, and other relevant factors. The direct manufacturing cost for a pack of that capacity is then estimated based on the gross capacity, the cost is reduced by application of a learning factor, and this cost becomes a term in the calculation of the total direct manufacturing cost of the vehicle.

Determining the correct gross battery capacity is important because this determines the energy consumption of the vehicle (which is in turn a result of battery weight) and also battery cost. Gross battery capacity is generally a function of the desired electric driving range, the fraction of gross battery capacity that is usable (the SOC swing, in percent), and the on-road DC energy consumption of the vehicle. The driving range is assumed to be 75 percent of the 55/45 2-cycle range which is consistent with higher volume BEVs in the market today and which we expect to be more representative of future BEVs.[18] SOC swing for a BEV is assumed to be about 90 to 95 percent. DC energy consumption is the average amount of on-road DC energy required from the battery per mile driven on the relevant cycles. Note that this is not the same as the energy consumption reported in the Fuel Economy guide, which includes charging losses incurred between the grid power outlet and the battery. Charging losses are important for calculating

[18] While it varies by model, the current FE label range for BEVs is between 70-75 percent of the 2-cycle range.

upstream emissions but must be excluded for battery sizing because battery capacity for a given range is a function of DC energy consumption. DC energy consumption is derived from a precomputed response surface generated by ALPHA results, using curb weight and other vehicle attributes as inputs to the response surface. Curb weight is intimately tied to battery capacity, via the effect of battery weight on total vehicle weight. This requires an iterative process that OMEGA must perform in order to determine curb weight simultaneously with arriving at the necessary battery size.

In the first step, OMEGA calculates the on-road DC energy consumption (Wh/mi) as a function of vehicle parameters including curb weight (which includes a battery weight determined by later steps). Next it estimates gross battery capacity, using DC energy consumption, driving range, and usable capacity, according to the formula:

$$(Wh)_{Gross\ Capacity} = \left(\frac{Wh}{mi}\right)_{DC\ energy\ consumption} \times \frac{driving\ range\ in\ miles}{0.90}$$

Next it estimates battery weight, using estimated gross capacity and an assumed specific energy (assumed to be 180-200 Wh/kg):

$$(kg)_{Battery\ Weight} = \frac{(Wh)_{Gross\ Capacity}}{Wh/kg}$$

Finally, it returns to the first step with the new battery weight, until the battery weight stops changing (converges).

2.5.2.1.2 Base year battery cost estimation

To begin estimating cost for a pack in a given year of the analysis, OMEGA first requires battery cost to be input as a base-year input cost function representing the pack cost per kWh, as a function of its gross kWh capacity, in the base year (2022).

The base year input cost function was defined as a relationship between the gross capacity of the battery (kWh) and the cost per kWh. It is generally understood and confirmed via BatPaC simulation that the cost per kWh for a pack of a given chemistry varies with the gross capacity of the pack, with packs of larger capacity generally indicating a lower cost per kWh than those of a smaller capacity. While power can also be a determinant of battery cost, for PEV batteries (as opposed to HEV batteries) energy capacity is the dominant factor, and through simulation exercises EPA determined that including power as an input variable in the costing of PEV battery packs would not meaningfully affect the results. In developing the input cost functions, PEV batteries were assigned a power-to-energy ratio generally appropriate to the vehicle, considering typical power requirements and the size of the battery.

To generate the BEV base year input cost function, EPA used Argonne National Laboratory's BatPaC model version 5.0. A copy of BatPaC version 5.0 was configured to generate a variety of battery packs that utilize pack topologies and cell sizes that are similar to those seen in emerging high-production battery platforms, such as for example the GM Ultium battery platform, the VW MEB vehicle platform, and the Hyundai E-GMP vehicle platform. EPA considers these platforms to exemplify the trend toward BEV-specific vehicle platforms with battery packs that can be assembled in several different capacities from various numbers of modules that utilize one or two standard cell sizes of relatively large capacity, generally forming a flat battery pack assembly suitable for residing in the vehicle floor. These platforms utilize pouch cells of relatively large capacity (78 to 100 Ampere-hours) that are used interchangeably in a range of pack sizes by varying the number of battery modules and their configuration within the pack.

The modeled battery packs were generated by enumerating all possible combinations of cell size (from 60 to 90 A-hr in steps of 5 A-hr) and module arrangement, with 24 cells per module. For battery chemistry, EPA selected an NMC811 cathode with a graphite anode, which among the chemistries readily modeled by BatPaC, represents in our judgment the most appropriate representative chemistry found in battery packs of this design being produced today that is also consistent with trends to balance performance with reduced cobalt content. Default costs provided in BatPaC for electrode powders and other constituents were used. While iron-phosphate cathodes are increasingly being used by some manufacturers, their lower specific energy and energy density may make them less appropriate for the BEV driving range of 300 miles modeled in the analysis.

Of the enumerated pack configurations, those having too high or low a pack voltage (below 300V or above 1000V) were eliminated.[19] We thus generated a range of engineering-feasible pack sizes and configurations, for which costs were determined and plotted as a function of pack capacity (kWh), for each of four annual production volumes (50,000, 125,000, 250,000, and 450,000), consistent with previous analyses.

Power-law equations were then generated from the plotted points, representing cost as a function of pack capacity and production volume. The resulting equations are shown below, for each of the four annual manufacturing volumes. The battery chemistry is the NMC811-G energy battery defined in BatPaC 5.0.

$$50k\ per\ year\text{: } \$/kWh = 284.28 \times (\text{gross } kWh)^{-0.192}$$
$$125k\ per\ year\text{: } \$/kWh = 270.69 \times (\text{gross } kWh)^{-0.188}$$
$$250k\ per\ year\text{: } \$/kWh = 261.61 \times (\text{gross } kWh)^{-0.184}$$
$$450k\ per\ year\text{: } \$/kWh = 254.62 \times (\text{gross } kWh)^{-0.182}$$

Figure 2-20 below shows these equations plotted on their respective curves.

[19] While most BEVs and PHEVs operate at about 350V to 400V, packs approaching 1000V were included in the plots due to the presence of dual-voltage packs in the market that can be charged at a similar voltage.

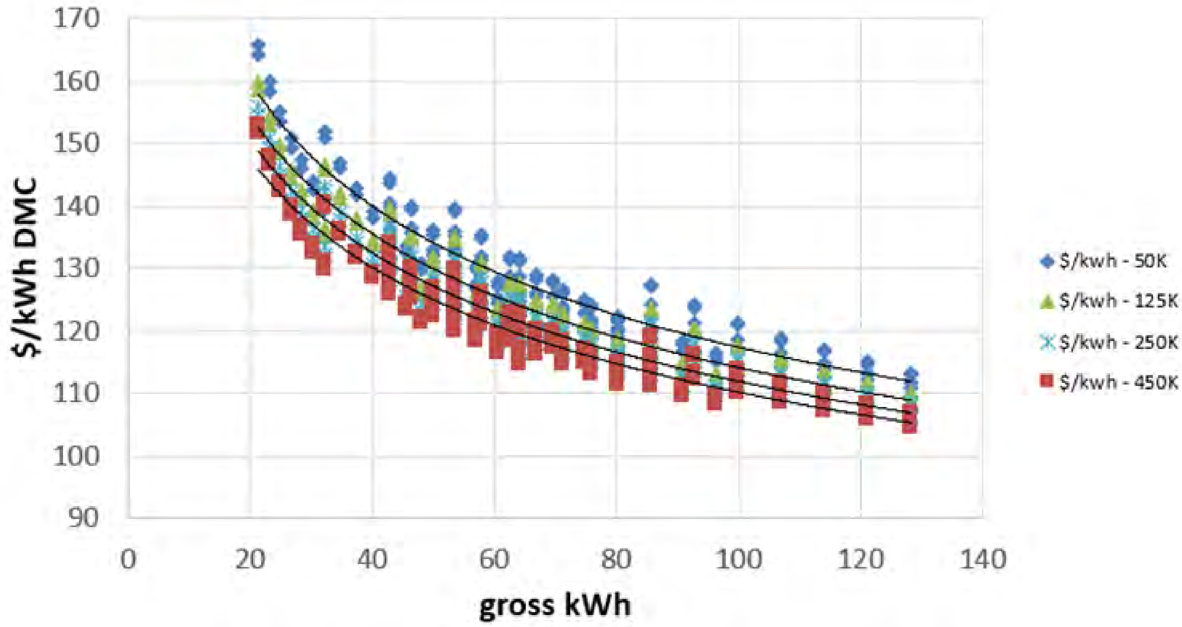


Figure 2-20. Direct manufacturing cost estimates for BEV packs at various annual production volumes for NMC811-G chemistry, base year 2022.

The equation for a production volume of 250,000 packs was then used as an input to OMEGA to represent a base year cost, applied to batteries produced in MY 2022. The annual volume of 250,000 is similar to that being produced in the largest plants today, such as those of Tesla, and also is appropriate for the purpose of causing the BatPaC model to calculate costs applicable to a production plant of 30 to 40 GWh capacity, which is a common plant capacity among the largest manufacturers today. The resulting cost for a 75 kWh battery, a commonly encountered size for BEV batteries in the market today, is about $120/kWh.

HEV battery batteries are much smaller in capacity than BEV batteries but must deliver a significant amount of power in proportion to their capacity. The higher power-to-energy ratio means that power plays as strong a role as energy capacity in determining cost. Due to the small total capacity, these batteries also must be composed of smaller capacity cells in order to have enough cells in series to achieve the approximately 300V pack voltage that is commonly seen in HEVs.

A population of HEV batteries was modeled in BatPaC 5.0, comprised of a single module of 72 cells of NMC811-G (Power) chemistry. These were configured for a range of capacities between 0.75 and 1.5 kWh, and power ratings between about 18 kW and 48 kW, based on expected power and energy requirements for a variety of vehicles styles and sizes. This resulted power-to-energy ratios ranging from about 25 to 35.

For HEV batteries (power split and P2), the following relationship between gross capacity and total pack cost was developed for NMC811-G (Power) chemistry in BatPaC 5.0. HEV batteries have a higher power-to-energy ratio than BEV batteries, and cost is therefore higher than for BEV batteries. Although HEV battery cost is more sensitive to power requirements than BEV batteries, it is possible to characterize HEV battery cost in terms of gross capacity as long as the higher power-to-energy ratio is maintained in the basis.

The plot below shows the derived cost per pack for a range of HEV pack gross capacities. The plot shows that there is not much variation in HEV total pack cost within the range of capacities likely to be used in HEVs.

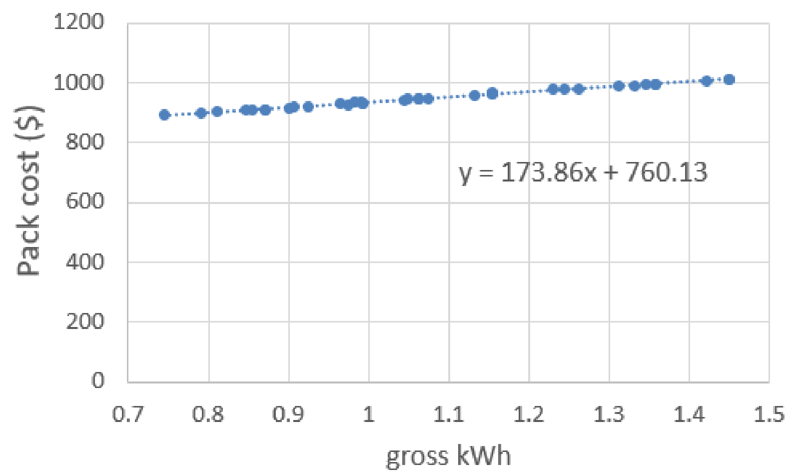


Figure 2-21. Base year cost per pack for HEV batteries as a function of gross capacity

The equivalent cost per gross kWh for HEV batteries is shown in the chart below. It demonstrates the fact that battery cost, when expressed on a dollar per kWh basis, is much higher for HEV batteries than for BEVs due to the difference in their power-to-energy ratio and their use of smaller cells to reach an appropriate voltage range for an HEV.

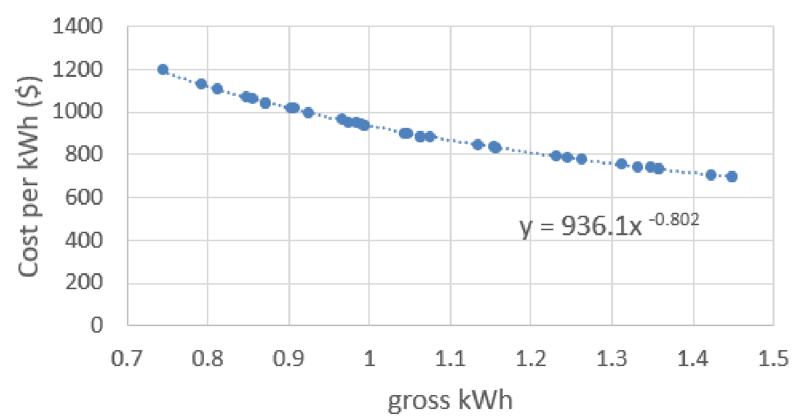


Figure 2-22. Base year cost per kWh for HEV batteries as a function of gross capacity

In general, MHEV batteries are even smaller in capacity than strong HEV batteries. These were given a single specification for all vehicles and costs were determined on that basis.

We also developed costs for PHEV batteries. PHEV battery costs were estimated by generating a population of packs constructed with cells of varying cell capacities appropriate to achieve a proper voltage of about 350V and with a sufficient power-to-energy ratio (varying from about 6.5 to 9.5) for the application. The chemistry was NMC811-G (Power formulation) as defined in BatPaC 5.0. We found that this formulation performed well in both shorter-range and longer-range PHEVs, with little impact on cost, and so would be suitable for estimating battery cost in a wide range of PHEV applications. These batteries have sufficient cooling capacity for applications in which the sustained speed is 70 miles per hour in EV mode (as defined in BatPaC 5.0), making them suitable for providing substantial all-electric range.

Power law equations were used to characterize the costs as a function of gross capacity in kWh and are depicted on Figure 2-27 below.

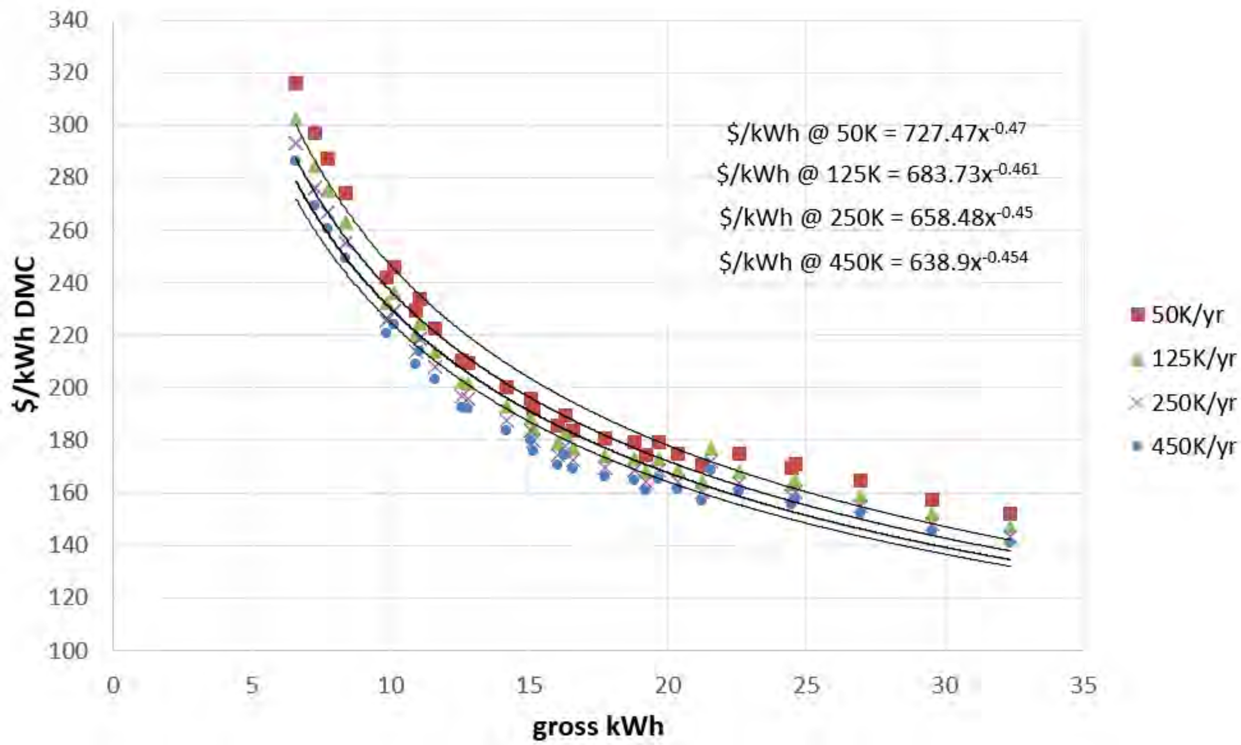


Figure 2-23: Direct manufacturing costs derived from BatPaC 5.0 for PHEV batteries

As described in the Preamble (IV.C.1), EPA has not specifically modeled the adoption of plug-in hybrid electric vehicle (PHEV) architectures in the analysis for this proposal. However, the agency recognizes that PHEVs can provide significant reductions in GHG emissions and that some vehicle manufacturers may choose to utilize this technology as part of their technology portfolio. EPA may rely upon these battery cost estimates and other information gathered in response to this proposal, and on EPA's on-going technical work, for estimating the battery costs for PHEVs for the final rule.

The BatPaC spreadsheet models used to develop the costs for BEVs, HEVs, and PHEVs are available in the Docket (US EPA 2023) and fully describe the BatPaC inputs that were used to generate the cloud of battery pack cost points that are visible in the plots.

2.5.2.1.3 Development of battery pack cost reduction factors for future years

To estimate battery pack costs for future years extending into the time frame of the rule and beyond, a dynamically generated learning factor was applied to the base year costs within OMEGA.

When the OMEGA model generates a compliant fleet in a given future year of the analysis, battery costs for BEVs in that year are determined dynamically, by calculating a learning cost reduction factor to apply to the base year cost. The learning factor is calculated based on the cumulative GWh of battery production necessary to supply the number of BEVs that OMEGA has thus far placed in the analysis fleet, up to that analysis year. This is consistent with "learning by doing," a standard basis for representing cost reductions due to learning in which a specific percentage cost reduction occurs with each doubling of cumulative production over time. This dynamic method of assigning a cost reduction due to learning means that OMEGA runs that result in different cumulative battery production levels will have result in somewhat different battery costs.

For the years 2022 through 2025, we suspended use of the learning factor, to reflect consensus views that elevated mineral prices are likely to cause battery costs to remain flat for a time (for more discussion and sources, see the discussion of the reference trajectory, later in this section).

For 2026 and later, we applied a learning factor. The learning factor equation is of the same form as that used in previous rules, assigning a cost reduction factor due to learning, as a function of cumulative production up to that point. The battery cost in a given year is calculated as follows:

1) Calculate the cumulative GWh needed by BEVs placed into the analysis fleet through last model year.

2) Calculate the cost reduction factor due to learning:[20]

$$\text{factor} = 4.1917 \times (\text{cumulative } GWh \text{ through last year})^{-0.225}$$

3) Calculate battery cost in the base year, as a function of pack kWh, according to the equation in RIA 2.5.2.1.2:

$$\$/kWh = 261.61 \times (\text{gross } kWh)^{-0.184}$$

4) Multiply the result of Step 3 by the result of Step 2.

To support comparison of the resultant costs generated by OMEGA to forecasts of future battery costs found in the literature, we also developed a reference battery cost trajectory derived from a survey of the most recent forecasts. This trajectory was used only for qualitative comparison to help understand how well the OMEGA-generated costs compare to consensus views of future battery costs.

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[20] The exponent in this equation was calibrated to match a reference cost of $75 per kWh in 2035 under a no action GWh demand scenario. This cost is part of a reference cost trajectory discussed later in this section.

In selecting the forecasts to consider, we noted that since the 2021 rule, it has become increasingly clear that mineral costs have risen sufficiently to interrupt historical trends of continuous battery cost reduction. For example, the BNEF 2021 battery price survey indicated that the pace of reduction had slowed considerably and predicted that costs may not reach $100/kWh (at pack level) until 2024. Elevated prices appear likely to persist for some amount of time due to speculation and increased demand as manufacturers work to secure long-term sources for their production needs. Although many forecasts of battery costs exist in the literature, most were developed prior to the manifestation of these recent mineral cost increases and may not fully capture their effects. Therefore, we gave particular attention to two sources that do reflect recent cost increases. Proprietary forecasts produced by Wood Mackenzie in Q3 2022 and provided to EPA as part of a subscription service (Wood Mackenzie 2022) include recent mineral cost considerations and forecasts. Another recent report by EDF/ERM (MacIntosh, Tolomiczenko and Van Horn 2022) includes a compilation of battery cost projections from a number of sources. Like most other projections of future battery costs found in the literature, these studies refer to direct manufacturing cost at the pack level and do not consider the effect of policy measures that may defray some of this cost from an accounting perspective, such as the IRA production tax credits, which are discussed in a later section. To develop the reference trajectory, we began with the base cost of $120 per kWh that was developed in Section 2.5.2.1.2, representing a 2022 direct manufacturing cost for a battery pack as described in that section (75 kWh, NMC811-G, at a production rate of 250,000 packs per year).

We then sought to identify average battery pack costs per kWh expected to occur in future years by considering estimates from the Wood Mackenzie data and the EDF/ERM report. The Wood Mackenzie data suggest that battery costs have risen from previous lows and are poised to remain somewhat elevated until about 2025 to 2026, after which they are expected to resume their decline as mineral supply and demand balance out. Similarly, the EDF/ERM report's compilation of battery cost projections (reproduced below in Figure 2-23) shows costs flat from 2022 to 2023, and also references a 2022 BNEF estimate that predicts costs will remain flat to 2024. Considering all of these sources, we chose to keep the base year pack cost per kWh of $120 unchanged through 2025, which represents a conservative rate of decline relative the sources.

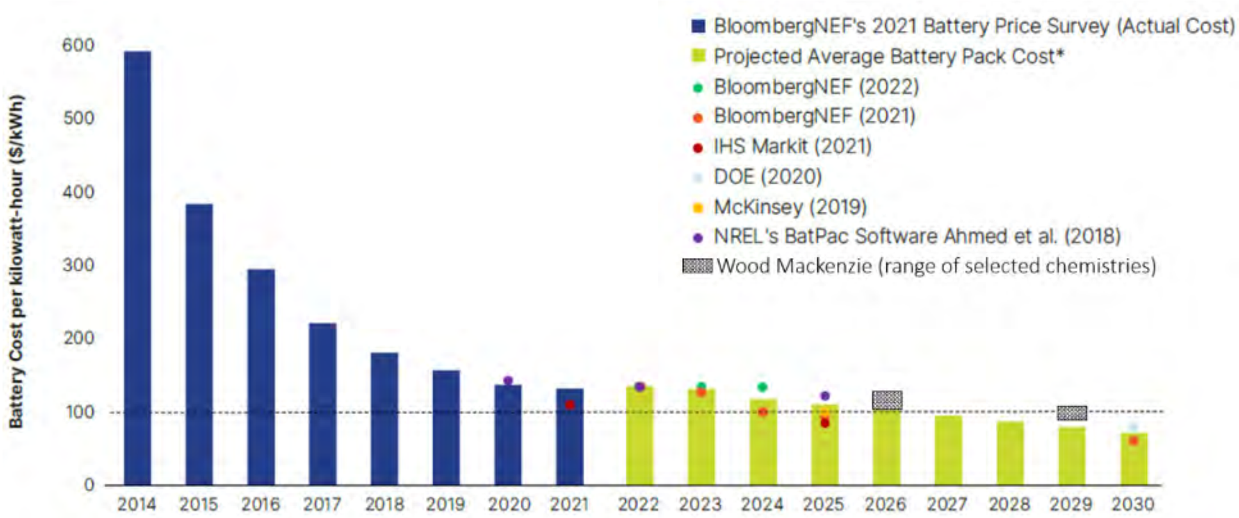

Figure 2-24 Projected battery pack costs from various sources summarized by EDF/ERM

Looking to 2026, the sources compiled in the EDF/ERM report suggest an average pack cost of $100/kWh. However, the midrange of Wood Mackenzie estimates for that year suggest a range of about $100-$130. We selected a point in between, at $110/kWh, giving a slightly larger weight to the EDF/ERM report due to its basis on multiple studies. Looking to 2029, the sources compiled in the EDF/ERM report suggest approximately $80/kWh, while the Wood Mackenzie forecast suggests about $90 to $110. Noting also that the DOE/ANL high case for battery cost in 2030 is $90/kWh, we selected $90/kWh which is between the Wood Mackenzie and EDF/ERM estimates.

The potential for cost reductions to reach these levels by 2026 and 2029 is also supported by our observation that analysts largely expect the price of lithium to stabilize at or near its historical levels by the mid-2020s,[21] suggesting that the elevated battery costs being reported today will not persist.

Past 2029, fewer pack cost estimates are found in the literature, and such long-term estimates are by their nature more uncertain than shorter-term estimates. Often, analysts model costs over the longer term by assuming an annual percentage cost reduction rate. Therefore we adopted this approach for the years past 2029. We have assumed that by this time, some of the generally anticipated improvements in battery manufacturing will have already taken place, suggesting a lower rate of learning than was seen in earlier years. Starting at the $90/kWh selected for 2029, we applied a 3 percent per year reduction, which results in $75/kWh in 2035. Past 2035, we applied a 1 percent per year reduction which results in a decline to $65/kWh by 2050.

This results in the reference trajectory for the cost of a representative 75 kWh battery as shown in Figure 2-24.

[21] For example, see Sun et al., "Surging lithium price will not impede the electric vehicle boom," Joule, doi:10.1016/j.joule. 2022.06.028 (https://dx.doi.org/10.1016/j.joule.2022.06.028).

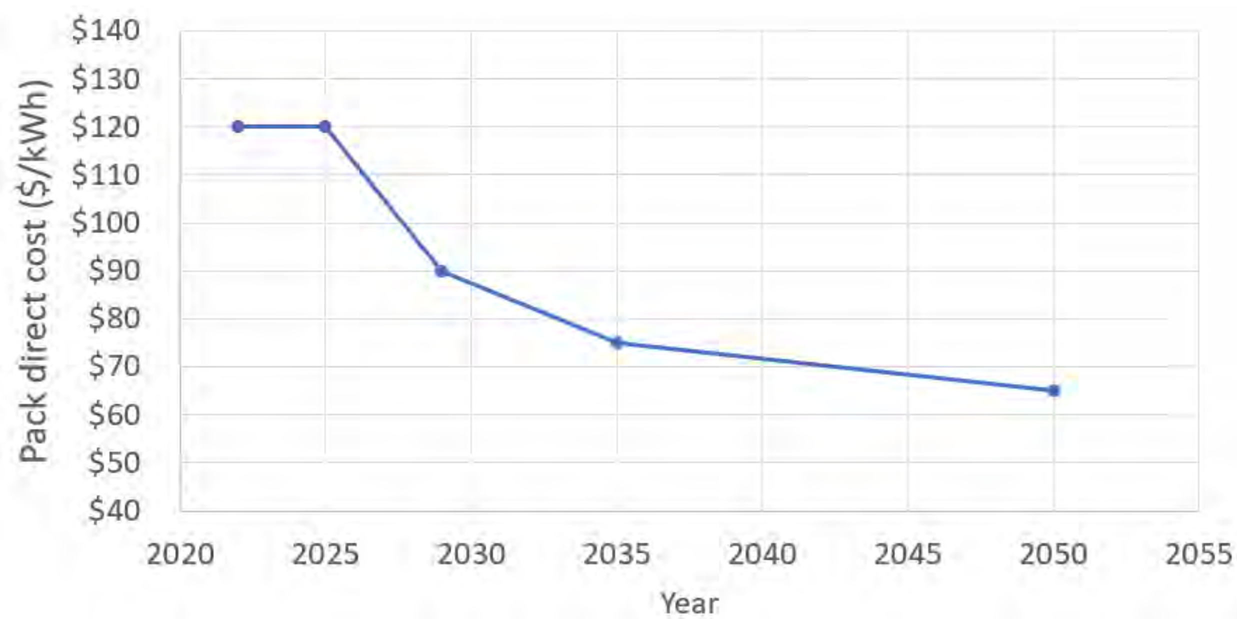

Figure 2-25. Reference trajectory of future battery pack manufacturing costs for a 75 kWh BEV pack

As stated previously, this reference trajectory was used only for qualitative comparison to the battery costs that are generated by OMEGA, which are dependent on a learning factor that is a function of the cumulative GWh of battery production in a given run of the model. Since the reference trajectory was developed using sources that predate the proposal, it is taken to represent approximate consensus views of where battery costs are considered likely to go in the absence of additional battery production resulting from the proposed standards.

As an example of how the pack direct manufacturing costs used in the analysis compare with the reference trajectory, Figure 2-25 shows the sales weighted average cost per kWh generated by OMEGA for the central case of the proposal, alongside the reference trajectory described above. Neither include the estimated impact of IRA 45X production tax credits for battery production, which are applied in a later step.[22] The Proposal costs compare quite favorably to the reference trajectory and vary generally as expected. From 2022 to 2025 they are somewhat lower, due to the substantially larger average pack size (96 kWh to nearly 100 kWh) compared to the 75 kWh of the reference trajectory. Past 2027, the Proposal costs are also lower than the reference trajectory, again due in part to the larger pack size, and increasingly, to the growing cumulative production volume due to the additional BEVs driven by the proposal.

[22] The impact of IRA 45X production tax credits on battery cost to manufacturers as modeled in OMEGA are developed and discussed in section 2.5.2.1.4.

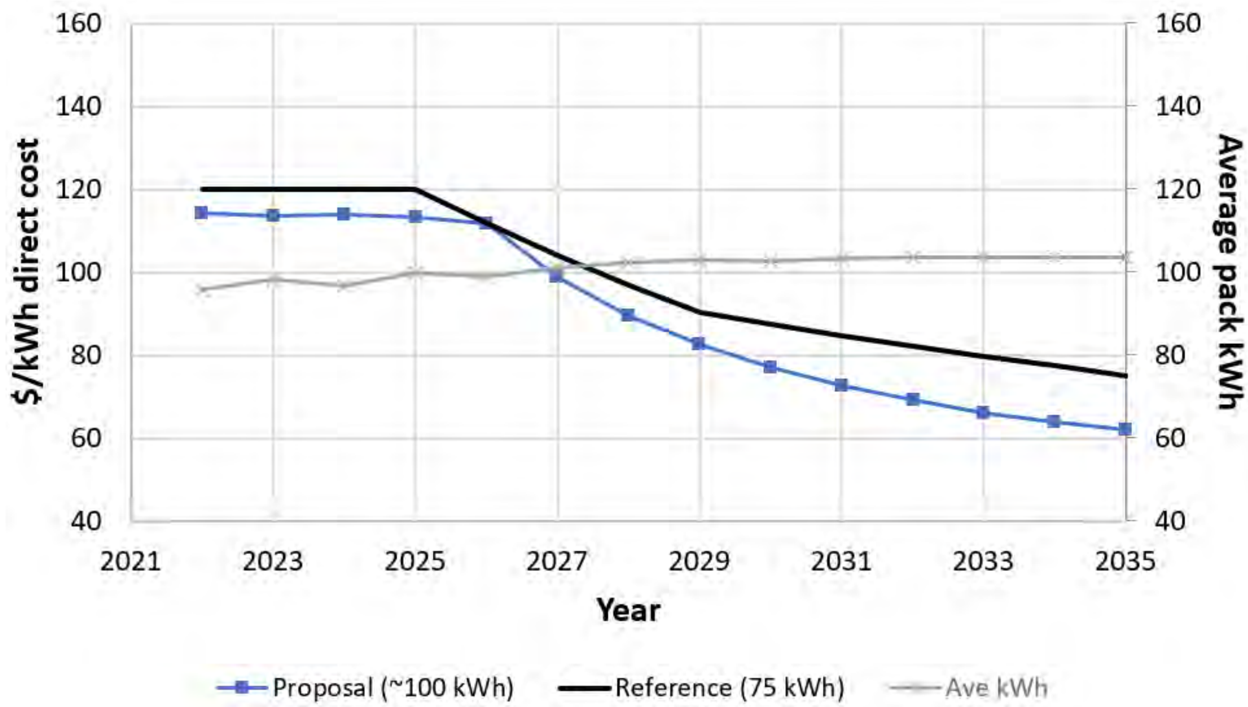

Figure 2-26: Example of pack direct manufacturing cost per kWh and average pack kWh generated by OMEGA

The 96 kWh to 103 kWh average pack capacity of the BEVs in the proposal is due in part to their use in relatively large vehicles, such as large SUVs and light trucks, which form a significant part of the OMEGA modeled compliance fleet and to which OMEGA directs a significant amount of electrification in its identification of a least cost compliance pathway. Another factor is the use of a 300-mile driving range for all light-duty BEVs and MDV pickup truck BEVs in the analysis, which is a longer average range than in some other studies, but which EPA believes is an appropriate modeling choice to reflect currently prevailing range expectations by consumers. For medium-duty van BEVs, we assumed a 150-mile range due to the predominant use of this vehicle type within commercial parcel delivery and comparable to currently available BEV MDV vans (see Chapter 3.1.2).

More discussion of the OMEGA model and the OMEGA results can be found in Preamble IV.C and elsewhere in this DRIA. For additional discussion of the battery costing method and sources considered, and a comparison between the battery costs derived in this analysis and those of the 2021 final rule analysis, please see Preamble § IV.C.2.

For additional discussion of the battery costing method and sources considered, and a comparison between the battery costs derived in this analysis and those of the 2021 final rule analysis, please see Preamble § IV.C.2.

2.5.2.1.4 Battery cost reductions due to Inflation Reduction Act

To reflect the anticipated effect of the Inflation Reduction Act on battery costs to manufacturers, we applied a further cost reduction based on the Section 45X Advanced

Manufacturing Production Tax Credit. This provision of the IRA provides a $35 per kWh tax credit for manufacturers of battery cells, and an additional $10 per kWh for manufacturers of battery modules, as well as 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 (all applicable to manufacture in the United States). The credits, with the exception of the critical minerals credit, phase out from 2030 to 2032.

We estimated that, across the PEV industry as a whole, the capability of manufacturers to take advantage of the $35 cell credit and the $10 module credit would ramp up over time, as new U.S. battery manufacturing facilities come on line, allowing manufacturing to increasingly take place in the U.S. We ramped the modeling value of the credit linearly from 60 percent of total cells and modules in 2023 (a conservative estimate of the current percentage of U.S.-based battery and cell manufacturing likely to be eligible today for the credit)[23] to 100 percent utilization in 2027, and then ramping down by 25 percent per year as the law phases out the credit from 2030 (75 percent) through 2033 (zero percent). Although a large percentage of 2023 U.S. BEV battery and cell manufacturing is represented by the production of one OEM, we believe that the many large U.S. battery production facilities that are being actively developed by suppliers and other OEMs (as described in IV.C.6 of the Preamble) will allow benefit of the credit to be accessible to all manufacturers by 2027. We also note that the high value of the credit provides a strong motivation for manufacturers to utilize it. For the purpose of modeling, the percentages above represent an average credit amount across the industry as a whole. Although some manufacturers and vehicles may realize the full value of the credit in any given year, the model requires an average value across the full market.

Figure 2-26 shows an example of the resulting effect on average pack direct manufacturing costs (DMC) generated by OMEGA in the central case of the proposal, after application of the 45X credit. The 45X cell and module credits per kWh were applied not to the direct manufacturing cost per kWh, but to the marked-up cost per kWh (that is, after multiplying the direct manufacturing cost by the 1.5 retail price equivalent (RPE)). 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, we felt that it was most appropriate to apply the 45X credit to the marked-up cost.. The 45X cell and module credits per kWh were applied by first marking up the direct manufacturing cost by the 1.5 RPE factor to determine the indirect cost (i.e., 50 percent of the manufacturing cost), then deducting the credit amount from the marked-up cost to create a post-credit marked-up cost. The post-credit direct manufacturing cost would then become the post-credit marked-up cost minus the indirect cost.

[23] U.S. Department of Energy, "FOTW #1192, June 28, 2021: Most U.S. Light-Duty Plug-In Electric Vehicle Battery Cells and Packs Produced Domestically from 2018 to 2020," June 28, 2021. https://www.energy.gov/eere/vehicles/articles/fotw-1192-june-28-2021-most-us-light-duty-plug-electric-vehicle-battery

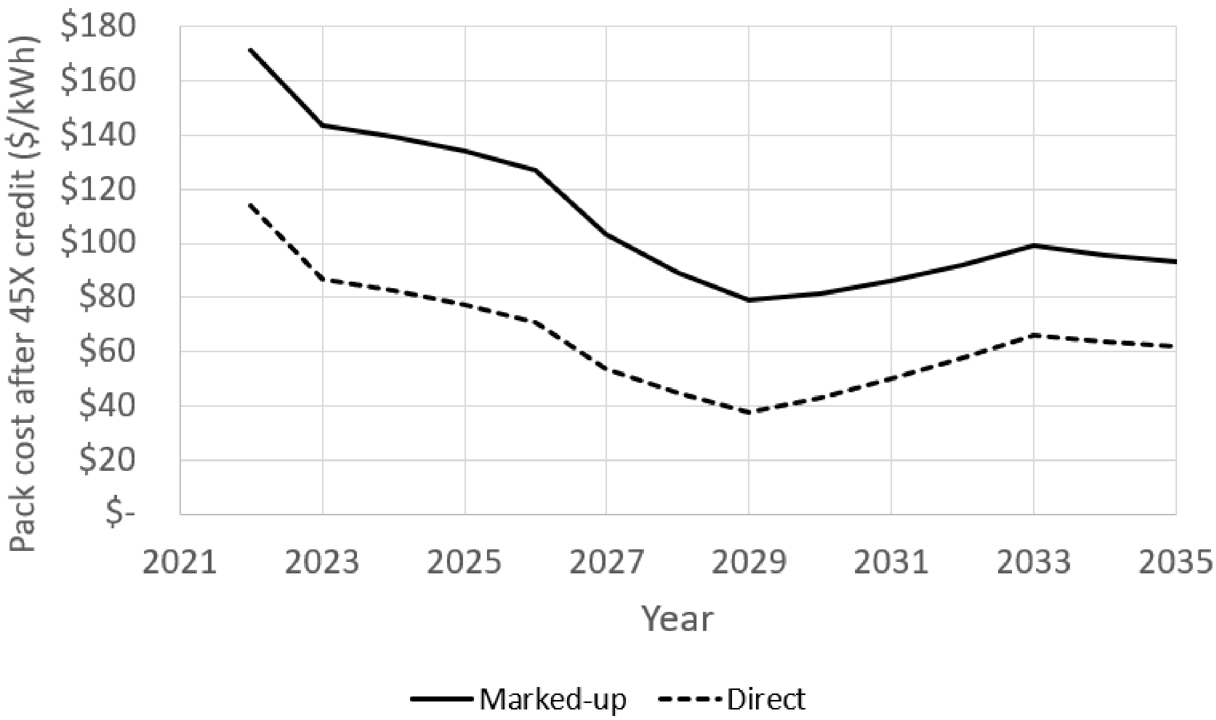

Figure 2-27: Volume weighted average pack direct manufacturing cost and marked-up cost per kWh after application of 45X credit

EPA did not apply a further cost reduction to represent the 10 percent electrode active material or critical mineral production credit, which are also available to be utilized by manufacturers. These credits are likely to have a substantial impact on reducing battery costs, and their exclusion from the currently modeled cost estimates represents a conservative assumption. The implementation of battery costs as OMEGA inputs are provided in 2.6.1.3.1.

2.5.2.2 BEV Non-Battery Cost Approach

EPA updated the non-battery powertrain costs that were used to determine the direct manufacturing cost of electrified powertrains. We referred to a variety of industry and academic sources, focusing primarily on teardowns of components and vehicles conducted by leading engineering firms (described in the rest of this section). The equations used in OMEGA for the non-battery electrified vehicle cost estimates used in the proposal may be found in 2.6.1.3.2.

2.5.2.2.1 Use of teardown studies

While EPA relies on a variety of sources to establish direct manufacturing costs for vehicle components, we have long considered teardown studies to be the preferred means for doing so. EPA has previously estimated non-battery costs by commissioning teardown studies of early-stage EV technologies. For past rulemakings we contracted with FEV North America to conduct teardowns of electrified vehicle components that were available at the time in order to establish direct manufacturing costs under high-volume production in a rigorous and transparent way.

Since then, the ongoing evolution of electrified vehicles has led to the emergence of improved or entirely new components that benefit from improved manufacturing efficiencies, component integration, and platform optimization. These developments call for significant updates to the way we characterized and quantified vehicle costs in the past. In some cases, specific components that we costed in the past may have become integrated with other components, or their design has changed so they use less costly materials or can be manufactured in a more efficient way. The vehicle platforms that incorporate these components may also have changed to optimize their integration with the rest of the vehicle.

Third-party teardowns of vehicles and components have also become more widely available from a number of engineering firms. EPA has acquired several of these studies to inform these changes and to represent the manufacturing cost of today's electrified vehicle components as accurately as possible. We have also conducted a new full-vehicle teardown of two new vehicles with FEV North America.

2.5.2.2.2 Munro and Associates teardowns

EPA purchased a set of vehicle and component teardown reports from Munro & Associates (Munro and Associates 2020a) (Munro and Associates 2021) (Munro and Associates 2020b) (Munro and Associates 2016) (Munro and Associates 2020c) (Munro and Associates 2018) to provide a new source of detailed cost data and to become more familiar with recent trends in component design and integration. EPA worked jointly with CARB to analyze the data in these reports to help inform our updated costs. The teardowns purchased from Munro are shown in Table 2-26.

Table 2-25: Munro Teardown Reports Used in the Analysis

Report	Technologies covered
12 motor side by side analysis	Model 3 front, Model 3 rear Model Y front, Model Y rear BMW i3, Chevy Bolt, Chevy Volt, Toyota Prius 2019 Jaguar I-PACE 2019 Audi e-tron front, 2019 Audi e-tron rear 2020 Nissan Leaf
6 inverter side by side analysis	Nissan Leaf Model 3 rear 2019 Jaguar I-PACE Audi e-tron Model Y front, Model Y rear
Model 3 report	Entire vehicle: Body and chassis, Electronics, Interior/Safety, Powertrain, Battery
Model Y report	Entire vehicle: Body and chassis, Electronics, Interior/Safety, Powertrain, Battery

Among these vehicles, we concluded that the components in the Tesla Model 3 and Model Y were most representative for the cost analysis because they are most likely to represent current and future capability and have potential for further improvement. Although components from a single manufacturer may be unique to that manufacturer's practices and intellectual property, in a competitive environment it is not likely to prevent other OEMs from achieving similar levels of integration and optimization. Additionally, the Tesla teardowns were costed by Munro at a consistent and large annual production volume of 200,000 to 250,000 units, whereas some of the other studies represented a lower volume that is not likely to represent future trends under the higher penetration of BEVs anticipated by the proposed rule. Costs were summarized on either a dollar per kW basis or a fixed cost basis, as applicable, and combined with cost estimates from other sources.

2.5.2.2.3 EPA-FEV comparative BEV-ICE vehicle teardown

We have also conducted a new full-vehicle teardown of two new vehicles with FEV North America (FEV Consulting Inc. 2022). We tore down a 2021 Volkswagen ID.4 BEV and a 2021 Volkswagen Tiguan, an ICE vehicle relatively equivalent to the ID.4 in size and function.

This project was initiated in part due to the realization that platform optimization is likely to affect a variety of cost comparisons between ICE and BEV vehicles. For example, platform optimization, particularly for BEVs, could potentially lead to differences in indirect costs that are experienced by the manufacturer (such as assembly cost, certification cost, and calibration cost). We also considered that the differences between a platform-optimized BEV and a platform-optimized ICE vehicle might call for an absolute costing approach, instead of assuming that a BEV can be costed as an ICE vehicle with ICE components removed and BEV components added.

The study was therefore designed not only to provide an additional source for vehicle component cost data, but also to inform several issues that are commonly cited with regard to the difference in cost between conventional and battery electric vehicles. Because ICE vehicles and BEVs are likely to be built on different dedicated platforms, the study was designed as a ground-up study for which a complete costed bill of materials would be developed for every component of each vehicle, including structural and other non-powertrain components. This would support our intention to move to a costing regime based on absolute vehicle costs instead of relative or incremental costs (as previously described in 2.5.1), and to allow comparisons to be made on a vehicle-system basis to identify significant potential cost efficiencies attributable to a dedicated BEV platform. FEV was also asked to comment on potential differences in indirect costs for BEV design, certification, and calibration that might become apparent on a close inspection of the components, their system integration, and their assembly characteristics. We also specified that a detailed labor assessment be performed for each component, in order to shed light on differences in amount and type of assembly labor required for production. An additional task under this work assignment was to evaluate the non-battery HEV and PEV costs EPA has described under section 2.6.1 of this DRIA, with respect to the cost values used and the method of scaling these costs across different vehicle performance characteristics and vehicle classes. Delivery of the teardown study results by FEV was completed in February 2023 and a peer review is planned to be completed in mid-2023. The FEV review of non-battery costs and scaling is available in a memo to the Docket entitled "EV Non-Battery Cost Review by FEV." In developing the costs used in this proposal, we have considered qualitative information gained thus far in conducting this project, and we expect to incorporate more information from the study in the final rule analysis.

2.5.2.2.4 Other teardowns

We also incorporated data from a 2017 UBS teardown of the Chevy Bolt EV (UBS AG 2017), and a 2018 teardown study of several EV components performed for CARB by Ricardo (Ricardo Strategic Consulting and Munro and Associates 2017).

UBS is a global financial services company originally from Switzerland and is one of the largest in the world. UBS contracted Munro & Associates to tear down a Chevy Bolt EV to better understand the profitability of 200+ mile EVs, particularly the Tesla Model 3. Because the teardown analysis was contracted to Munro & Associates, this suggests that the costs derived in the study are comparable to those of the Munro reports that EPA purchased, as well as the Ricardo teardown studies performed for CARB, which was subcontracted also to Munro & Associates.

Since it was released, the UBS study has become a widely cited resource across the industry, as it was one of the first publicly accessible teardowns to provide individual component costs that were well documented and derived from what was a state-of-the-art vehicle at the time. The study also provided valuable insight into the breakdown of battery costs for this vehicle and related its content to the outlook for raw materials markets.

Also in 2017, CARB published a teardown of selected power electronics and thermal systems in a report titled "Advanced Strong Hybrid and Plug-In Hybrid Engineering Evaluation and Cost Analysis." (Ricardo Strategic Consulting and Munro and Associates 2017). The selected components were identified as representing the state-of-the-art for production vehicles at the time, and included two electric machines (one from the Toyota Prius and one from the Chevy Volt), two inverter modules (one from the Prius and one from Audi), and one DC-DC converter from the Ford Fusion. As with the UBS teardown, this teardown was subcontracted by Ricardo to Munro & Associates.

2.5.2.2.5 Published and other sources

The NAS Phase 3 report was published in 2021 (National Academies of Sciences, Engineering, and Medicine 2021). This report included cost estimates for various electric vehicle components including batteries and non-battery components, derived from a survey of a number of quantitative sources in the literature, combined with a qualitative assessment of their validity. The sources cited by NAS had significant overlap with the sources EPA used in its analysis, including reference to a presentation to NAS by Munro and Associates, as well as the 2017 UBS teardown and other sources. Accordingly, the costs in the NAS report were quite similar to those that were ultimately used in the EPA analysis. In some cases, the costs we used differ from the costs cited by NAS, largely because EPA had access to a larger diversity of teardown reports, some of which were not available to NAS at the time of their research.

In 2021 and 2022, CARB developed ZEV component costs for use in their ACC II program, and ultimately published two versions of a ZEV costing workbook (California Air Resources Board 2022) and invited public comment on the costs it reported. When EPA developed its cost estimates, CARB staff worked jointly with EPA to analyze the teardown data and much of this work was reflected in CARB's costs. Owing to the differences between specific goals of the CARB ACC II cost analysis and that of EPA, some costs in the CARB workbook were developed differently to reflect differences in vehicle configuration or performance expectations resulting from the specific regional focus and regulatory environment of the CARB program. In general, the costs used by EPA and those within the CARB workbook are in good alignment.

In October 2022, ICCT released a report (Slowik, et al. 2022) that included an analysis of future EV component and battery costs. As with many third-party studies, the ICCT report differs from the EPA analysis in certain aspects of its approach and assumptions. In general, the costs EPA developed are not inconsistent with the costs assumed by ICCT.

2.5.3 Approach to cost reduction through manufacturer learning

Within OMEGA, learning factors are applied to technology costs as shown in Table 2-27. These learning factors were generated with the expectation that learning on ICE body structure technologies would slow, relative to their traditional rates, in favor of a focus on BEV technologies.

Importantly, the learning factors shown are multiplicative scaling factors indexed to 2022. The costs presented below in Chapter 2.6 represent first year costs and the learning factors shown in Table 2-27 are applied to those first-year costs to arrive at costs for subsequent years.

Learning was applied to BEV and HEV battery costs by dynamic application of a cumulative GWh-based learning equation that was described in Section 2.5.2.1.3.

Table 2-26 Learning Factors Applied in OMEGA, Indexed to 2022[a]

Model Year	ICE Powertrain & Glider Costs	BEV Non-Battery Costs
2022	1.00	1.00
2023	1.00	0.86
2024	0.99	0.79
2025	0.99	0.74
2026	0.99	0.70
2027	0.98	0.67
2028	0.98	0.65
2029	0.98	0.63
2030	0.97	0.61
2031	0.97	0.59
2032	0.97	0.58
2033	0.96	0.57
2034	0.96	0.56
2035	0.96	0.55
2036	0.95	0.54
2037	0.95	0.53
2038	0.95	0.52
2039	0.95	0.51
2040	0.94	0.51
2041	0.94	0.50
2042	0.94	0.50
2043	0.94	0.49
2044	0.93	0.49
2045	0.93	0.48
2046	0.93	0.48
2047	0.92	0.47
2048	0.92	0.47
2049	0.92	0.46
2050	0.92	0.46
2051	0.92	0.45
2052	0.91	0.45
2053	0.91	0.45
2054	0.91	0.44
2055	0.91	0.44

[a]Learning factors are indexed to 2022.

2.5.4 Indirect costs

To produce a unit of output, vehicle manufacturers incur direct and indirect costs. Direct costs include cost of materials and labor costs. Indirect costs are all the costs associated with producing the unit of output that are not direct costs – for example, they may be related to production (such as research and development, R&D), corporate operations (such as salaries, pensions, and health care costs for corporate staff), or selling (such as transportation, dealer support, and marketing). Indirect costs are generally recovered by allocating a share of the costs to each unit of good sold. Although it is possible to account for direct costs allocated to each unit of good sold, it is more challenging to account for indirect costs allocated to a unit of goods sold. To make a cost analysis process more feasible, markup factors, which relate total indirect costs to total direct costs, have been developed. These factors are often referred to as a retail price equivalent (RPE) markup.

EPA has frequently used cost multipliers to predict the resultant impact on costs associated with manufacturers' responses to regulatory requirements. The best approach, if it were possible, to determining the impact of changes in direct manufacturing costs on a manufacturer's indirect costs would be to estimate the cost impact on each indirect cost element. However, doing this within the constraints of an agency's time or budget is not always feasible, or the technical, financial, and accounting information to carry out such an analysis may simply be unavailable.

The RPE multiplier, or RPE markup factor, is based on an examination of historical financial data contained in 10-K reports filed by manufacturers with the Securities and Exchange Commission. It represents the ratio between the retail price of motor vehicles and the direct costs of all activities that manufacturers engage in. The RPE markup provides, at an aggregate level, the relative shares of revenues (Revenue = Direct Costs + Indirect Costs + Net Income) to direct manufacturing costs as shown in Table 2-28. Using the RPE markup implicitly assumes that incremental changes in direct manufacturing costs produce common incremental changes in all indirect cost contributors as well as net income. However, a concern in using the RPE markup in cost analysis for new technologies added in response to regulatory requirements is that the indirect costs of vehicle modifications are not likely to be the same for different technologies. For example, less complex technologies could require fewer R&D efforts or less warranty coverage than more complex technologies. In addition, some simple technological adjustments may, for example, have no effect on the number of corporate personnel and the indirect costs attributable to those personnel. The use of a single RPE markup, with its assumption that all technologies have the same proportion of indirect costs, is likely to overestimate the costs of less complex technologies and underestimate the costs of more complex technologies.

Table 2-27 Retail Price Equivalent Factors in the Heavy-Duty and Light-Duty Industries (Rogozhin 2009)

Cost Contributor	Contribution to Cost
Direct manufacturing cost	1.0
Warranty	0.03
R&D	0.05
Other (administrative, retirement, health, etc.)	0.36
Profit (cost of capital)	0.06
Retail price equivalent	1.50

To address this concern, modified multipliers were developed by EPA, working with a contractor, for use in past EPA rulemakings. (Rogozhin 2009) Those modified multipliers were referred to Indirect Cost Multipliers, or ICMs, and EPA applied low magnitude ICMs (i.e., <the 1.5 RPE) to low complexity technologies and high magnitude ICMs (i.e., >the 1.5 RPE) to high complexity technologies. This way, we could analyze the possible pathways toward compliance with GHG regulations via, for example, application of many low complexity technologies versus few high complexity technologies. In other words, we could weigh one technology against another in a more finely tuned way.

The ICM approach served us well when dealing with incremental technology applications and incremental costs for those technologies as was done in the 2010 and 2012 final rules (75 FR 25324 2010, 77 FR 62624 2012). However, as noted above, we no longer use that approach to estimating compliance pathways. In contrast, since we now consider the whole vehicle and its total cost and performance toward compliance, we no longer need the fine tuning of one technology versus another that the ICM approach provided. As a result, for this analysis, we are using the full RPE markup as the indirect cost markup as we did in our 2021 final rule (86 FR 74434 2021).

2.6 Inputs and Assumptions for Compliance Modeling

2.6.1 Powertrain Costs

2.6.1.1 ICE Powertrain Costs

Table 2-28 shows the ICE -specific powertrain costs used as inputs to OMEGA. Note that hybrid electric vehicles (HEV) and mild HEVs are treated as ICE vehicles when calculating these powertrain costs.

Table 2-28: ICE Powertrain Cost in OMEGA

Item	Cost Curve (Note: Markup = 1.5)	Dollar Basis	Note	Example system cost (6CYL, 3L, 4000 lb CW, size class 3)
Cylinders	(-28.814 * CYL + 726.27) * CYL * Markup	2019	CYL=# of cylinders	$4,980
Displacement	400 * LITERS * Markup	2019	LITERS=engine displacement	$1,800
Gasoline Direct Injection (GDI)	(43.237 * CYL + 97.35) * Markup	2019	CYL=# of cylinders	$535
turb11	(-13.149 * CYL^2 + 220.34 * CYL - 124.73) * Markup	2012	Turbocharging with boost ~18 bar	$1,086
turb12	(-13.149 * CYL^2 + 220.34 * CYL - 124.73) * Markup	2012	Turbocharging with boost ~24 bar	$1,086
Cooled EGR	114 * Markup	2012		$171
Deac (Partial, Discrete)	(-1.0603 * CYL^2 + 28.92 * CYL - 8.6935) * Markup	2006	Deac=cylinder deactivation	$190
Deac (Full, Continuous)	154 * Markup	2017		$231
atk2	(4.907 * CYL^2 - 29.957 * CYL + 130.18) * Markup	2010	atk2=Atkinson cycle engine	$191
TRX10	1390.20 * Markup	2018	TRX=transmission	$2,085
TRX11	1431.20 * Markup	2018		$2,147
TRX12	1653.20 * Markup	2018		$2,480
TRX21	1568.20 * Markup	2018		$2,352
TRX22	1791.20 * Markup	2018		$2,687
TRXCV	1000 * Markup	2019	TRXCV=HEV transmission	$1,500
High efficiency alternator	150 * Markup	2015		$225
Start stop	(0.0149 * CURBWT + 276.82) * Markup	2015		$505
TWC substrate	(6.108 * LITERS * TWC_SWEPT_VOLUME + 1.95456) * Markup	2012	TWC=3way catalyst; TWC swept volume=1.2	$36
TWC washcoat	(5.09 * LITERS * TWC_SWEPT_VOLUME) * Markup	2012		$27
TWC canning	(2.4432 * LITERS * TWC_SWEPT_VOLUME) * Markup	2012		$13
TWC swept volume	1.2 multiplier applied to engine displacement			
TWC Pt grams/liter	0			
TWC Pd grams/liter	2			
TWC Rh grams/liter	0.11			
GPF	(14.1940 * LITERS + 39.2867) * Markup	2021	GPF=gasoline particulate filter	$123
TWC PGM	(PT_GRAMS_PER_LITER_TWC * LITERS * TWC_SWEPT_VOLUME * PT_USD_PER_OZ * OZ_PER_GRAM + PD_GRAMS_PER_LITER_TWC * LITERS * TWC_SWEPT_VOLUME * PD_USD_PER_OZ * OZ_PER_GRAM + RH_GRAMS_PER_LITER_TWC * LITERS * TWC_SWEPT_VOLUME * RH_USD_PER_OZ * OZ_PER_GRAM) * Markup		PGM=Platinum group metals (e.g., Pt, Pd, Rh)	$1,155
Troy oz/gram	0.0322			Values are used in the TWC PGM calculation
PT_USD_PER_OZ	1030		USD=US dollars; OZ=Troy ounce	
PD USD PER OZ	2331			
RH USD PER OZ	17981			
Diesel exhaust aftertreatment system	700 * LITERS * Markup	2020	LITERS=engine displacement	$3,150
LV battery	(3 * VEHICLE_SIZE_CLASS + 51) * Markup	2019	LV=low voltage	$90
HVAC	(11.5 * VEHICLE_SIZE_CLASS + 195.5) * Markup	2019		$345
turb_scaler	1.2 multiplier applied to ($Cylinders + $Displacement)			1.2 * ($4,980+$1,800)=$8,136

Diesel engine cost scaler	1.5 multiplier applied to 1.2 * ($Cylinders + $Displacement)			1.5 * 1.2 * ($4,980+$1,800)=$12,204
Markup	1.5		The RPE markup factor to account for indirect costs	

2.6.1.1.1 Cost per cylinder and cost per liter

The most basic piece of ICE powertrain technology is the engine. OMEGA considers the basic engine cost as a group of cylinders and mass of material (steel, aluminum). As such the engine costs are estimated based on the number of cylinders and the displacement of the engine as shown below.

The OMEGA direct manufacturing cost (DMC) per cylinder and DMC per liter curve is based on the values shown in Table 2-30.

Table 2-29: Cost per Cylinder and Cost per Liter in OMEGA

Item	DMC	Dollar Basis
$/cylinder, 8 cylinder engine	500	2019
$/cylinder, 6 cylinder engine	550	2019
$/cylinder, 4 cylinder engine	600	2019
$/cylinder, 3 cylinder engine	650	2019
$/liter, all engines	400	2019

Using these values, the following cost curves were generated for use in OMEGA.

$$CylinderCost = (-28.814 \times CYL + 726.27) \times CYL \times Markup$$

$$DisplacementCost = 400 \times LITERS \times Markup$$

Where,

CYL = the number of cylinders on the engine

LITERS = the total displacement of the engine

Markup = the markup to cover indirect costs

2.6.1.1.2 Gasoline Direct Injection

The costs for gasoline direct injection (GDI) are based on costs used in past EPA analyses. Those costs are shown in Table 2-30.

Table 2-30: Gasoline Direct Injection System Cost in OMEGA

Item	DMC	Dollar Basis
GDI, 3 cylinder engine	244	2012
GDI, 4 cylinder engine	244	2012
GDI, 6 cylinder engine	368	2012
GDI, 8 cylinder engine	442	2012

Using these values, the following cost curve was generated for use in OMEGA.

$$GasolineDirectInjection = (43.237 \times CYL + 97.35) \times Markup$$

Where,

CYL = the number of cylinders on the engine

Markup = the markup to cover indirect costs

2.6.1.1.3 Turbocharging

OMEGA estimates two levels of turbocharging, although the costs are identical for both. These costs are based on past EPA analyses as shown in Table 2-31.

Table 2-31: Turbocharging Costs in OMEGA

Item	DMC	Dollar Basis
TURB11, 3 cylinder engine	463	2012
TURB11, 4 cylinder engine	463	2012
TURB11, 6 cylinder engine	780	2012
TURB11, 8 cylinder engine	780	2012
TURB12, 3 cylinder engine	463	2012
TURB12, 4 cylinder engine	463	2012
TURB12, 6 cylinder engine	780	2012
TURB12, 8 cylinder engine	780	2012

Using these values, the following cost curve was generated for use in OMEGA.

$$TURB11 = TURB12 = (-13.149 \times CYL^2 + 220.34 \times CYL - 124.73) \times Markup$$

Where,

CYL = the number of cylinders on the engine

Markup = the markup to cover indirect costs

In addition, any turbocharged engine includes a turbo scaler of 1.2 applied to the cylinder and displacement costs described above.

$$TurboEngineCost = 1.2 \times (CylinderCost + DisplacementCost) + TURB$$

Where,

CylinderCost = costs determined by the CylinderCost equation above

DisplacementCost = costs determined by the DisplacementCost equation above

TURB = the cost of TURB11 or TURB12 as appropriate

1.2 = the turbo scaler to account for more robustness in the turbocharged engine

2.6.1.1.4 Cooled Exhaust Gas Recirculation

The cost of cooled exhaust gas recirculation (CEGR) is based on past EPA analysis and is calculated in OMEGA as below.

$$CooledEGR = 114 \times Markup$$

Where,

Markup = the markup to cover indirect costs

2.6.1.1.5 Cylinder Deactivation

The costs of cylinder deactivation are based on past EPA analyses as shown in Table 2-32.

Table 2-32: Cylinder Deactivation Costs in OMEGA

Item	DMC	Dollar Basis
Partial discrete, 3 cylinder engine	76	2006
Partial discrete, 4 cylinder engine	76	2006
Partial discrete, 6 cylinder engine	136	2006
Partial discrete, 8 cylinder engine	152	2006
Full continuous, all engines	154	2017

Using these values, the following cost curves were generated for use in OMEGA.

$$Deac_{PD} = (-1.0603 \times CYL^2 + 28.92 \times CYL - 8.6935) \times Markup$$
$$Deac_{FC} = 154 \times Markup$$

Where,

CYL = the number of cylinders on the engine

Markup = the markup to cover indirect costs

2.6.1.1.6 Atkinson Cycle Engine

The costs for Atkinson cycle engine (ATK) are based on costs used in past EPA analyses. Those costs are shown in Table 2-33.

Table 2-33: Atkinson Cycle Engine Costs in OMEGA

Item	DMC	Dollar Basis
ATK, 3 cylinder engine	86	2010
ATK, 4 cylinder engine	86	2010
ATK, 6 cylinder engine	129	2010
ATK, 8 cylinder engine	204	2010

Using these values, the following cost curves were generated for use in OMEGA.

$$AtkinsonCycleEngine = (4.907 \times CYL^2 - 29.957 \times CYL + 130.18) \times Markup$$

Where,

CYL = the number of cylinders on the engine

Markup = the markup to cover indirect costs

2.6.1.1.7 Transmissions

Transmission costs are based on past EPA analysis, with the addition of an estimated cost for a base or null transmission, loosely defined as a 5-speed automatic transmission with no efficiency or shift improvement upgrades. Those costs are shown in Table 2-34. Note that the null transmission is not shown in Table 2-34 since OMEGA does not apply it, but it is needed since the past EPA transmission costs were relative to that null transmission. EPA has estimated that null transmission as costing $800 (direct manufacturing cost in 2012 dollars).

Table 2-34: Transmission Costs in OMEGA

Item	DMC	Dollar Basis
TRX11, front/rear wheel drive	841	2012
TRX12, front/rear wheel drive	1063	2012
TRX21, front/rear wheel drive	978	2012
TRX22, front/rear wheel drive	1201	2012
TRX11, all/4 wheel drive	1009	2012
TRX12, all/4 wheel drive	1276	2012
TRX21, all/4 wheel drive	1174	2012
TRX22, all/4 wheel drive	1441	2012
TRXCV, for Powersplit HEV	1000	2019

These costs are used as-is in OMEGA other than OMEGA's application of the markup to account for indirect costs.

2.6.1.1.8 High Efficiency Alternator

OMEGA's high efficiency alternator cost is based on past EPA analyses and is calculated according to the equation shown below.

$$HighEfficiencyAlternator = 150 \times Markup$$

Where,

Markup = the markup to cover indirect costs

2.6.1.1.9 Start-Stop

The costs of start-stop systems are based on past EPA analyses as shown in Table 2-35.

Table 2-35: Start-stop System Costs in OMEGA

Curb Weight	DMC	Dollar Basis
<=3800	321	2015
3800<curb weight<=4800	364	2015
Curb weight<=8500	400	2015

Using these values, the following cost curve was generated for use in OMEGA.

$$StartStop = (0.0149 \times CURBWT + 276.82) \times Markup$$

Where,

CURBWT = the curb weight, in pounds, of the vehicle

Markup = the markup to cover indirect costs

2.6.1.1.10 Gasoline Particulate Filter

The gasoline particulate filter (GPF) cost is a new cost for this analysis. This is described in detail in Chapter 3.2.2. The cost curve used in OMEGA is shown below. Note that the GPF costs are applied only in the action case if GPFs are expected for compliance with new gasoline PM standards.

$$GPF = (14.194 \times LITERS + 39.2867) \times Markup$$

Where,

LITERS = the engine displacement in liters

Markup = the markup to cover indirect costs

2.6.1.1.11 Three-way Catalyst

OMEGA's three-way catalyst (TWC) costs are based largely on the approach used in the light-duty highway Tier 3 criteria pollutant rule. In the Tier 3 rule, EPA presented cost curves to estimate costs for the individual components of a TWC: the substrate; the washcoat; the canning; and, the platinum group metals (PGM, consisting of platinum (Pt), palladium (Pd) and rhodium (Rh)). The four cost curves are shown below.

$$TWC_{substrate} = (6.108 \times 1.2 \times LITERS + 1.955) \times Markup$$

$$TWC_{washcoat} = (5.09 \times 1.2 \times LITERS) \times Markup$$

$$TWC_{canning} = (2.4432 \times 1.2 \times LITERS) \times Markup$$

$$TWC_{PGM} = \left(Pt_{gpl} \times Pt_{\$/TroyOz} + Pd_{gpl} \times Pd_{\$/TroyOz} + Rh_{gpl} \times Rh_{\$/TroyOz}\right) \times 1.2 \times LITERS \times \frac{TroyOz}{gram}$$

Where,

LITERS = the engine displacement in liters

1.2 = factor to account for the swept volume of the TWC (i.e., total TWC volume is 1.2x engine displacement

Pt_{gpl} = Platinum grams/liter, set to 0 in this analysis

Pd_{gpl} = Palladium grams/liter, set to 2 in this analysis

Rh_{gpl} = Rhodium grams/liter, set to 0.11 in this analysis

$Pt_{\$/TroyOz}$ = Platinum cost per Troy ounce, set to \$1,030 in this analysis

$Pd_{\$/TroyOz}$ = Palladium cost per Troy ounce, set to \$2,331 in this analysis

$Rh_{\$/TroyOz}$ = Rhodium cost per Troy ounce, set to \$17,981 in this analysis

TroyOz = Troy ounces

TroyOz/gram = 0.0322, or 31.1 grams per Troy Oz

Markup = the markup to cover indirect costs

2.6.1.1.12 Diesel Exhaust Aftertreatment System

OMEGA's diesel exhaust aftertreatment system (diesel EAS) costs are structured for consistency with the recent heavy-duty final rule (88 FR 4296 2023). The cost curve is as shown below.

$$Diesel\ EAS = (700 \times LITERS) \times Markup$$

Where,

Diesel EAS = diesel exhaust aftertreatment system cost

LITERS = the engine displacement in liters

Markup = the markup to cover indirect costs

2.6.1.2 HEV-specific and Mild HEV-specific Powertrain Costs

Strong hybrid electric vehicle (HEV) and mild-HEV (MHEV) powertrain costs are broken into non-battery and battery costs. In addition to the costs presented here, the costs associated with ICE powertrains presented in 2.6.1.1 would also apply for HEVs and MHEVs. Note that, throughout this discussion, we use the term "HEV" to refer to a strong hybrid and mild HEV or MHEV to refer to a mild hybrid.

2.6.1.2.1 HEV and MHEV Non-Battery

HEV and MHEV non-battery costs are shown in Table 2-36.

Table 2-36: HEV & MHEV Non-Battery Costs in OMEGA

Item	Cost Curve (Note: Markup = 1.5)	Dollar Basis	Note	Example system cost (10 kW power, vehicle size class=3
Single motor	(6.91 * kW - 8.64) * Markup	2019		$89
Single Inverter	(2.4 * kW + 231) * Markup	2019		$383
DC-DC converter kW	3.5	2019		
Onboard charger & DC-DC converter	39.754 * DC-DC converter kW * Markup	2019	Onboard charger kW = 0 for HEV and MHEV	$209
High voltage orange cables	(9.5 * VehicleSizeClass + 161.5) * Markup_	2019		$285
Brake sensors & actuators	200 * Markup	2019		$300
Markup	1.5		The RPE markup to account for indirect costs	

2.6.1.2.2 HEV and MHEV Battery

OMEGA uses the HEV battery cost curve described in Chapter 2.5.2.1.2 and shown below. OMEGA uses this equation for both mild and strong HEVs.

$$HEV\ Battery = (936.1 \times kWh^{-0.802}) \times kWh \times Markup$$

Where,

kWh = the gross energy capacity of the battery in kilowatt hours

Markup = the markup to account for indirect costs

2.6.1.3 BEV Powertrain Costs

For this analysis, EPA updated the battery costs and non-battery powertrain costs that were used to determine the cost of electrified vehicles. The sources and methods for deriving these costs were described in section 2.5.2.

The following sections detail the specific electrification-related costs used in the analysis.

BEV-specific powertrain costs are broken into non-battery and battery costs.

2.6.1.3.1 BEV Battery

2.6.1.3.1.1 Battery cost estimation curve by kWh

As described previously in Section 2.5.2.1.2, for base year 2022 BEV battery costs, OMEGA employs the BEV battery cost curve for 250,000 packs per year shown below.

$$BEV\ Battery = 261.61 \times kWh^{-0.184} \times kWh \times Markup$$

Where,

kWh = the gross energy capacity of the battery in kilowatt hours

Markup = the markup to account for indirect costs shown in Table 2-37

2.6.1.3.2 BEV Non-Battery

EPA reviewed several recent teardown reports to develop direct manufacturing costs for permanent magnet synchronous motors (PMSMs) and for induction motors.

The primary sources we consulted to establish an estimate of base year electric machine costs included the 2017 UBS teardown of the Chevy Bolt, the CARB teardown performed by Ricardo, the Munro 12-motor teardown report, and the full-vehicle Munro teardown reports for the 2017 Tesla Model 3 Long Range RWD and the 2020 Tesla Model Y AWD Performance. The Munro reports are proprietary commercial products describing teardowns performed by Munro & Associates, copies of which EPA licensed to support its research.

The reports provided cost data points for a variety of PMSM and induction machines of various power ratings and a range of designs. As shown in Table 2-27, costs for several PMSM motors were available in these reports.

Table 2-37: PMSM Motors Described in Munro Reports

PMSM motors			kW
Tesla	2017	Model 3 LR RWD	192
Tesla	2020	Model Y AWD Perf - Rear	219
GM	2017	Chevy Bolt EV	150
BMW	2015	i3	125
Nissan	2019	Leaf	110
Jaguar	2019	i-Pace EV400 90 kWh AWD	147
GM	2016	Chevy Volt PHEV	41
Toyota	2016	Prius HEV	53

Of these, we focused on the Tesla components as best representing the state of the art for optimized, high-volume production of these devices, and compared them to several other examples. The cost breakdown for electric machines in these reports included only the rotor, stator, and shaft and did not include supporting parts such as the housing, resolver, and mounts which the reports costed separately. In order to develop a total motor cost per kW that includes these components, we took an average of the share of the cost of these parts and determined that the cost of the stator, rotor and shaft should be multiplied by 1.1 (PMSM) and 1.3 (induction) to represent the total cost.

By averaging the costs from the available sources that we considered to be the best examples of current technology, we arrived at a cost of $4.29 per kW for a PMSM electric machine, which represents the mean of the selected rotor/stator/shaft costs multiplied by 1.1 to account for the added cost of housing, resolver, and mounts.

For induction motors, costs for the following components were available in these reports (Table 2-38).

Table 2-38: Induction Motors Described in Munro Reports

Induction motors			kW
Tesla	2020	Model Y AWD Perf - Front	158
Tesla	2018	Model 3 PremLR AWD - Front	147
Audi	2019	Audi e-tron - Front	141
Audi	2019	Audi e-tron - Rear	172

By the same process we arrived at a cost of $2.40 per kW for an induction machine, which represents the mean of the selected rotor/stator/shaft costs, multiplied by 1.3 to add the cost of the housing, resolver, and mounts.

While developing these costs, EPA consulted informally with the Department of Energy Vehicle Technologies Office (DOE VTO) to compare the developing cost estimates with their perspectives on current and future cost expectations for EV components and to better interpret the existing USCAR cost targets for these components. With regard to the emerging cost estimates, they were seen as being consistent with general expectations between the consulting staff at the agencies. While some of the emerging costs for electric machines and various power electronics were somewhat higher than USCAR targets and others were lower, it was noted that the USCAR targets represent DOE's assessment of an attainable future cost at the time of their development in about 2017, and the fact that the merging costs were derived from teardown data from vehicles and components that were not available at the time would be expected to provide a reliable characterization of current day costs even if they deviated significantly from those targets.

2.6.1.3.2.1 Power electronics costs

EPA reviewed teardown reports to develop direct manufacturing costs for the major power electronics components that are found in BEVs and PHEVs. These include inverters used for the traction motor (two versions, one in silicon IGBT form and another in silicon carbide), onboard charger, DC fast charging circuit, power management and distribution module, and DCDC converter. This section also describes the cost assumed for high voltage wiring.

The primary sources for silicon IGBT inverter cost were the Munro teardown reports. We arrived at an averaged and rounded figure of $2.50 per kW for an IGBT inverter, based on these sources.

EPA also considered an inverter based on a silicon carbide (SiC) design. A SiC inverter currently has a higher cost compared to silicon IGBT designs, but offers a higher switching frequency, which allows the inverter to operate at a higher efficiency. This makes it a particularly good fit for an induction motor, which has lower efficiency in some operating regions than the more costly PMSM machine. Based on consideration of the information available in the Munro teardowns, we arrived at an approximate cost of $4 per kW for a SiC inverter, and selected this design in configurations that employ an induction machine. Based on verbal conversations with Munro, we expect that the cost could be reduced sufficiently in the next five years to be comparable with the IGBT design, and so we consider this estimate to be conservative.

2.6.1.3.2.2 Gearbox costs

The 2017 UBS teardown of the Chevy Bolt established a cost for its single speed gear reduction at $400. This figure was deemed consistent with the cost estimated by various Munro teardowns of other BEVs which varied slightly around this figure. We adopted a cost of $410 for this component.

2.6.1.3.2.3 AWD costs

AWD is typically achieved in a BEV by use of two or more traction motors, with at least one driving each axle. While a number of configurations are possible, the most common and cost effective was taken to be a configuration with an induction motor on the front and a PMSM on the rear, both having its own single-speed gear reduction. The cost difference to add AWD to a BEV with a PMSM already providing 2WD was thus taken to be the cost of a second motor (induction machine), a second inverter (SiC based to improve the efficiency of the induction motor), a second single-speed gear reduction, a second cooling loop to serve the second motor and inverter, and two additional half-shafts.

2.6.1.3.2.4 Summary of BEV non-battery costs

Costs for other non-battery components and subsystems were derived in a similar manner from the sources outlined above. The full set of BEV non-battery costs as implemented in OMEGA is shown in Table 2-40.

Table 2-39 BEV Non-battery Powertrain Costs in OMEGA

Item	Cost Curve (Note: Markup = 1.5)	Dollar Basis	Note	Example system cost (80 kWh battery, 150 kW power, vehicle size class=3
Single motor	(4.29 * kW) * Markup	2019		$965
Single Inverter	(2.5 * kW) * Markup	2019		$563
Dual Motor	(4.29 * kW/2) * Markup	2019		$483
Dual Inverter	(2.5 * kW/2) * Markup	2019		$282
Dual induction motor	(3.12 * kW/2) * Markup	2019		$351
Dual induction inverter	(4 * kW/2) * Markup	2019		$150
DC-DC converter kW	3.5	2019		
Onboard charger & DC-DC converter	39.754 * (OBC kW+DC-DC converter kW) * Markup	2019	Onboard charger kW: For battery kWh<70, OBC kW=7; For 70<kWh<100, OBC kW=11; For kWh>100, OBC kW=19	39.754*(11+3.5)*1.5=$865
High voltage orange cables	(9.5 * VehicleSizeClass + 161.5) * Markup_	2019		$285
Single speed gearbox	410 * Markup	2019		$615
Powertrain cooling box	300 * Markup	2019		$450
Dual single speed gearbox	410 * 2 * Markup	2019		$1,230
Dual powertrain cooling box	300 * 2 * Markup	2019		$900
Charging cord kit	200 * Markup	2019		$300
DC fast charge circuitry	160 * Markup	2019		$240
Power management & distribution	720 * Markup	2019		$1,080
Additional pair of half shafts	190 & Markup	2019		$285
Markup	1.5		The RPE markup to account for indirect costs	

2.6.1.4 PHEV Powertrain Costs

While EPA has not specifically modeled the adoption of plug-in hybrid electric vehicle (PHEV) architectures within the analysis for this proposal, the agency recognizes that PHEVs can provide significant reductions in GHG emissions and that some vehicle manufacturers may choose to utilize this technology as part of their technology offering portfolio in response to customer interests and in response to EPA emission standards. Some auto manufacturers are already doing so today. In order to potentially include an analysis of PHEVs for the final rule, EPA has developed powertrain costs for PHEV applications based primarily upon the costs developed for BEVs and HEVs in Chapter 2.6.1.3 and Chapter 2.6.1.2, respectively. PHEV-specific powertrain costs are subdivided into battery and non-battery costs. PHEV non-battery costs also include an ICE and a series/parallel hybrid transmission. The costs associated with ICE powertrains presented in 2.6.1.1 would also apply for PHEVs.

2.6.1.4.1 PHEV Battery Costs

As described in the Preamble (IV.C.1), EPA has not specifically modeled the adoption of plug-in hybrid electric vehicle (PHEV) architectures in the analysis for this proposal. However, as described in DRIA 2.5.2.1.2, we did develop battery cost estimates for PHEVs, which are described fully in that section.

EPA may rely upon those battery cost estimates and other information gathered in response to this proposal, and on EPA's on-going technical work, for estimating the battery costs for PHEVs for the final rule.

2.6.1.4.2 PHEV Non-Battery Costs

As described in the Preamble (IV.C.1), EPA has not specifically modeled the adoption of plug-in hybrid electric vehicle (PHEV) architectures in the analysis for this proposal. However, the agency recognizes that PHEVs can provide significant reductions in GHG emissions and that some vehicle manufacturers may choose to utilize this technology as part of their technology portfolio. As also described in Preamble IV.C.1, EPA has requested comment on the possibility of including modeling of PHEVs in the final rule analysis.

In general, EPA anticipates that modeling of PHEVs in the final rule analysis would utilize power electronic costs, P4 gearbox costs and AWD costs based upon the BEV non-battery costs presented in Chapter 2.6.1.3.2.

In addition, here we also present costs for a series/parallel hybrid transmission for PHEVs, consisting of:

- Motor-generator
- Starter-generator
- Clutch-pack to lock the ICE and starter generator to the motor generator for parallel operation

An example of such a series/parallel hybrid drive system for transverse front-drive applications is shown in Figure 2-25. Yamagishi and Ishikura provided a detailed description of application of a similar series/parallel drive system to the Honda Clarity PHEV (Yamagishi and Ishikura 2018). An application of this type of series/parallel drive to a front-engine/rear-drive application would require use of a drive shaft and separate, rear-mounted differential.

AWD vehicles include the cost of a series/parallel hybrid transmission with the addition of a P4 electric machine to either the front or rear depending on the application.

The full set of PHEV non-battery/non-ICE costs that could potentially be implemented in OMEGA in the final rule analysis is summarized in Table 2-40. An example of potential PHEV ICE costs is summarized in Table 2-41.

The specific example used within the tables is an LDT4 with OMEGA size-class 7 vehicle with:

- A combined electric drive system power of 240 kW
- A P4 induction machine for front axle electric-only drive
- A 3.0L Miller Cycle engine coupled to a series/parallel (S/P) drive single-speed transmission with a drive shaft and rear differential for rear axle drive

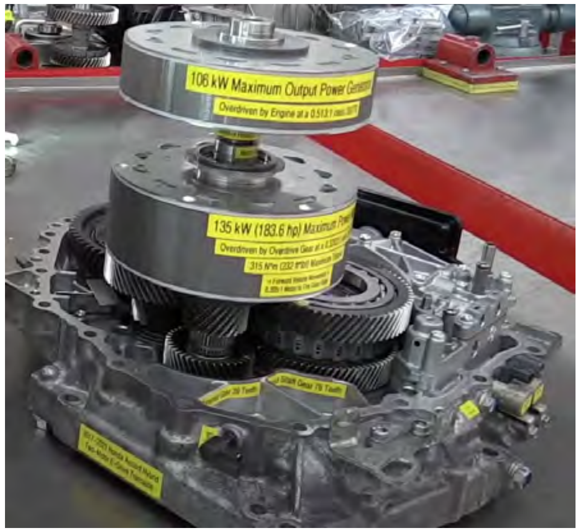

Figure 2-28: An example of a series/parallel hybrid drive system for a transverse/front-drive application with a portion of the outer casing and stators removed to show internal details. Adapted from a presentation by Prof. J.D. Kelly, Weber State University (Kelly 2020).

Table 2-40: Potential PHEV Non-battery/Non-ICE Powertrain Costs

Item	Cost Curve (Note: Markup = 1.5)	Dollar Basis	Note	Example system cost: (LDT4 PHEV, 33 kWh battery, 240 kW combined electric power, 3.0L Miller/CVVL/CEGR engine, 6200 lb CW, size class 7)
MGPM	(4.29 * 180kW) * Markup	2019		$1,158
MGPM IGBT Inverter	(2.5 * 180kW) * Markup	2019		$675
SGPM	(4.29 * 180kW) * Markup			$1,158
SGPM IGBT Inverter	(2.5 * 180kW) * Markup			$675
P4-MGinduction	(3.12 * 60kW) * Markup	2019		$281
P4-MGinduction SiC Inverter	(4 * 60kW) * Markup	2019		$360
DC-DC converter kW	3.5	2019		
Onboard charger & DC-DC converter	39.754 * (OBC kW+DC-DC converter kW) * Markup	2019	Onboard charger kW: For battery kWh<70, OBC kW=7; For 70<kWh<100, OBC kW=11; For kWh>100, OBC kW=19	39.754*(7+3.5)*1.5=$626
High voltage orange cables	(9.5 * VehicleSizeClass + 161.5) * Markup_	2019		$342
S/P transmission	600 * Markup	2019		$900
Driveshaft and differential	200 * Markup	2019		$300
P4 single speed gearbox	410 * Markup	2019		$615
Dual powertrain cooling box	300 * 2 * Markup	2019		$900
Charging cord kit	200 * Markup	2019		$300
DC fast charge circuitry (packs ≥ 20 kWh nominal only)	160 * Markup	2019		$240
Power management & distribution	720 * Markup	2019		$1,080
Additional pair of half shafts	190 * Markup	2019		$285
Markup	1.5		The RPE markup to account for indirect costs	

Table 2-41: Potential PHEV ICE Costs

Item	Cost Curve (Note: Markup = 1.5)	Dollar Basis	Note	Example system cost (6CYL, 3.0L Miller/CVVL/CEGR engine, 6200 lb CW, size class 7)
Cylinders	(-28.814 * CYL + 726.27) * CYL * Markup	2019	CYL= 4	$4,980*
Displacement	400 * LITERS * Markup	2019	LITERS= 3.0	$1,800*
Gasoline Direct Injection (GDI)	(43.237 * CYL + 97.35) * Markup	2019	CYL= 4	$535
turb12	(-13.149 * CYL2 + 220.34 * CYL - 124.73) * Markup	2012	Turbocharging with boost ~24 bar	$819
Cooled EGR	114 * Markup	2012		$171
atk2	(4.907 * CYL2 - 29.957 * CYL + 130.18) * Markup	2010	atk2=Atkinson cycle engine	$133
TWC substrate	(6.108 * LITERS * TWC_SWEPT_VOLUME + 1.95456) * Markup	2012	TWC=3way catalyst; TWC swept volume=1.2	$36
TWC washcoat	(5.09 * LITERS * TWC_SWEPT_VOLUME) * Markup	2012		$27
TWC canning	(2.4432 * LITERS * TWC_SWEPT_VOLUME) * Markup	2012		$13
TWC swept volume	1.2 multiplier applied to engine displacement			
TWC Pt grams/liter	0			
TWC Pd grams/liter	2			
TWC Rh grams/liter	0.11			
GPF	(14.1940 * LITERS + 39.2867) * Markup	2021	GPF=gasoline particulate filter	$123
TWC PGM	(PT_GRAMS_PER_LITER_TWC * LITERS * TWC_SWEPT_VOLUME * PT_USD_PER_OZ * OZ_PER_GRAM + PD_GRAMS_PER_LITER_TWC * LITERS * TWC_SWEPT_VOLUME * PD_USD_PER_OZ * OZ_PER_GRAM + RH_GRAMS_PER_LITER_TWC * LITERS * TWC_SWEPT_VOLUME * RH_USD_PER_OZ * OZ_PER_GRAM) * Markup		PGM=Platinum group metals (e.g., Pt, Pd, Rh)	$1,155
Troy oz/gram	0.0322			Values are used in the TWC PGM calculation
PT_USD_PER_OZ	1030		USD=US dollars; OZ=Troy ounce	
PD USD PER OZ	2331			
RH USD PER OZ	17981			
LV battery	(3 * VEHICLE_SIZE_CLASS + 51) * Markup	2019	LV=low voltage	$108
HVAC	(11.5 * VEHICLE_SIZE_CLASS + 195.5) * Markup	2019		$414
turb_scaler*	1.2 multiplier applied to ($Cylinders + $Displacement)			$6,559*
Markup	1.5		The RPE markup to account for indirect costs	
* Cylinder and displacement costs are used in the turbo_scaler calculation to determine engine long-block costs. The 1.2 multiplier accounts for additional costs to support turbocharging.				

2.6.1.5 Powertrain Costs for All Vehicles

These are additional powertrain costs that apply to all vehicles regardless of fuel used.

2.6.1.5.1 Air Conditioning

Air conditioning (AC) system costs are based on past EPA analyses and are shown in Table 2-40.

Table 2-42 Air Conditioning System Costs in OMEGA

Item	DMC	Dollar Basis
AC efficiency improvements	40 * Markup	2010
AC leakage control	63 * Markup	2010
Markup	1.5	

OMEGA uses these costs as-is, other than applying the markup to account for indirect costs.

2.6.1.5.2 Low voltage battery

The low voltage battery is estimated using the equation and weight bins shown below.

$$LowVoltageBattery = (3 \times VehicleSizeClass + 51) \times Markup$$

$$WeightBins = \left\{ \begin{matrix} 1: CURBWT \leq 3200, \\ 2: 3000 < CURBWT \leq 3800, \\ 3: 3800 < CURBWT \leq 4400, \\ 4: 4400 < CURBWT \leq 5000, \\ 5: 5000 < CURBWT \leq 5600, \\ 6: 5600 < CURBWT \leq 6200, \\ 7: 6200 < CURBWT \leq 14000 \end{matrix} \right\}$$

Where,

VehicleSizeClass = the applicable value 1 through 7 depending on the vehicle curb weight, in pounds, and according to the WeightBins dictionary

WeightBins = the seven curb weight bins into which each vehicle is categorized

CURBWT = the vehicle curb weight, in pounds

Markup = the 1.5 RPE markup to account for indirect costs

2.6.1.5.3 Heating and Ventilation

Heating and ventilation system costs are new and are estimated using the equation shown below.

$$HeatingAndVentilation = (11.5 \times VehicleSizeClass + 195.5) \times Markup$$

Where,

VehicleSizeClass = the applicable value 1 through 7 depending on the vehicle curb weight, in pounds, and according to the WeightBins dictionary shown for low voltage battery costs

Markup = the 1.5 RPE markup to account for indirect costs

2.6.2 Glider Costs

Glider cost curves in OMEGA represent three different body-styles: sedan, CUV/SUV and pickup; two different structure styles: unibody and ladder frame; two different primary materials: steel and aluminum; as well as non-structural elements. The relevant curves used in OMEGA are shown in Table 2-44. Note that "structure_mass_lbs" term shown in the table is determined according to the structure mass curves shown in Table 2-45.

Note that, unlike past EPA GHG analyses, OMEGA no longer models mass as a compliance strategy in discrete percentages of mass reduction. Instead, OMEGA calculates mass based on the factors shown in Table 2-45, with the compliance strategy decision based primarily on steel versus aluminum structure. Footprint may also change which would impact the mass of the vehicle, but the mass associated with potential footprint changes is a secondary effect of the footprint decision. In other words, footprint does not change as a result of mass reduction strategies and, instead, mass may change as a result of footprint strategies. The cost of the resultant mass is estimated using the equations shown in Table 2-44.

Table 2-43 Glider Costs in OMEGA

Item	Body-style	Structure Material	DMC	Dollar Basis
Unibody structure	Sedan	Steel	(1.5 * structure_mass_lbs + 1500) * markup	2020
Unibody structure	Sedan	Aluminum	(3.4 * structure_mass_lbs + 1500) * markup	2020
Unibody structure	CUV/SUV	Steel	(1.5 * structure_mass_lbs + 1700) * markup	2020
Unibody structure	CUV/SUV	Aluminum	(3.4 * structure_mass_lbs + 1700) * markup	2020
Ladder structure	CUV/SUV	Steel	((1.5 * structure_mass_lbs + 550) + (1.5 * (0.66 * structure_mass_lbs) + 2000)) * markup	2020
Ladder structure	CUV/SUV	Aluminum	((1.5 * structure_mass_lbs + 550) + (3.4 * (0.66 * structure_mass_lbs) + 2000)) * markup	2020
Ladder structure	Pickup	Steel	((1.5 * structure_mass_lbs + 550) + (1.5 * (0.66 * structure_mass_lbs) + 2000)) * markup	2020
Ladder structure	Pickup	Aluminum	((1.5 * structure_mass_lbs + 550) + (3.4 * (0.66 * structure_mass_lbs) + 2000)) * markup	2020
Unibody structure	Pickup	Steel	(1.5 * structure_mass_lbs + 1700) * markup	2020
Unibody structure	Pickup	Aluminum	(3.4 * structure_mass_lbs + 1700) * markup	2020
Non-structure	Sedan	Various	(24.3 * delta_footprint + 2.4* delta_footprint * (vehicle.height_in - vehicle.ground_clearance_in)) * markup	2020
Non-structure	CUV/SUV	Various	(24.9 * delta_footprint + 2.6 * delta_footprint * (vehicle.height_in - vehicle.ground_clearance_in)) * markup	2020
Non-structure	Pickup	Various	(18.2 * delta_footprint + 2.1 * delta_footprint * (vehicle.height_in - vehicle.ground_clearance_in)) * markup	2020
Markup			1.5 RPE markup to account for indirect costs	

Table 2-44 Mass Calculations in OMEGA

Item	Body-style	Structure	Material	Value
Null structure mass	Sedan	Ladder		2.2 * (5.5045 * footprint + 105.4)
Null structure mass	Sedan	Unibody		2.2 * (5.5045 * footprint + 105.4)
Null structure mass	CUV/SUV	Ladder		2.2 * (7.7955 * footprint + 127.48)
Null structure mass	CUV/SUV	Unibody		2.2 * (10.077 * footprint - 76.528)
Null structure mass	Pickup	Ladder		2.2 * (7.7955 * footprint + 127.48)
Null structure mass	Pickup	Unibody		2.2 * (10.077 * footprint - 76.528)
Structure mass lbs			Steel	null_structure_mass
Structure mass lbs		Ladder	Aluminum	(0.63 * 0.66 + 0.34)* null_structure_mass
Structure mass lbs		Unibody	Aluminum	0.65 * null_structure_mass
Delta glider non-structure mass	Sedan			(15.1 * delta_footprint + 2.3 * delta_footprint * (vehicle.height - vehicle.ground_clearance)/12)
Delta glider non-structure mass	CUV/SUV			(17.3 * delta_footprint + 2.5 * delta_footprint * (vehicle.height - vehicle.ground_clearance)/12)
Delta glider non-structure mass	Pickup			(18.1 * delta_footprint + 1.9 * delta_footprint * (vehicle.height - vehicle.ground_clearance)/12)
Note: footprint is in square feet; height and ground clearance are in inches; mass values are in pounds; 2.2 converts kilograms to pounds				

2.6.3 Consumer demand assumptions and S-Curves

OMEGA estimates the share of BEVs demanded within each of three body styles as a function of the relative consumer generalized costs for BEV and ICE vehicles, and a share weight parameter. The share weight parameter changes over time to account for factors that are not included in the generalized costs, such as greater access to charging infrastructure or greater availability and awareness BEVs. The determination of consumer generalized costs and share weights for ICE and BEVs are described in more detail in Chapter 4.1.

2.6.4 Consideration of constraints in modeling real-world technology adoption

2.6.4.1 Redesign schedules

Consistent with past rulemakings, EPA has included redesign cycles as a constraint to restrict introduction of new technology for a given vehicle model to the cadence of a typical product cycle time. As implemented for the proposal, OMEGA may only redesign a vehicle every 5 years for unibody vehicles and every 7 years for body-on-frame vehicles. An example of behavior for one manufacturer's vehicles can be seen in Figure 2-25.

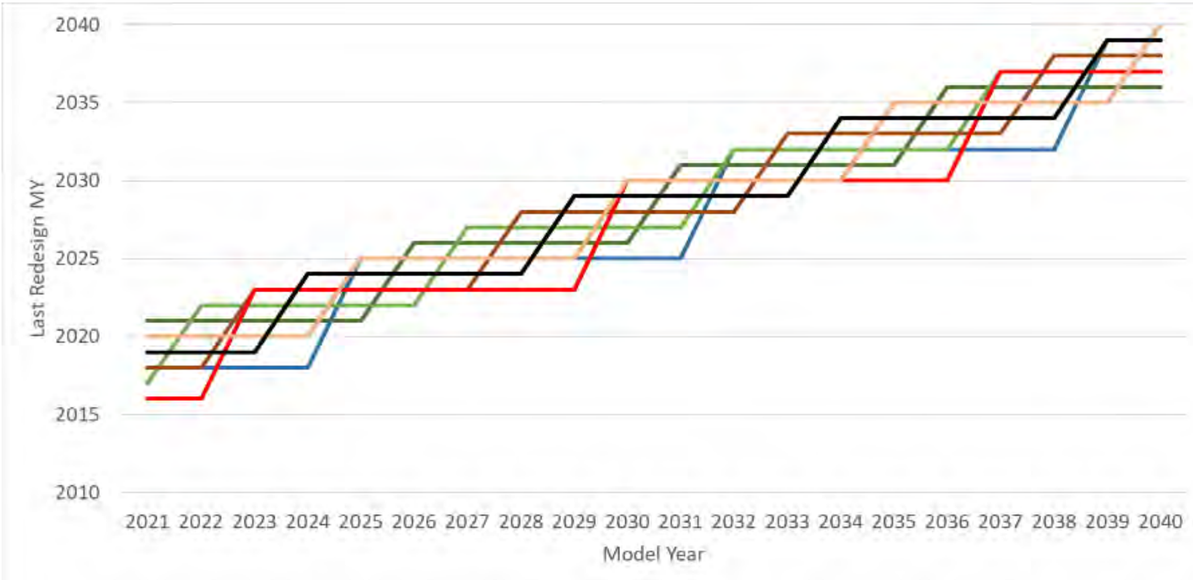

Figure 2-29. Redesign Years for Select Vehicles

EPA has populated its base year vehicles file with the year of last redesign for each model in the light duty fleet. Applying OMEGA's redesign constraints above with the distribution of redesign years across the industry yielded the following distribution redesigns on a sales basis.

Table 2-43 provides a count of the discrete vehicle models and sales in MY 2032, the year in which they were last redesigned, and the corresponding sales volume that was redesigned in prior years. As can be seen, there is a fairly even distribution of vehicle model redesign years. Note that many vehicles which were redesigned in MY 2026 were eligible for another redesign in MY 2031.

Table 2-45: MY 2032 Vehicles: Year of Last Redesign

Year Redesigned	# of Models	Total Sales	% of Sales
2026	10	83,818	1%
2027	38	823,932	5%
2028	201	2,601,172	17%
2029	284	2,849,875	19%
2030	284	3,250,190	21%
2031	358	4,136,099	27%
2032	284	1,641,242	11%
Totals	**1459**	**15,386,328**	**100%**

2.6.4.2 Materials and mineral availability

The development of EPA's constraint on BEV production, which is primarily based on a bound on battery production and lithium availability, can be found in RIA 3.1.3.2.

Table 2-44 shows the limits, in terms of maximum industry GWh (available for production of U.S. vehicles) that resulted from this assessment and that are applied in OMEGA.

Table 2-46: Industry Maximum Battery Production Limits (GWh), by Model Year

MY	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
GWh limit	79	150	261	372	483	580	720	860	1000	1100	1200	1300	1400	1500

2.6.5 Manufacturing capacity

In addition to availability of critical minerals, the ability to perform final assembly of vehicles that use them could also be understood as a potential constraint on increased production of BEVs. However, EPA notes that major manufacturers are already building a large amount of assembly plant manufacturing capacity both in the U.S. and abroad to meet future demand for these vehicles, and these efforts are poised to continue. Unlike critical minerals which have fundamental constraints on their production due to limited presence of these resources as well as a relatively long lead time for increasing their extraction, vehicle assembly capacity is a relatively well understood process that can respond relatively quickly to the necessary investment commitments. Given the existing activities among automakers in this area, and the relatively long lead time before MY 2027 when the proposed rule would begin, EPA did not specifically impose a limit on vehicle assembly capacity. However, as described in DRIA 3.1.3.2, EPA did represent a reasonable rate of battery manufacturing ramp-up by using information about battery manufacturing facilities announced or in operation, and estimates of lithium availability, to develop a constraint on annual GWh battery demand for use by OMEGA. For more discussion of manufacturing capacity and critical minerals, please see DRIA 3.1.3.1, DRIA 3.1.3.2, and Preamble IV.C.6.

2.6.6 Fuel Prices used in OMEGA

OMEGA uses fuel prices to estimate generalized costs as part of the compliance modeling algorithm. OMEGA also uses these fuel prices in estimating fuel expenditures and fuel savings that are included in the benefit-cost analysis results present in Chapter 10 of this draft RIA.

Note that, as discussed in Chapter 5 of this DRIA, EPA has estimates of future retail electricity prices that include impacts of the Inflation Reduction Act. Those retail electricity prices are lower than those shown in Table 2-45. The analysis done in OMEGA does not use those lower electricity prices because EPA did not have analogous liquid fuel prices to use, i.e., we did not have liquid fuel price projections that include impacts of the Inflation Reduction Act. For internal consistency, we have chosen to use AEO 2021 fuel price projections for both liquid fuels and electricity.

Table 2-47 AEO2021 Fuel Prices Used in OMEGA (2020 dollars)

	Gasoline		Diesel		Electricity	
Calendar Year	Pre-tax ($/gallon)	Retail ($/gallon)	Pre-tax ($/gallon)	Retail ($/gallon)	Pre-tax ($/kWh)	Retail ($/kWh)
2027	2.01	2.56	2.52	3.10	0.103	0.124
2028	2.08	2.63	2.58	3.16	0.103	0.125
2029	2.12	2.67	2.62	3.19	0.103	0.125
2030	2.21	2.80	2.68	3.29	0.103	0.125
2031	2.22	2.81	2.72	3.32	0.103	0.125
2032	2.28	2.87	2.76	3.36	0.102	0.124
2033	2.30	2.89	2.79	3.38	0.103	0.125
2034	2.34	2.93	2.80	3.40	0.103	0.125
2035	2.37	2.95	2.82	3.41	0.103	0.125
2036	2.41	2.98	2.84	3.42	0.102	0.125
2037	2.44	3.02	2.88	3.46	0.102	0.124
2038	2.48	3.05	2.90	3.49	0.101	0.124
2039	2.49	3.06	2.91	3.48	0.101	0.123
2040	2.55	3.11	2.96	3.54	0.101	0.123
2041	2.58	3.14	3.00	3.57	0.100	0.123
2042	2.60	3.16	3.02	3.59	0.100	0.123
2043	2.62	3.18	3.06	3.62	0.099	0.122
2044	2.63	3.19	3.07	3.63	0.099	0.122
2045	2.62	3.17	3.07	3.62	0.099	0.122
2046	2.66	3.21	3.11	3.67	0.098	0.121
2047	2.68	3.22	3.13	3.68	0.098	0.121
2048	2.69	3.24	3.14	3.68	0.098	0.121
2049	2.69	3.23	3.16	3.70	0.097	0.120
2050	2.70	3.23	3.16	3.69	0.096	0.119
2051	2.70	3.23	3.16	3.69	0.096	0.118
2052	2.71	3.24	3.15	3.69	0.095	0.118
2053	2.71	3.24	3.15	3.68	0.094	0.117
2054	2.72	3.24	3.15	3.68	0.093	0.116
2055	2.73	3.24	3.15	3.67	0.093	0.115
2056	2.73	3.25	3.15	3.67	0.092	0.114
2057	2.74	3.25	3.15	3.67	0.091	0.114
2058	2.74	3.25	3.15	3.66	0.091	0.113
2059	2.75	3.25	3.15	3.66	0.090	0.112
2060	2.75	3.26	3.15	3.65	0.089	0.111

2.6.7 Gross Domestic Product Price Deflators

To adjust all monetary inputs used in OMEGA to a consistent dollar basis, OMEGA uses the gross domestic product (GDP) implicit price deflators shown in Table 2-46. These deflators were generated by the Bureau of Economic Analysis, Table 1.1.9, revised on March 25, 2021.

Table 2-48: Gross domestic product implicit price deflators

Calendar Year	GDP Implicit Price Deflator
2001	79.790
2002	81.052
2003	82.557
2004	84.780
2005	87.421
2006	90.066
2007	92.486
2008	94.285
2009	95.004
2010	96.111
2011	98.118
2012	100.000
2013	101.755
2014	103.638
2015	104.624
2016	105.722
2017	107.710
2018	110.296
2019	112.265
2020	113.625

2.6.8 Inflation Reduction Act

OMEGA explicitly accounts for two elements of the Inflation Reduction Act in compliance modeling: the battery production tax credit and the BEV purchase incentive.

The IRS Section 45X battery production tax credit is treated within the modeling as a reduction in direct manufacturing costs, which in turn is assumed to result in a reduction in purchase price for the consumer after the application of the Retail Price Equivalent (RPE) factor. The credit phases out by statute from 2030 through 2032. As described previously in section 2.5.2.1.4, we estimated the average amount of the credit in 2023 at 60 percent of the maximum $45, and ramped the value upward linearly each year until it reaches the maximum $45 in 2027. For discussion of the justification of this choice, please see Section 2.5.2.1.4 and Preamble IV.C.2. The resulting value of the credit applied in OMEGA, in terms of dollars per kWh of gross battery capacity, is shown in Table 2-47. These represent an average credit amount across the industry as a whole. Although some manufacturers and vehicles may realize the full value of the credit in any given year, the model requires an average value across the full market.

Table 2-49: IRA Battery Production Tax Credits in OMEGA

Year	Tax credit value ($/kWh)
2023	$27
2024	$31.50
2025	$36
2026	$40.50
2027	$45
2028	$45
2029	$45
2030	$33.75
2031	$22.50
2032	$11.25
2033	$0

The IRS 30D and 45W Clean Vehicle Credits are reflected in lower consumer purchase costs, and therefore have an influence on the shares of BEVs demanded by consumers. The reduction in costs for the consumer makes BEVs relatively more attractive than ICE alternatives, compared to the case with no purchase incentives. The purchase incentive is assumed to be realized entirely by the consumer and does not impact the producer generalized cost value or the manufacturing cost. While the restrictions imposed by the IRA on the 30D credit (income, MSRP, critical mineral content, and manufacturing content) limit the vehicles which are eligible for the full $7,500 incentive under 30D, we believe that manufacturers will work to increase the number of vehicles that qualify over time due to the high marketing value of the credit. Further, we expect that the IRS 45W Clean Commercial Vehicle Credit, which is not subject to many of the restrictions on the 30D credit, will likely impact a significant portion of BEV sales, through fleet purchases and also through vehicle leasing to consumers. For these reasons, we have conceptualized the purchase incentive as a combination of 30D and 45W credits. The OMEGA modeling ramps in the purchase incentive from $3,750 in MY2023 to a maximum of $6,000 in MY2027, as shown in Table 2-51. See also the discussion in Preamble IV.C.2.

Table 2-50: IRS 30D and 45W Clean Vehicle Credit in OMEGA

Model Year	Combined BEV Purchase Incentive Value
2022	$0
2023	$3750
2024	$4000
2025	$4250
2026	$4500
2027	$4750
2028	$5000
2029	$5250
2030	$5500
2031	$5750
2032	$6000
2033	$0

Chapter 2 References

75 FR 25324. 2010. (May 7). https://www.govinfo.gov/content/pkg/FR-2010-05-07/pdf/2010-8159.pdf.

77 FR 62624. 2012. (October 15). https://www.govinfo.gov/content/pkg/FR-2012-10-15/pdf/2012-21972.pdf.

86 FR 74434. 2021. (December 30). https://www.govinfo.gov/content/pkg/FR-2021-12-30/pdf/2021-27854.pdf.

88 FR 4296. 2023.

California Air Resources Board. 2022. ZEV Cost Modeling Workbook. March. https://ww2.arb.ca.gov/sites/default/files/2022-06/ZEV_Cost_Modeling_Workbook_Update_March_2022_1.xlsx.

FEV Consulting Inc. 2022. "Cost and Technology Evaluation, Conventional Powertrain Vehicle Compared to an Electrified Powertrain Vehicle, Same Vehicle Class and OEM." Contract Report for the U.S. EPA, Contract No. 68HERC19D00008.

Foundation, The R. 2022. "The R Project for Statistical Computing." https://www.r-project.org/.

ICF International. 2022. EPA-420-R-23-004: Peer Review of Electrified Vehicle Simulations within EPA's ALPHA Model. US EPA.

Kelly, John D. 2020. Understanding the Honda E-Drive (audio-video presentation). December 12. Accessed February 7, 2023. https://youtu.be/QLUIExAnNcE.

Kevin Bolon, Andrew Moskalik, Kevin Newman, Aaron Hula, Anthony Neam, and Brandon Mikkelsen. 2018. "Characterization of GHG Reduction Technologies in the Existing Fleet." SAE Technical Paper 2018-01-1268. doi:10.4271/2018-01-1268.

Kleijnen, Jack P.C. 2015. "Response Surface Methodology." In Handbook of Simulation Optimization, by Michael C. Fu, 81-104. New York, NY: Springer. doi:10.1007/978-1-4939-1384-8.

Lee, SoDuk; Cherry, Jeff; Safoutin, Michael; Neam, Anthony; McDonald, Joseph; Newman, Kevin;. 2018. "Modeling and Controls Development of 48 V Mild Hybrid Electric Vehicles." SAE Technical Paper 2018-01-0413. doi:10.4271/2018-01-0413.

Lenth, Russell. 2021. "Response-Surface Analysis." https://cran.r-project.org/web/packages/rsm/rsm.pdf.

MacIntosh, R., S. Tolomiczenko, and G. Van Horn. 2022. "Electric Vehicle Market Update." ERM Report to the Environmental Defense Fund. https://blogs.edf.org/climate411/files/2022/09/ERM-EDF-Electric-Vehicle-Market-Report_September2022.pdf.

Moskalik, Andrew. 2020. "Using Transmission Data to Isolate Individual Losses in Coastdown Road Load Coefficients." SAE International Journal of Advances and Current Practices in Mobility 4 (1): 2156-2171. doi:10.4271/2020-01-1064.

Munro and Associates. 2018. "2017 Tesla Model 3 Cost Analysis."

Munro and Associates. 2020c. "2020 Tesla Model Y Cost Analysis."

Munro and Associates. 2020b. "3 Inverter Side-by-Side Analysis."

Munro and Associates. 2021. "6 Inverter Side-by-Side Analysis."

Munro and Associates. 2016. "BMW i3 Cost Analysis."

Munro and Associates. 2020a. "Twelve Motor Side-by-Side Analysis."

National Academies of Sciences, Engineering, and Medicine. 2021. Assessment of Technologies for Improving Light-Duty Vehicle Fuel Economy 2025-2035. The National Academies Press. doi:10.17226/26092.

Newman, K., Kargul, J., and Barba, D. 2015b. "Benchmarking and Modeling of a Conventional Mid-Sized Car Using ALPHA." SAE Technical Paper 2015-01-1140. doi:10.4271/2015-01-1140.

Newman, K., Kargul, J., and Barba, D. 2015a. "Development and Testing of an Automatic Transmission Shift Schedule Algorithm for Vehicle Simulation." SAE International Journal of Engines 8 (3). doi:10.4271/2015-01-1142.

Paul Dekraker, John Kargul, Andrew Moskalik, Kevin Newman, Mark Doorlag, and Daniel Barba. 2017. "Fleet-Level Modeling of Real World Factors Influencing Greenhouse Gas Emission Simulation in ALPHA." SAE Int. J. Fuels Lubr. 10 (1): 217-235. doi:10.4271/2017-01-0899.

Ricardo Strategic Consulting and Munro and Associates. 2017. "Advanced Strong Hybrid and Plug-In Hybrid Engineering Evaluation and Cost Analysis." Report prepared for the California Air Resources Board, CARB Agreement 15CAR018.

Rogozhin, A.,et al. 2009. "Using indirect cost multipliers to estimate the total cost of adding new technology in the automobile industry." International Journal of Production Economics.

RTI International. 2018. Peer Review of EPA’s Response Surface Equation Report, Report EPA-420-R-18-006. EPA. https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=P100VK3Z.txt.

Slowik, P., A. Isenstadt, L. Pierce, and S. Searle. 2022. Assessment of Light-Duty Electric Vehicle Coss and Consumer Benefits in the United States in the 2022-2035 Time Frame. International Council on Clean Transportation. https://theicct.org/wp-content/uploads/2022/10/ev-cost-benefits-2035-oct22.pdf.

U.S. EPA. 2023a. Advanced Light-Duty Powertrain and Hybrid Analysis (ALPHA) Tool. Accessed February 2, 2023. https://www.epa.gov/regulations-emissions-vehicles-and-engines/advanced-light-duty-powertrain-and-hybrid-analysis-alpha.

—. 2022c. "ALPHA Documentation 0.2.0 documentation." Accessed 11 17, 2022. https://epa-alpha-model.readthedocs.io/_/downloads/en/latest/pdf/.

—. 2023. "Battery Cost Estimation Spreadsheets for US EPA LMDV NPRM." Docket EPA-HQ-OAR-2022-0829.

—. 2023c. Combining Data into Complete Engine ALPHA Maps. Accessed February 2, 2023. https://www.epa.gov/vehicle-and-fuel-emissions-testing/combining-data-complete-engine-alpha-maps.

—. 2023b. Complete Electric Motor ALPHA Maps. https://www.epa.gov/vehicle-and-fuel-emissions-testing/combining-data-complete-emotor-alpha-maps.

U.S. EPA. 2016. "Cost Reduction through Learning in Manufacturing Industries and in the Manufacture of Mobile Sources, EPA-420-R-16-018." https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100PUSX.PDF.

—. 2022e. "Data from Cars used for Testing Fuel Economy." https://www.epa.gov/compliance-and-fuel-economy-data/data-cars-used-testing-fuel-economy.

—. 2016a. "EPA-420-R-16-020: Proposed Determination on the Appropriateness of the Model Year 2022-2025 Light-Duty Vehicle Greenhouse Gas Emissions Standards under the Midterm Evaluation." November. https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100Q3DO.pdf.

—. 2016b. "EPA-420-R-16-021: Proposed Determination on the Appropriateness of the Model Year 2022-2025 Light-Duty Vehicle Greenhouse Gas Emissions Standards under the Midterm Evaluation: Technical Support Document." November. Accessed November 3, 2022. https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100Q3L4.pdf.

—. 2017a. "EPA-420-R-17-001: Final Determination on the Appropriateness of the Model Year 2022-2025 Light-Duty Vehicle Greenhouse Gas Emissions Standards under the Midterm Evaluation." https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100QQ91.pdf.

—. 2017b. "EPA-420-R-17-002: Final Determination on the Appropriateness of the Model Year 2022-2025 Light-Duty Vehicle Greenhouse Gas Emissions Standards under the Midterm Evaluation: Response to Comments." January. https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100QQ9Y.pdf.

—. 2022b. Technical Publications and Presentations Concerning Benchmarking. Accessed 11 17, 2022. https://www.epa.gov/vehicle-and-fuel-emissions-testing/benchmarking-advanced-low-emission-light-duty-vehicle-technology.

U.S. EPA; U.S. DOT-NHTSA; CARB. 2016. "EPA-420-D-16-900: Draft Technical Assessment Report: Midterm Evaluation of Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards for Model Years 2022 - 2025." July. https://nepis.epa.gov/Exe/ZyPDF.cgi/P100OXEO.PDF?Dockey=P100OXEO.PDF.

UBS AG. 2017. "Q-Series: UBS Evidence Lab Electric Car Teardown – Disruption Ahead?" https://neo.ubs.com/shared/d1wkuDlEbYPjF/.

W. Zhuanga, S. Li (Eben), X. Zhangc, D. Kum, Z. Song, G. Yin, F. Ju,. 2020. "A survey of powertrain configuration studies on hybrid electric vehicles." Journal of Applied Energy 262 (114553). doi:10.1016/j.apenergy.2020.114553.

Wood Mackenzie. 2022. Battery & raw materials - investment horizon outlook to 2032. Wood Mackenzie.

Yamagishi, Tomoya, and Takashi Ishikura. 2018. "Development of Electric Powertrain for CLARITY PLUG-IN HYBRID, SAE No. 2018-01-0415." Int. J. Alt. Power. (SAE) 7 (3): 323-333. doi:10.4271/2018-01-0415.

Chapter 3: Analysis of Technologies for Reducing GHG and Criteria Pollutant Emissions

This chapter summarizes our assessment of the feasibility of the proposed greenhouse gas (GHG) and criteria pollutant emission standards. It includes a description of the emissions control technologies considered for criteria pollutant exhaust and evaporative emissions, GHG emissions control, on-board diagnostics, and specific considerations with regards to plug-in hybrid electric vehicles (PHEVs).

3.1 Technology Feasibility

The levels of stringency in the proposed standards continue a trend of increased emissions reductions which have been adopted by prior EPA rules. As with prior rules and as part of the development of this proposed rulemaking, EPA assessed the feasibility of the proposed standards in light of current and anticipated progress by automakers in developing and deploying new emissions-reducing technologies.

Compliance with the EPA GHG standards over the past decade has been achieved predominantly through the application of advanced technologies to internal combustion engine (ICE) vehicles. For example, in the analyses performed for the 2012 rule (77 FR 62624 2012), the Draft Technical Assessment Report (TAR) for the Midterm Evaluation (MTE) of the 2022-2025 standards (U.S. EPA, CARB, U.S. DOT NHTSA 2016), the 2016 Proposed Determination (U.S. EPA 2016), and the 2021 rule (86 FR 74434 2021), a significant portion of EPA's analysis included an assessment of technologies available to manufacturers for achieving compliance with the standards. Advanced ICE technologies were identified as playing a major role in manufacturer compliance with the emission reductions required by those rules. Automakers have also relied to varying degrees on a range of electrification technologies, including hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and battery-electric vehicles (BEVs). As described in detail in Preamble I.A.2.ii, these technologies have been advancing rapidly over the past decade. As battery costs have continued to decline, automakers have begun to include BEVs and PHEVs (together referred to as PEVs or plug-in electric vehicles) as an integral and growing part of their current and future product lines, leading to increasing penetrations of these clean vehicles and an increasing diversity of models planned for high-volume production. Preamble I.A.2.ii also described how PEVs are increasingly popular among a rapidly growing proportion of consumers who have become familiar with their benefits. Thus, PEVs are already delivering significant emission reductions through their increasing presence in the fleet and are poised to deliver greater reductions as their penetration continues to grow.

As described throughout this chapter, EPA has assessed the feasibility of the proposed standards in light of current and anticipated progress by automakers in developing and deploying new emissions-reducing technologies. Chapter 3.1 describes our assessment of technology feasibility in general, by examining recent trends in technology application to light- and medium-duty vehicles, and also addressing issues specifically related to PEV feasibility. Section 3.1.1 discusses recent trends and feasibility of light-duty vehicle technologies that manufacturers have available to meet the proposed standards. Similarly, Section 3.1.2 discusses recent trends in electrification of medium-duty vehicles. Section 3.1.3 describes our assessment of feasibility of PEV technology.

3.1.1 Light-duty Vehicle Technologies and Trends

3.1.1.1 Advanced ICE technologies

Innovation in the automobile industry has led to a wide array of technology available to manufacturers to achieve CO_2 emissions, fuel economy, and performance goals (U.S. EPA 2022). Figure 3-1 illustrates manufacturer-specific technology usage for model year 2021, with larger circles representing higher usage rates (U.S. EPA 2022). These technologies are all being used by manufacturers to, in part, reduce CO_2 emissions and increase fuel economy. Each of the fourteen largest manufacturers have adopted several of these technologies into their vehicles, with many manufacturers achieving very high penetrations of several technologies. It is also clear that manufacturers' strategies to develop and adopt new technologies are unique and vary significantly. Each manufacturer is choosing technologies that best meet the design requirements of their vehicles, and in many cases, that technology is changing quickly.

Engine technologies such as turbocharged engines (Turbo) and gasoline direct injection (GDI) allow for more efficient engine design and operation. Cylinder deactivation (CD) allows for use of only a portion of the engine when less power is needed, while stop/start systems can turn off the engine entirely at idle to save fuel. Hybrid vehicles use a larger battery to recapture braking energy and provide power when necessary, allowing for a smaller, more efficiently operated engine. The hybrid category includes strong hybrid systems that can temporarily power the vehicle without engaging the engine and smaller "mild" hybrid systems that cannot propel the vehicle on their own. Transmissions that have more gear ratios, or speeds, allow the engine to more frequently operate near peak efficiency. Two categories of advanced transmissions are shown in Figure 3-1.

In model year 2021, hybrid vehicles reached a new high of 9 percent of all production. This increase was mostly due to the growth of hybrids in the truck SUV and pickup vehicle types. The combined category of battery electric vehicles (BEVs), plug-in hybrid vehicles (PHEVs), and fuel cell electric vehicles (FCEVs) increased to 4 percent of production in model year 2021 and are projected to reach 8 percent of production in model year 2022, due to expected growth in EV production across the industry. News media have reported global EV sales reached 10 percent of all new car sales in 2022 (Boston 2023).

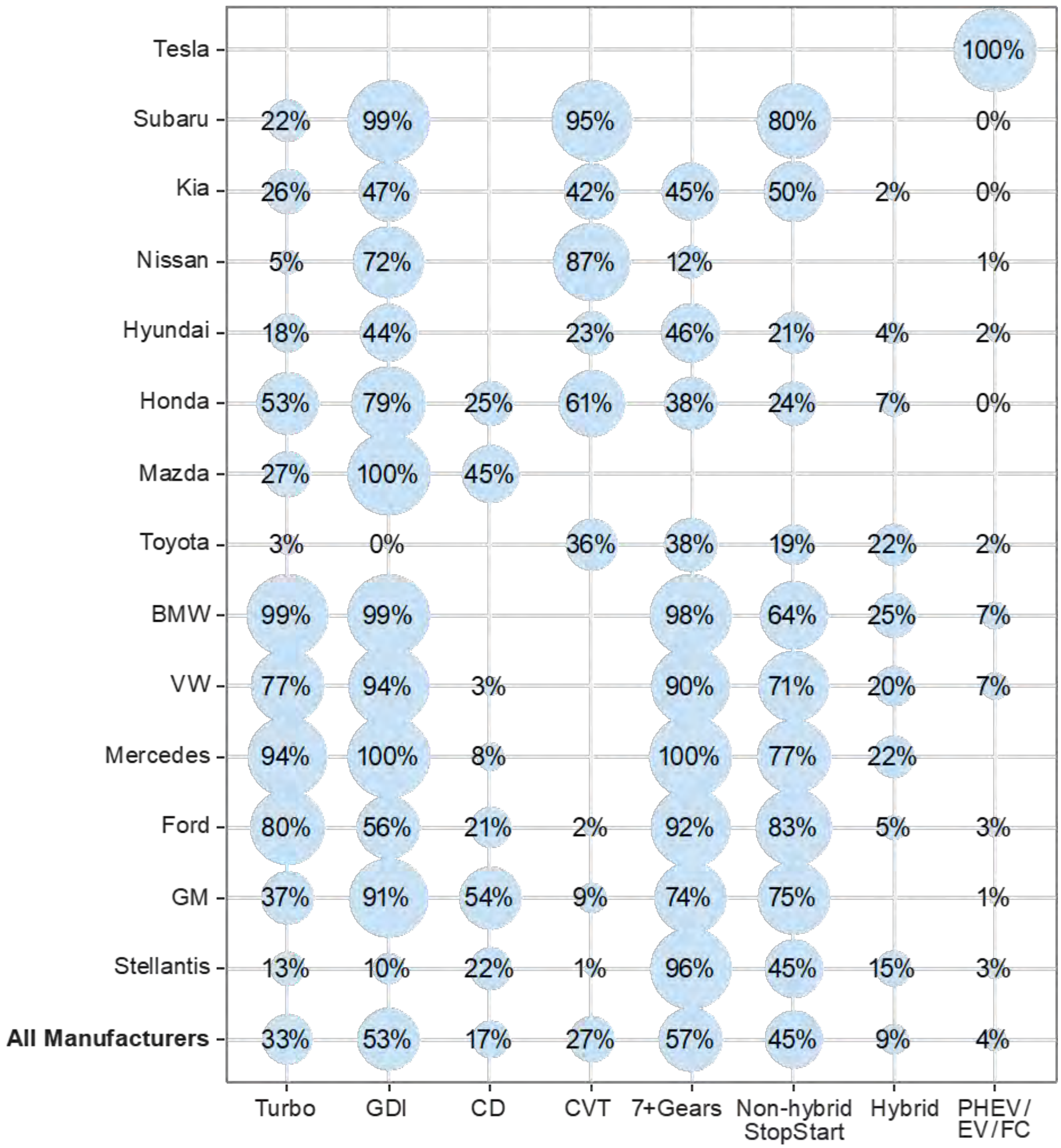

Figure 3-1 Manufacturer Use of Key Technologies in Model Year 2021

3.1.1.2 Hybrid Electric Technologies

Hybrid electric vehicles (HEVs) were first introduced in the U.S. marketplace in model year 2000 with the Honda Insight. As more models and options were introduced, hybrid production increased to 3.8 percent of all vehicles in model year 2010, before declining somewhat over the next several years. However, in model year 2021 hybrid production reached a new high at 9.3 percent and is projected to reach 10.1 percent in model year 2022, as shown in Figure 3-2 (U.S. EPA 2022).

The growth in hybrid vehicles is largely attributable to growth outside of the sedan/wagon vehicle type. In model year 2020 the production of hybrids in the truck SUV category (largely mild HEVs) surpassed the production of sedan/wagon hybrids for the first time and did so by more than 50 percent. Hybrids also began to penetrate the pickup and minivan/van vehicle types. However, there remain very few hybrid car SUVs. Sedan/wagon hybrids accounted for only 21 percent of all hybrid production in model year 2021.

The growth of hybrids in the pickup vehicle type is largely due to the introduction of "mild" hybrid systems that are capable of regenerative braking and many of the same functions as other hybrids but utilize a smaller battery and an electrical motor that cannot directly drive the vehicle. These mild hybrids account for about a third of hybrid production in model year 2021.

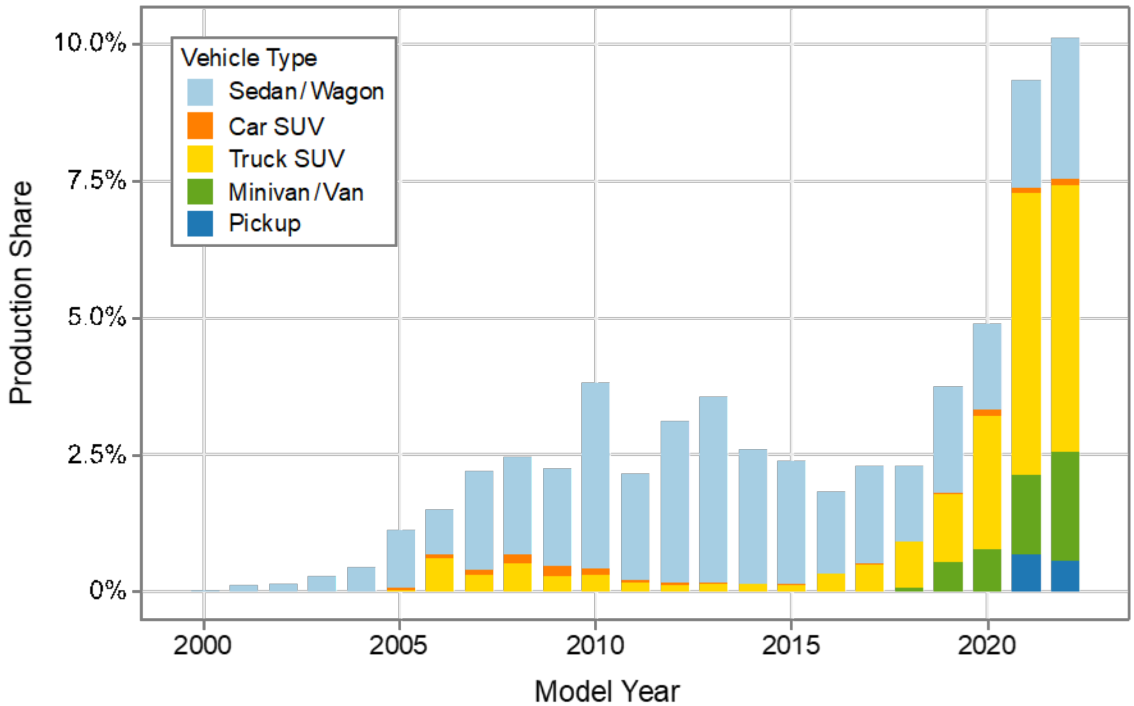

Figure 3-2 Gasoline Hybrid Engine Production Share by Vehicle Type

3.1.1.3 Plug-in Electric Vehicle Technologies

The previously described trend in application of BEV and PHEV technologies to light-duty vehicles is evidence of a continuing shift toward electrification across the vehicle industry. As described in detail in the Executive Summary of the Preamble (I.A.2.ii), recent trends in market penetration of PEVs show that demand for these vehicles in the U.S. is rapidly increasing, as the production of new PEVs (including both BEVs and PHEVs) is growing rapidly and roughly doubling every year. As also described at length in that section, manufacturers have increasingly begun to shift research and development investment away from ICE technologies and are allocating large amounts of new investment to electrification technology. For more discussion of these rapidly increasing trends, see Preamble Section I.A.2.ii.

The production of BEVs and PHEVs has increased rapidly in recent years. Prior to model year 2011, BEVs were available, but generally only in small numbers for lease in California. In model year 2011 the first commercially available PHEV, the Chevrolet Volt, was introduced along with the Nissan Leaf BEV. Many additional models have been introduced since, and in model year 2021 combined BEV/PHEV production reached 4 percent of all new vehicles. Combined BEV and PHEV production is projected to reach a new high of 8 percent of all production in model year 2022. The trend in BEVs, PHEVs, and FCEVs are shown in Figure 3-3 (U.S. EPA 2022).

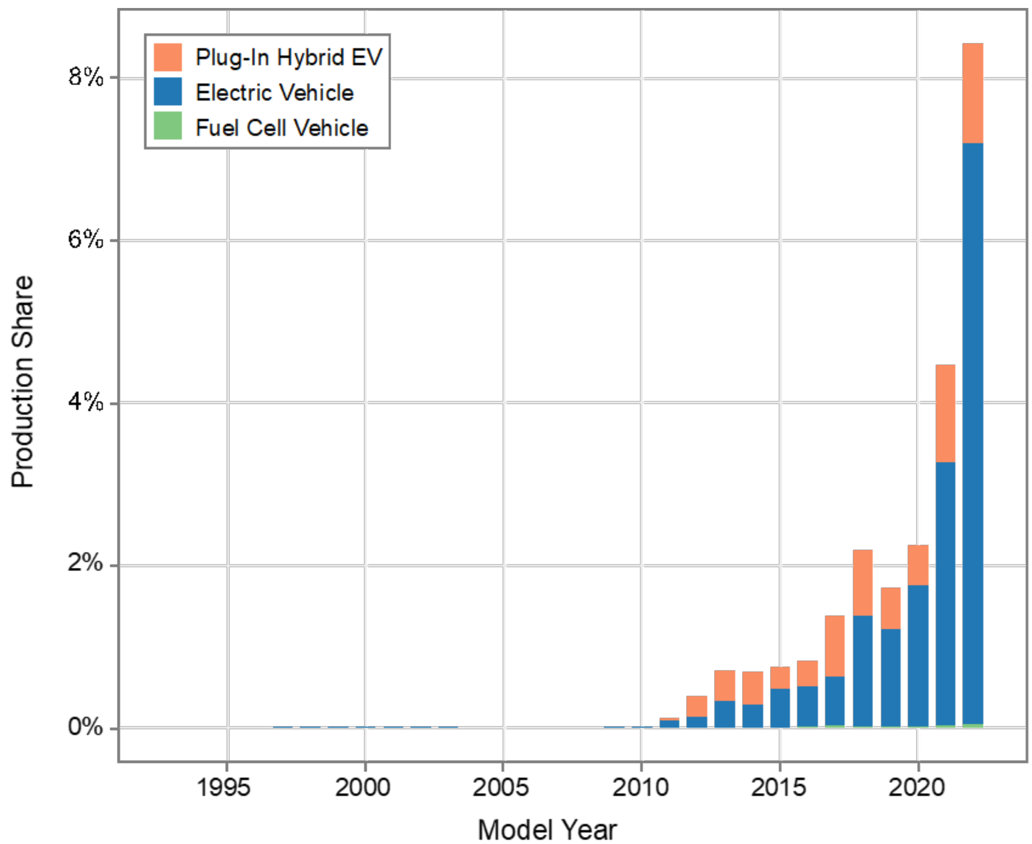

Figure 3-3 Production Share of BEVs, PHEVs, and FCEVs

The inclusion of model year 2021 BEV and PHEV sales reduces the overall new vehicle average CO_2 emissions by 14 g/mi, and this impact will continue to grow if BEV and PHEV production increases. In model year 2021 there were three hydrogen FCEV models produced, but they were only available in the state of California and Hawaii and in very small numbers. However there continues to be interest in FCEVs as a future technology. Figure 3-4 and Figure 3-5 (U.S. EPA 2022) show the production share by vehicle type for BEVs and PHEVs. Early production of BEVs was mostly in the sedan/wagon vehicle type, but recent model years have shown growth in car SUVs and truck SUVs. Electric pickup trucks are entering the market in model year 2022, along with new EV models across many of the vehicle types. Production of PHEVs has shifted from exclusively sedan/wagons to mostly truck SUVs, with limited production across the sedan/wagon, car SUV, and minivan/van vehicle types.

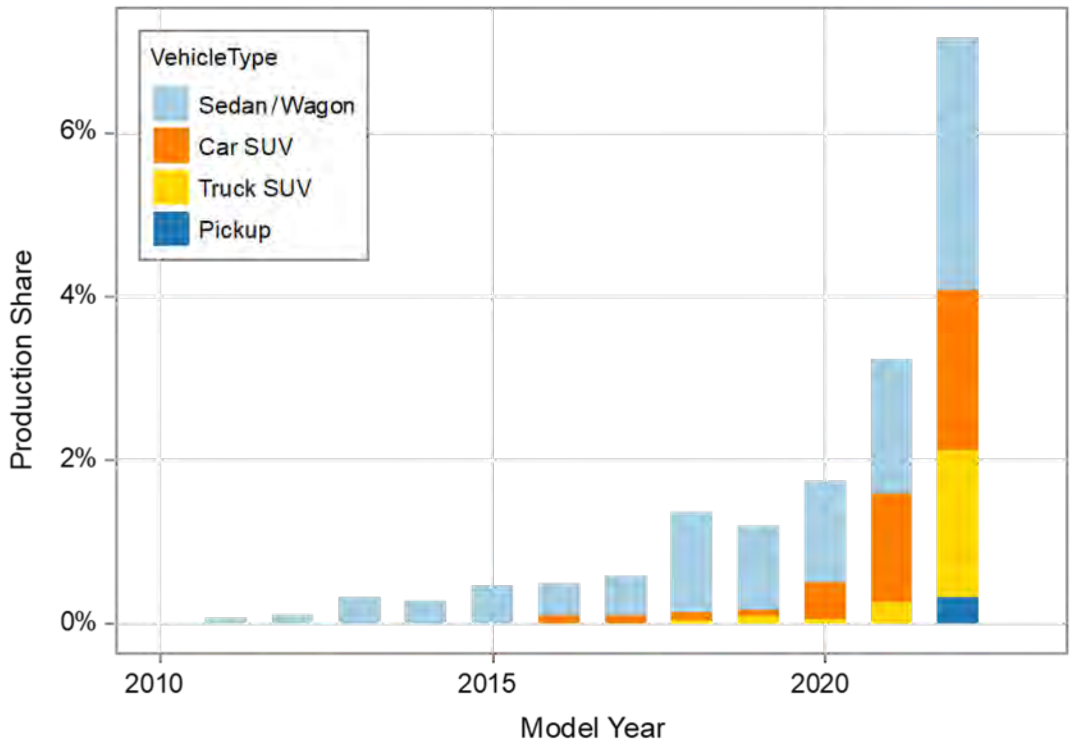

Figure 3-4 Electric Vehicle Production Share by Vehicle Type

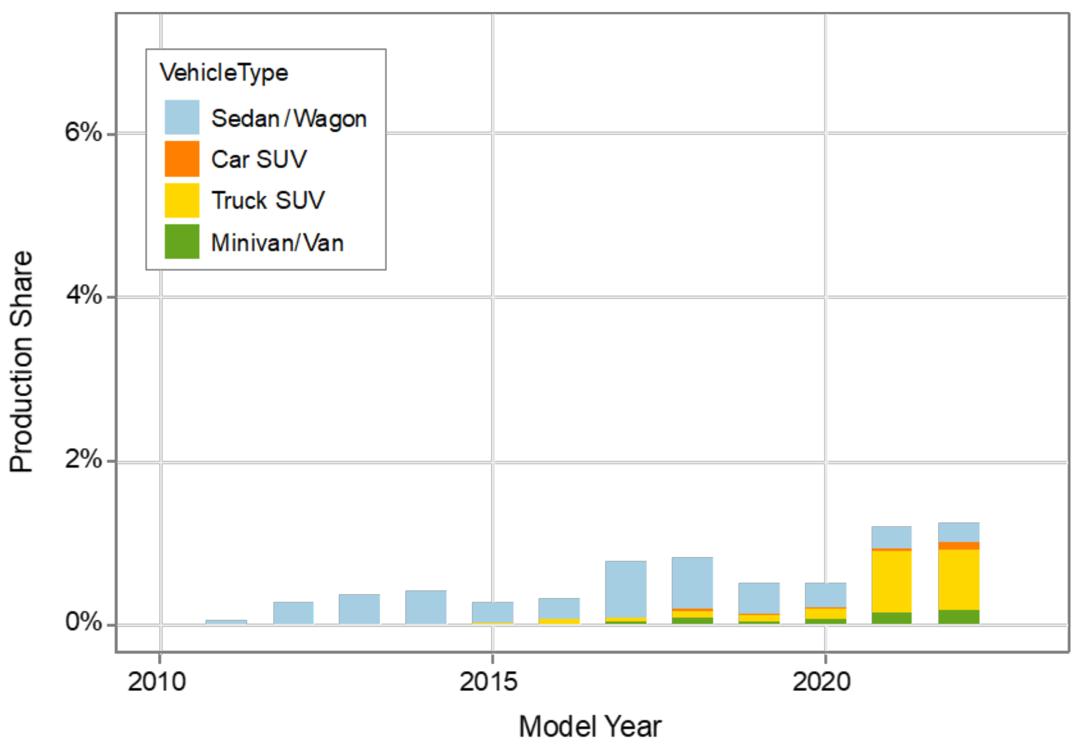

Figure 3-5 Plug-In Hybrid Vehicle Production Share by Vehicle Type

Figure 3-6 (U.S. EPA 2022) shows the range and fuel economy trends for EVs and PHEVs. The average range of new BEVs has climbed substantially. In model year 2021 the average new BEV range is 298 miles, or about four times the range of an average BEV in 2011. The range values shown for PHEVs are the charge-depleting range, where the vehicle is operating on energy in the battery from an external source. This is generally the electric range of the PHEV, although some vehicles also use the gasoline engine in small amounts during charge depleting operation. The average charge depleting range for PHEVs has remained largely unchanged since model year 2011.

Along with improving range, the fuel economy of electric vehicles has also improved as measured in miles per gallon of gasoline equivalent (mpge). The fuel economy of electric vehicles increased by about 18 percent between model years 2011 and 2021. The combined fuel economy of PHEVs has been more variable but is about 30 percent lower in model year 2021 than in model year 2011. This decrease may be attributable to the growth of truck SUV PHEVs.

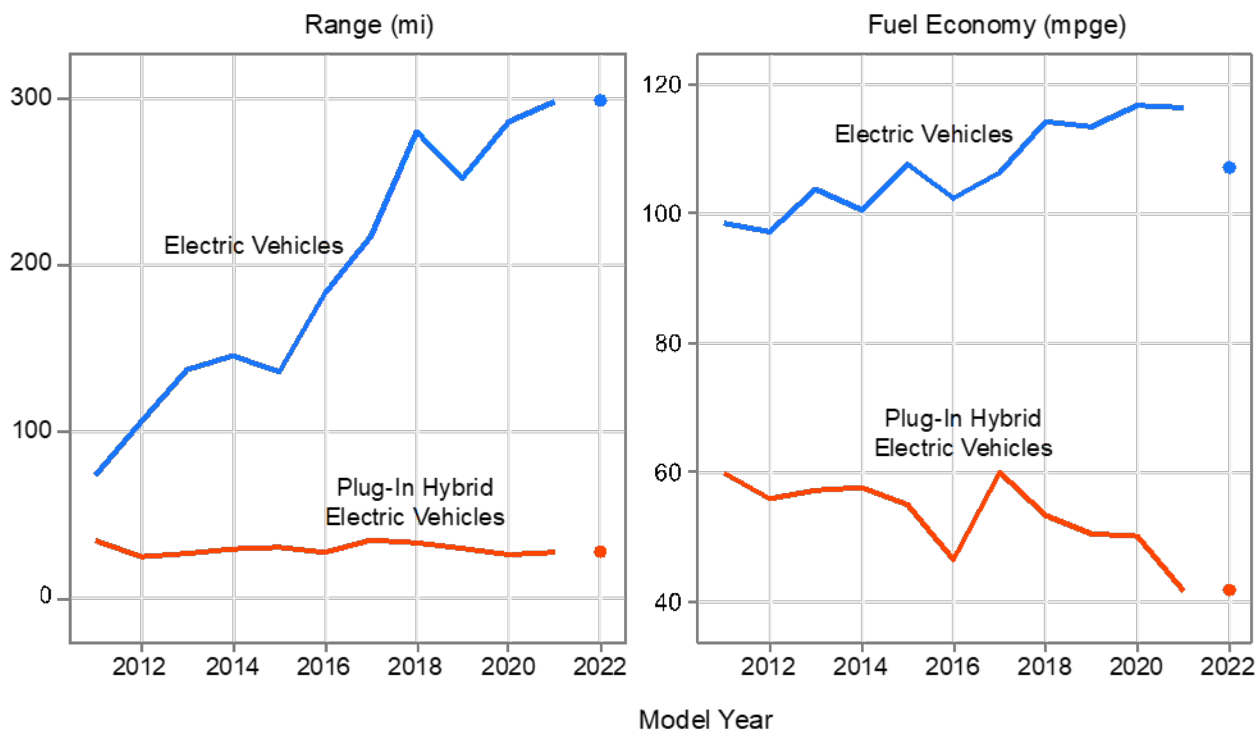

Figure 3-6 Charge Depleting Range and Fuel Economy for BEVs and PHEVs

Figure 3-7 (U.S. EPA 2022) shows the model year 2021 production volume of BEVs, PHEVs and FCEVs. More than 600,000 BEVs, PHEVs, and FCVs were produced in the 2021 model year. Of those vehicles, about 73 percent were BEVs, 27 percent were PHEVs, and less than 1 percent were FCEVs.

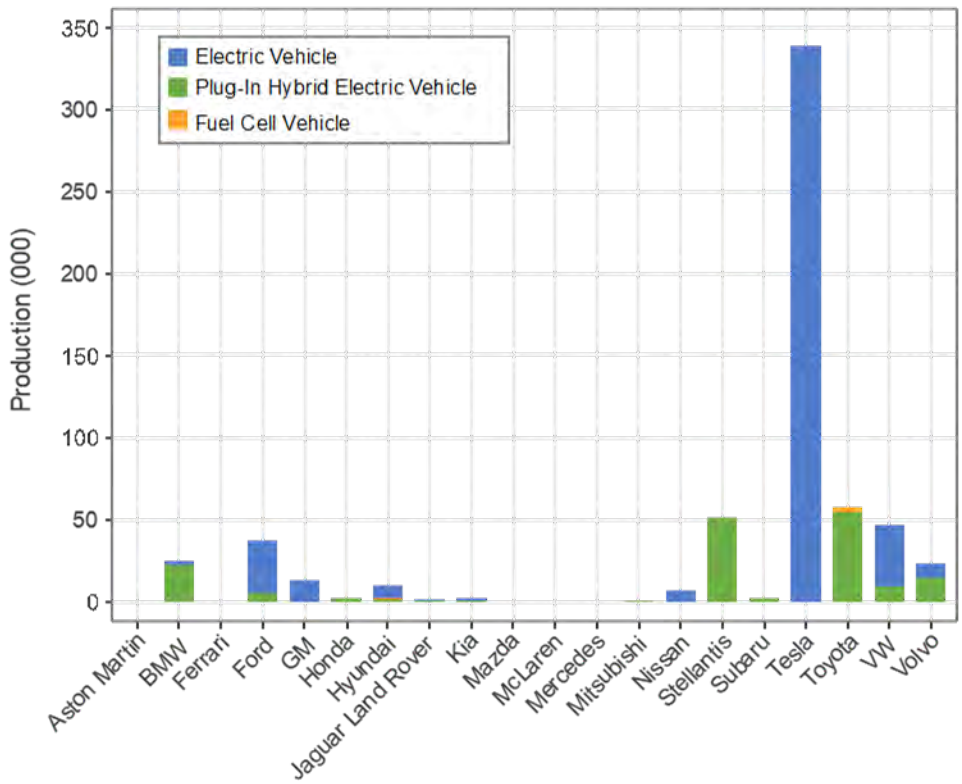

Figure 3-7 Model Year 2021 Production of BEVs, PHEVs, and FCEVs

3.1.2 Medium-duty Vehicle Technologies and Trends

The medium-duty sector is also experiencing a shift toward electrification in a similar manner to the light-duty sector and within several important market segments. As cited in I.A.2 of the Preamble, numerous commitments to produce all-electric medium-duty delivery vans have been announced by large fleet owners including FedEx, Amazon, and Wal-Mart, in partnerships with various OEMs. This abrupt shift to full electrification from a fleet that is currently predominantly gasoline- and diesel-powered suggests that the operators of these fleets consider full electrification as the best available and most cost-effective technology for meeting their mission objectives, while also reducing the emissions from their business operations. Owing to the large size of these vehicle fleets, this segment alone is likely to represent a significant portion of the future electrification of the medium-duty vehicle fleet.

As described in draft RIA Chapter 1.2.2.1 and within § III.A of the Preamble to this proposed rule, the Agency is proposing to use the term "Medium-duty vehicle" (MDV) for the first time within its regulations. MDVs are comprised of the following weight categories:

- Class 2b - 8,501 pounds to 10,000 pounds rated gross vehicle weight (GVWR)
- Class 3 - 10,001 to 14,000 pounds GVWR

For more information, please refer to § III.A.1 of the Preamble to this proposal. MDVs can either be "incomplete" chassis cabs onto which customized body work or beds are added after their original manufacture or are "complete" pickup trucks or vans. Examples of incomplete vehicles customized for specific applications include motorhomes, ambulances, wreckers, panel vans, flatbeds, etc. (see Figure 3-8). In model year 2020, less than 5 percent of MDV sales were incomplete vehicles, with the remainder being complete.

Figure 3-8: Examples of incomplete MDV chassis finished with customized bodies for specific applications.

MDV pickup trucks are generally built with heavier frames and designed with sufficient brake and suspension systems to support significantly higher towing capability than found in light-duty pickup trucks. MDV pickup truck applications have considerable tow capability, which can be in excess of 20,000 pounds gross combined weight rating (GCWR) pickups with gasoline engines and can be over 40,000 pounds GCWR for pickups with diesel engines. MDV vans have comparable payload carrying ability to MDV pickups; however, they typically have significantly lower tow capability with GCWR comparable to, or less than, many light-duty pickups.

There are both diesel engine and spark-ignition gasoline engine applications in MDV. Their shares of MDV sales are shown for both pickups, vans, and incomplete vehicles in Table 3-1. Both gasoline and diesel engines used in van applications and some gasoline engines used in pickup truck applications are derived from light-duty applications. Examples include the:

- Mercedes Benz OM654 diesel engine in the MY2023 Sprinter Van (engine family shared with the C-Class and E-Class passenger cars and GLC CUV sold outside the U.S.)

- Mercedes Benz M274 turbocharged GDI engine in the MY2023 Sprinter Van (engine family shared with the C-Class and E-Class passenger cars and GLC light-duty CUV)
- Ford 3.5L EcoBoost in the MY2015-2023 Transit Van (engine family shared with the 2011-2016 Ford F150 light-duty pickup)
- GM LWN diesel engine in the Chevrolet and GMC vans (engine family shared with Chevrolet Colorado light-duty pickup)
- RAM 6.4L Hemi in the RAM 2500 and 3500 pickups (engine family shared with RAM light-duty pickups, and Dodge, Jeep and Chrysler passenger cars and light-duty CUVs)
- GM L8T naturally aspirated GDI engine used in Chevrolet Silverado 2500HD and 3500HD pickups and G3500 vans and sharing the GM "Generation V" V8 engine family with many GM light-duty trucks, CUVs, SUVs and some passenger cars.

Table 3-1: Percentage of MY2020 sales and sales volumes of pickup, van, and incomplete MDVs by fuel type

	Pickups		**Vans**		**Incomplete Vehicles**		**Grand Total**
Fuel Type*	Gasoline	Diesel	Gasoline	Diesel	Gasoline	Diesel	
MY2020 sales share	24.2%	37.1%	30.4%	3.7%	4.5%	0.1%	100%
MY2020 sales	213,796	327,488	269,038	32,351	40,043	978	883,694

*Other sources of powertrain energy, including electrification, accounted for <1% of MDV sales in MY2020.

While many gasoline engine families used for pickup truck applications share engine families and/or key design elements with light-duty applications, in some cases engine block materials may shift from aluminum in light-duty applications to iron for MDV applications (e.g., GM L8T engine). In other cases, engine families are solely used in MDV and are also shared with heavier weight-class trucks above MDV, for example Ford's 7.3 L Super-duty naturally aspirated, port-fuel-injected, naturally aspirated gasoline engine used in the F250 and F350 MDV pickups, which is also used in the heavier Ford F450/550/600 and F650/750. Diesel equipped MDV pickup trucks are equipped with 6L and larger engines, some of which have peak torque ratings in excess of 1000 ft-lbs. Diesel engines used in MDV pickup trucks have no light-duty counterparts and most also share engine families with significantly heavier classes of vehicles (e.g., weight classes 4 through 7) (Title 40 CFR § 86.1803-01 2023).

The use of commercial vans for last mile delivery in the U.S. has grown significantly since the start of the global COVID-19 pandemic, primarily through the growth of e-commerce[24]. In the U.S., 2021 e-commerce sales totaled $870 billion, which represents an increase of over 14 percent from 2020, and over 50.5 percent compared to 2019. U.S. E-commerce represented just over 13.2 percent of all retail sales in 2021 (U.S. Census Bureau 2022). Globally, the automotive

[24] Commercial transactions, including retail sales, conducted electronically on the internet.

market supporting e-commerce was valued at over $66 billion in 2021 and is expected to grow to over $75 billion by the end of 2022 and to over $213 billion by 2029. (Fortune Business Insights 2022). Based on the results of a recent pilot study of the electrification of commercial delivery vans and step vans, the North American Council for Freight Efficiency identified this segment as "100% electrifiable" (North American Council for Freight Efficiency 2021).

Vans using dedicated battery-electric vehicle (BEV) architectures are beginning to enter the U.S. market. The first mass-produced models became available for MY2023 and additional production volume and models have been announced for MY2024. Initial dedicated BEV van chassis have been predominantly targeted towards parcel delivery and include the GM BrightDrop Zevo 400 and Zevo 600; and the Rivian EDV 500 and EDV 700 (Figure 3-9). Both GM and Rivian share key electric powertrain and battery storage components between their light-duty and/or MDPV BEV products and their dedicated BEV commercial van products, which provides improved economies of scale for their commercial BEV MDV vans. EPA does not require manufacturers to the electric range of MDVs, however manufacturers and key customers (e.g., Amazon and FedEx) appear to be targeting approximately 150 miles of range based public data battery pack capacity of approximately 135 kWh for the EDV700, approximately 115-kWh for the Zevo 400, and standard capacity of approximately 115-kWh for the Zevo 600 with an optional 165-kWh capacity (Seabaugh 2022) (BrightDrop 2022) (Battery Design 2022).[25]

Figure 3-9: Rivian EDV 700 (left) and GM BrightDrop ZEVO 600 MDV (right) vans operated by Amazon and FedEx, respectively.

Although no PHEV pickup truck or MDV applications currently exist nor have they been explicitly been modeled within the proposed rule, EPA believes the PHEV architecture may lend itself well to future applications, particularly MDV pickup truck applications at or below 10,000 pounds GVWR and MDV vans used outside of last-mile delivery applications. One major manufacturer, Stellantis, recently announced at the 2023 Consumer Electronics Show that a range-extender will be an option on their new full-size electric pickup (Riley 2023). A MDV PHEV pickup architecture would provide several benefits: some amount of zero emission electric range (depending on battery size); increased total vehicle range during heavy towing and

[25] BrightDrop useable pack capacity calculated from: public data on GM ultium prismatic NCMA cells at 103 Ah cell capacity, 3.7 VDC nominal cell voltage; public data on GM Ultium modules at 24 cells per module; and BrightDrop public data on the availability of 14 module and 20 module Ultium battery packs (Battery Design 2022) (BrightDrop 2022).

hauling operations using both charge depleting and charge sustaining modes (depending on ICE-powertrain sizing); job-site utility with auxiliary power capabilities similar to portable worksite generators, and the efficiency improvements normally associated with strong hybrids that provide regenerative braking, extended engine idle-off, and launch assist for high torque demand applications. Depending on the vehicle architecture, PHEVs used in MDV pickup applications may also offer additional capabilities, similar to BEV pickups, with respect to torque control and/or torque vectoring to reduce wheel slip during launch in trailer towing applications. In addition, PHEVs may help provide a bridge for commercial consumers that may not be ready to adopt a fully electric MDV pickup.

EPA has initiated contract work to investigate likely technology architectures of both PHEV and internal combustion engine range-extended electric light-duty and MDV pickup trucks that we anticipate will provide data in time for the final rule. Costs for potential PHEV designs for this application are outlined in DRIA 2.6.1.4.

While the agency anticipates that electrification of vans will be a cost-effective compliance strategy for meeting the proposed GHG and criteria pollutant standards, vehicle manufacturers may also choose to improve their conventional, ICE-based vehicles. MDV GHG emissions can be reduced via improving powertrain efficiency or by making improvements to road loads through improved aerodynamics, reduced tire rolling resistance and reduced vehicle weight. For a summary of conventional MDV GHG emissions control technology, please refer to Chapter 2.5 of the Heavy-duty Phase 2 GHG Regulatory Impact Analysis. MDV emissions that contribute to criteria air pollutants can be reduced by improvements to engine management systems, fuel systems, evaporative emissions control systems, catalyst systems, and via the addition of modern exhaust filtration systems such as the gasoline particulate filter (GPF). Many of the anticipated controls for future MDVs share significant design elements with criteria pollutant emissions controls used for light-duty applications and are discussed in more detail in Chapter 3.4.

3.1.3 PEV Feasibility

3.1.3.1 PEV Technological Feasibility

These trends in light- and medium-duty vehicle technology show that BEV and PHEV technologies are already being increasingly employed across the fleet in both light-duty and medium-duty applications. This market shift toward electrification is also evidence that BEVs and PHEVs are seen not only as an effective and feasible means to comply with emissions regulations but also as an effective and attractive solution that can serve the functional needs of a large portion of light- and medium-duty vehicle buyers. This ongoing market shift also represents an opportunity to accelerate needed reductions in criteria pollutant and GHG emissions by encouraging and accelerating continued rapid uptake of these technologies in the U.S. light- and medium-duty vehicle fleet.

As noted previously, zero- and near-zero emissions technologies are more feasible and cost-effective now than at the time of prior rulemakings. The developments in vehicle electrification that have brought this about are driven in part by the industry's need to compete in a diverse market, as zero-emission transportation policies continue to be implemented across the world. Section I.A.2 of the Preamble provided a comprehensive analysis of recent events in the advance of electrification of the automotive sector, and established a number of important points, which are reviewed briefly below (U.S. EPA 2023). Citations for the content in this section can be found in the parallel discussions in Section I.A.2 of the Preamble, unless specifically cited here.

One conclusion of that discussion was that advancement of vehicle electrification is likely being driven in part by automakers' need to compete in a diverse global marketplace in which many jurisdictions are continuing to implement zero-emission transportation policies. Specifically:

- At least 20 countries across the world, as well as numerous local jurisdictions, have announced plans to shift all new passenger car sales to zero-emission vehicles in the coming years -- Norway by 2025; Austria, the Netherlands, Denmark, Iceland, India, Ireland, Israel, Scotland, Singapore, Sweden, and Slovenia by 2030, Canada, Chile, Germany, Thailand, and the United Kingdom by 2035, and France, Spain, and Sri Lanka by 2040.

- Many of these announcements extend to light commercial vehicles as well, and several also target a shift to 100 percent all-electric medium- and heavy-duty vehicle sales (Norway targeting 2030, Austria 2035, and Canada and the United Kingdom 2040).

- Together, the countries that had, by the end of 2022, set a target of 100 percent light-duty zero-emission vehicle sales by 2035, represent at least 25 percent of today's global light-duty vehicle market.

- Countries of the European Union that were not represented in that total will drive the total even higher, as the European Parliament approved a measure in 2023 to phase out sales of ICE passenger vehicles in its 27 member countries by 2035.

- In 2021, BEVs and PHEVs together already comprised about 18 percent of the new vehicle market in Western Europe, led by Norway which reached almost 80 percent BEV and 88 percent combined BEVs and PHEVs in 2022.

- In the U.S., an increasing number of U.S. states have taken actions to shift the light-duty fleet toward zero-emissions technology, including California, New York, Massachusetts, and Washington state, likely to be followed by Oregon and Vermont.

In addition to spurring industry development of BEV and PHEV technology, developments such as these suggest a growing global consensus that BEV and PHEV technologies are feasible candidates for increased use as an emissions-reducing technology. For additional details and citations regarding these domestic and global developments, please refer to Preamble I.A.2.ii.

The Preamble also established that demand for these vehicles in the U.S. is rapidly increasing, even under current standards. Major points established by that discussion include (U.S. EPA 2023):

- The production of new PEVs (including both BEVs and PHEVs) is roughly doubling every year, projected to be 8.4 percent of U.S. light-duty vehicle production in 2022, up from 4.4 percent in MY 2021 and 2.2 percent in MY 2020.

- In California, new light-duty zero-emission vehicle (ZEV) sales in 2022 reached about 19 percent of all new cars, up from 12 percent in 2021 and more than twice the share from 2020.
- The number of BEV and PHEV models offered for sale in the U.S. more than doubled between MY 2015 and MY 2021, and is expected to increase to more than 80 models by MY 2023 and more than 180 by 2025.
- In 2022, BEVs alone accounted for about 807,000 U.S. new car sales, or about 5.8 percent of the new light-duty passenger vehicle market, up from 3.2 percent BEVs the year before.

Before the Inflation Reduction Act (IRA) became law, analysts were already projecting that significantly increased penetration of plug-in electric vehicles would occur in the United States and in global markets. Studies cited in the Preamble established that:

- In 2021, IHS Markit predicted a nearly 40 percent U.S. PEV share by 2030.
- More recent projections by Bloomberg New Energy Finance suggest that under current policy and market conditions, and prior to the IRA, the U.S. was on pace to reach 40 to 50 percent PEVs by 2030; when adjusted for the effects of the Inflation Reduction Act, this estimate increases to 52 percent.
- Another study by the International Council on Clean Transportation (ICCT) and Energy Innovation that includes the effect of the IRA estimates that the share of BEVs will increase to 56 to 67 percent by 2032.
- Similarly, Goldman Sachs projects a 50 percent share for BEVs in the U.S. in 2030, 70 percent in 2035 and 85 percent in 2040.

Although the assumptions and other inputs to these forecasts vary, they point to greatly increased penetration of electrification across the U.S. light-duty fleet in the coming years, without specifically considering the effect of increased emission standards under this proposed rule.

A similar trend was seen in forecasts reviewed for the global market, showing that the shift toward electrification in the U.S. is part of a global phenomenon:

- Global light-duty passenger PEV sales (including BEVs and PHEVs) reached 6.6 million in 2021, bringing the total number of PEVs on the road to more than 16.5 million globally.
- Global sales of fully-electric BEVs rose to 7.8 million in 2022, an increase of about 68 percent from the previous year and representing about 10 percent of the new global light-duty passenger vehicle market.
- In June 2022, Bloomberg New Energy Finance predicted that global sales will rise to 21 million in 2025 (implying an annual growth rate of about 39 percent from 2022),

with total global vehicle stock reaching 77 million BEVs by 2025 and 229 million BEVs by 2030.

We also observed that the year-over-year growth in U.S. BEV sales suggests that an increasing share of new vehicle buyers are concluding that a PEV is the best vehicle to meet their needs, for example:

- PEV owners often describe specific advantages of PEVs as key factors motivating their purchase, such as responsive acceleration, improved performance and handling, quiet operation, lower cost of ownership, and the ability to charge at home.
- A 2022 survey from Consumer Reports shows that, even at a time when many consumers are not yet as familiar with BEVs as with ICE vehicles, more than one third of Americans would either seriously consider or definitely buy or lease a BEV today if they were in the market for a vehicle.
- According to the U.S. Bureau of Labor Statistics, growth in PEV sales is driven in part by growing consumer demand and growing automaker commitments to electrification.
- Most PEV owners who purchase a subsequent vehicle choose another PEV, and often express resistance to returning to an ICE vehicle after experiencing PEV ownership.
- Many analysts believe that as PEVs continue to increase their market share, PEV ownership will continue to broaden its appeal as consumers gain more exposure and experience with the technology and with the benefits of PEV ownership, with some analysts suggesting that a "tipping point" for PEV adoption may then result.

We also noted that, while the purchase price of BEVs is typically higher than for most comparable ICE vehicles at this time, the price difference is widely expected to narrow or disappear, particularly for BEVs, as the cost of batteries and other components fall in the coming years. More specifically, we observed that:

- An emerging consensus suggests that purchase price parity is likely to occur by the mid-2020s for some vehicle segments and models, and for a broader segment of the market on a total cost of ownership (TCO) basis.
- By some accounts, a compact car with approximately 150 miles of range may already be possible to produce and sell for the same price as a compact ICE vehicle.
- Many analysts expect examples of price parity to increasingly appear over the mid- to late-2020s for larger vehicles and those with a longer range.
- Prospects for price parity improve greatly when considering state and federal purchase incentives. For example, the Clean Vehicle Credit of up to $7,500 provided under the Inflation Reduction Act may in many cases exceed the current price premium for some BEV models.
- Many expect TCO parity to precede price parity by several years, as it accounts for the reduced cost of operation and maintenance for BEVs; for example, Kelley Blue Book

already estimates that the lowest TCO for the full-size pickup and luxury car classes of vehicle are BEVs.

- TCO parity is of particular interest to commercial and fleet operators, for whom lower TCO is a compelling business consideration.

We also showed that a proliferation of announcements by automakers in the past two years, signaling a rapidly growing shift in product development focus among automakers away from internal-combustion technologies and toward electrification, provides further evidence of the feasibility of BEVs and PHEVs as an emissions-reducing technology. Section I.A.2 of the Preamble introduces and cites many of these announcements, which are repeated here for context:

- In January 2021, General Motors announced plans to shift its light-duty vehicles entirely to zero-emissions by 2035.
- In March 2021, Volvo announced plans to make only electric cars by 2030, and Volkswagen announced that it expects half of its U.S. sales will be all-electric by 2030.
- In April 2021, Honda announced a full electrification plan to take effect by 2040, with 40 percent of North American sales expected to be fully electric or fuel cell vehicles by 2030, 80 percent by 2035 and 100 percent by 2040.
- In May 2021, Ford announced that they expect 40 percent of their global sales will be all-electric by 2030.
- In June 2021, Fiat announced a move to all electric vehicles by 2030, and in July 2021 its parent corporation Stellantis announced an intensified focus on electrification across all of its brands.
- In July 2021, Mercedes-Benz announced that all of its new architectures would be electric-only from 2025, with plans to become ready to go all-electric by 2030 where possible.
- In August 2021, the Alliance for Automotive Innovation expressed continued commitment to their members' announcements of a shift to electrification and expressed their support for the goal of achieving 40 to 50 percent sales of zero-emission vehicles by 2030.
- In December 2021, Toyota announced plans to introduce 30 BEV models by 2030.
- According to a tabulation of these and many other OEM announcements, the sales collectively implied by such announcements to date would conservatively amount to about 50 percent new light-duty zero-emission vehicle sales in the U.S. by 2030.

- In addition, numerous commitments to produce all-electric medium-duty delivery vans have been announced by large fleet owners including FedEx, Amazon, and Wal-Mart, in partnerships with various OEMs.

We also noted that these announcements and others like them continue a pattern over the past several years in which most major manufacturers have taken steps to aggressively invest in zero-emission technologies and reduce their reliance on the internal-combustion engine in various markets around the globe:

- One cited analysis indicated that 37 of the world's automakers are planning to invest a total of almost $1.2 trillion by 2030 toward electrification, a large portion of which will be used for construction of manufacturing facilities for vehicles, battery cells and packs, and materials. This would support up to 5.8 terawatt-hours of battery production and 54 million BEVs per year globally.

- Another cited analysis showed that a significant shift in North American investment is occurring toward electrification technologies, with more than 90 percent ($36 billion of about $38 billion) of total automaker manufacturing facility investments announced in 2021 being slated for electrification-related manufacturing in North America, with a similar proportion and amount on track for 2022.

- In September 2021, Toyota announced large new investments in battery production and development to support an increasing focus on electrification, and in December 2021, announced plans to increase this investment.

- In December 2021, Hyundai closed its engine development division at its research and development center in Namyang, South Korea in order to refocus on BEV development.

- In summer 2022, Hyundai invested $5.5 billion to fund new battery and electric vehicle manufacturing facilities in Georgia, and recently announced a $1.9 billion joint venture with SK to fund additional battery manufacturing in the U.S.

- In September 2022, jointly with the Environmental Defense Fund, General Motors announced a set of recommendations that "seek to accelerate a zero-emissions, all-electric future for passenger vehicles in model year 2027 and beyond," including a recommendation that EPA establish standards to achieve at least a 60 percent reduction in GHG emissions (compared to MY 2021) and 50 percent zero-emitting vehicles by MY 2030.

The shift to PEVs is anticipated to accelerate in the United States over the next decade as provisions of the Inflation Reduction Act of 2022 (IRA) begin to take effect (Public Law 117-169 2022). The IRA has key provisions that will reduce the cost of PEVs to consumers, reduce the cost of battery manufacturing in the U.S. for automakers, and foster significant emissions reductions from the U.S. electric power sector. These include:

- Vehicle Provisions including the Domestic Manufacturing Conversion Grant Program, Advanced Technology Vehicle Manufacturing Program, and expanded authorities for the DOE Loan Programs Office
- Clean Vehicle Tax Credits including 30D, 45W, 25E and 30C
- Advanced Manufacturing Production Credit
- Power Sector Provisions
- Clean Electricity Production and Investment Tax Credits
- Renewable electric generation incentives
- Grid battery storage incentives
- Existing Nuclear Production Tax Credit
- Extends nuclear EGU service life
- Carbon Capture and Storage 45Q Tax Credit

For further discussion of the impacts of the IRA on the electric power sector, please refer to Chapter 5.2.3 of the DRIA.

Taken together, the developments summarized in this section indicate that proven, zero-emission PEV technology is an available and feasible way to greatly reduce emissions and is capable of being implemented across a large portion of the fleet.

In Preamble V.B, we addressed the overall technological feasibility and lead time necessary for manufacturers to meet the proposed standards using the array of proven, advanced vehicle technologies that are available to them. There we noted that the technological readiness of the auto industry to meet the proposed standards for model years 2027-2032 is best understood in the context of over a decade of light-duty vehicle emissions reduction programs in which the auto industry has introduced emissions-reducing technologies in a wide lineup of ever more cost effective, efficient, and high-volume vehicle applications. The developments outlined in this section further underscore the fact that PEV technology is already poised to enter the fleet in increasing penetrations.

In considering feasibility of the proposed standards, EPA also considers the impact of available compliance flexibilities on automakers' compliance options, as well as constraints posed by the typical cadence of manufacturer redesign cycles. In Preamble V.B we described how EPA's technical assessment for this proposal accounts for redesign limits.[26] Once a redesign opportunity is encountered, we have assumed limits to the rate at which a manufacturer can ramp in the transition from an ICE to a BEV vehicle. We have also applied limits to the ramp up of battery production, considering the time needed to increase the availability of raw materials and

[26] In our compliance modeling, we have limited vehicle redesign opportunities in our compliance modeling to every 7 years for pickup trucks, and 5 years for all other vehicles.

expand battery production facilities. These limits as they are applied in OMEGA are discussed in DRIA Chapter 2.

Overall, it is our assessment that PEV technology is technologically feasible to play a strong role in manufacturer compliance with the proposed standards, and that there is sufficient lead time for the industry to more deploy this technology to successfully comply with the proposed standards.

Preamble V.B describes the level of PEV penetration indicated by our compliance analysis, which in the central case of the proposal indicates roughly two-thirds of the light-duty passenger vehicles sold in 2032 would be BEVs. We believe that the discussion in this section outlining the rapid growth in BEV penetration that is already occurring, the breadth and significance of manufacturer plans and investments that underscore this movement, and the overall momentum evident in the industry, provides strong evidence for the feasibility of BEV technology and supports our assessment that the projected levels of BEV penetration under the scenarios of the proposal are feasible and achievable at a reasonable cost. This conclusion is further supported by our analysis of critical minerals, manufacturing capacity, and mineral security, which is introduced in Preamble IV.C.6 and further examined in the next section of this DRIA.

For a full discussion of technological feasibility and lead time for compliance with the proposed standards, please see Preamble V.B.

While EPA has not explicitly modeled the adoption of PHEV architectures within the analysis for this proposal, the agency recognizes that PHEVs can also provide significant reductions in GHG emissions and that some vehicle manufacturers may choose to utilize this technology as part of their technology offering portfolio in response to customer demands/needs and in response to EPA emission standards (as some firms are already doing today). PHEVs have been available in the light-duty vehicle market in the U.S. for more than a decade and many models are now available across a larger breadth of vehicle types, including sedans, such as the Toyota Prius Prime; and cross-over SUVs, such as the Subaru Crosstrek, Ford Escape PHEV, Kia Niro Plug-in Hybrid, Kia Sportage Plug-In Hybrid, Hyundai Tucson Plug-In Hybrid, Mitsubishi Outlander PHEV and Toyota RAV4 Prime. Stellantis currently offers a minivan PHEV, the Chrysler Pacifica Hybrid; and two large PHEV SUVs are available, the Jeep Grand Cherokee 4xe and Lincoln Corsair Grand Touring. This further confirms that the modeling for the proposed standards is illustrative of a reasonable path to compliance for automakers, but is not intended to be prescriptive and may be conservative (i.e., overestimate costs of compliance), as discussed further in Preamble V.B.

3.1.3.2 Critical Minerals and Manufacturing

In Section IV.C.6 of the Preamble, we provided a comprehensive analysis of recent events in the growth of U.S. and global battery manufacturing capacity, reviewed the role and importance of critical minerals, and considered the outlook for critical mineral supply and demand. In that discussion, we established a number of important points, which are reviewed briefly in this section. The remainder of this section details how we used this information to develop a modeling constraint meant to represent a production-based limit on the rate of penetration of PEV technology into the fleet during the time frame of the proposed standards. Citations for the content in this section can be found in the parallel discussions in Preamble IV.C.6, unless specifically cited here.

The Preamble discussion established a number of key observations about the status of critical minerals and manufacturing capacity, and the outlook for development of the supply chain in response to industry investment and government policy (U.S. EPA 2023):

- Although much of the supply chain supporting the manufacture of PEVs is located outside of the U.S., more than half of battery cells and 84 percent of assembled packs in PEVs sold in the U.S. from 2010 to 2021 were produced in the U.S.
- This suggests that PEV production in the U.S. need not be heavily reliant on foreign manufacture of battery cells or packs as PEV penetration increases and domestic mineral and cell production comes online.
- Many automakers are building battery and cell manufacturing facilities in the U.S. and are also taking steps to secure domestically sourced minerals and commodities to supply production for these plants.
- Analysis of constructed and planned plant capacity for assembly of cells and packs indicates that battery manufacturing capacity does not appear to pose a critical constraint to expected uptake of PEVs, either globally or domestically.
- Domestically, construction announcements made by the major automakers indicate that the U.S. will have more than 800 GWh of cell or battery manufacturing capacity by 2025, and 1000 GWh by 2030, enough to supply from 10 to 13 million BEVs per year.

We also drew observations regarding which minerals are of greatest concern as a potential constraint on PEV production during the time frame of the rule:

- Mineral demand for ICE catalyst production is relatively stable and would not be expected to increase as a result of electrification.
- Rare earths used in permanent magnet motors have potential alternatives in the use of induction machines or other electric machine technologies that do not require rare-earth magnets, or in the use of advanced ferrite or other advanced magnets.
- On a sheer quantity basis and probably also on a value basis, battery minerals are likely to be the most important mineral-related constraint on PEV production during the time frame of the rule.
- Of these, the most attention is commonly given to lithium, nickel, cobalt, and graphite.
- Currently, most mining and refining of these minerals occurs outside of the U.S. and they are largely imported as refined products.
- The U.S. does not lack significant deposits of these minerals, and has formerly produced them, but relatively little mining and refining capacity is currently in operation or remains undeveloped.

- The development of mining and refining capacity in the U.S. is a primary focus of industry toward building a robust domestic supply chain for electrified vehicle production.
- For example, LG Chem has announced plans for a cathode material production facility in Tennessee, said to be sufficient to supply 1.2 million high-performance electric vehicles per year by 2027.

We also noted that further development of a domestic mineral supply chain will be 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 provisions that incentivize domestic production of batteries and critical minerals, including a $7,500 Clean Vehicle Credit for vehicles manufactured in North America that use domestically produced components and mineral products, and production tax credits that apply to domestically produced cells, modules, electrode active materials, and critical minerals, that can reduce battery manufacturing cost by a third 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 matching private investment, 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.

We also noted the following observations about forecast global supplies of refined critical minerals:

- According to analyses by Department of Energy's Li-Bridge, no shortage of cathode active material or lithium chemical supply is seen globally through 2035 under current projections of global demand.
- The International Energy Agency reached similar conclusions for cobalt and nickel, projecting that lithium would be in sufficient supply through at least 2028, before consideration of new DOE projections of additional capacity that could further boost lithium supply beyond current IEA and BNEF projections.
- Despite recent short-term fluctuations in price, the price of lithium is expected to stabilize at or near its historical levels by the mid-2020s, further suggesting that a critical long-term shortage is not expected to develop.

In the context of all of the findings reviewed above, EPA recognizes that the global minerals industry is already anticipating and preparing for accelerated growth in demand for critical minerals resulting from already-existing expectations of greatly increased global PEV 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 proposed 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 proposed standards but from these ongoing forces that are already driving the global industry to increase mineral 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 proposed standards.

In modeling potential PEV penetration into the fleet as a result of the proposed standards, EPA considered how best to represent any limitations that are likely to be imposed by the supply chain. Potential constraints on availability of minerals that are used in the manufacture of PEVs are particularly relevant to projecting practical limits on the rate of penetration of PEVs into the fleet in the future. EPA considered data from industry analysts, including Wood Mackenzie and Benchmark Minerals Intelligence, to pursue a quantitative and qualitative understanding of the future availability of these critical battery minerals during the time frame of the rule.

From a modeling perspective, the question of how to constrain the modeled rate of BEV penetration to remain within limits imposed by the developing supply chain is an important one. As part of the rulemaking analysis, EPA uses its OMEGA model to identify compliance pathways (in other words, applications of available technology to the fleet) by which manufacturers can meet the standards. The OMEGA model selects among available advanced vehicle technologies and applies them to the fleet in the most cost-effective way, given the cost of each technology and its effectiveness at achieving manufacturer compliance within the fleet averaging structure of the program. Although BEV technology has a higher absolute cost than many other technologies, it is particularly attractive to manufacturers because BEVs achieve zero tailpipe emissions and are credited with such under the compliance accounting. On the other hand, there is likely to be a limit to the rate at which BEV technology can phase into the fleet due to various constraining forces such as growth in consumer acceptance, timing of refresh/redesign cycles, activation of battery cell and pack manufacturing capacity, and critical mineral availability, particularly in the early years of the analysis. If these constraints were not represented, the OMEGA model might select BEV technology at a rate that results in a faster penetration of BEVs into the fleet than these real-world constraints might practically allow. EPA implemented several constraints in the OMEGA model to account for these factors.

Consumer acceptance is discussed in more detail in Chapter 4 of this DRIA, and its representation by means of S-curves in the OMEGA model is discussed in Chapter 2.6.5. Refresh/redesign cycles are also represented in the OMEGA model and are discussed in more detail in Chapter 2.6.4.1 of this DRIA as well as IV.C of the Preamble.

To account for potential limits posed by battery manufacturing capacity and critical minerals, EPA implemented a constraint in terms of Gigawatt-hours (GWh) of lithium-ion battery production per year that could be available for BEVs supplying the U.S. new vehicle fleet. As described below, we developed this constraint by considering estimates of existing and announced battery production capacity in North America and comparing these forecasts to estimates of projected lithium supply and demand. To develop a modeling constraint on PEV production, we considered available data on forecast battery manufacturing capacity, global lithium demand, and global lithium chemical production. As all such estimates concern prediction of future events and are by nature uncertain (particularly in the out years), we adopted a simplified approach that provided what we consider to be a reasonable and conservative view of future PEV production capacity as constrained by manufacturing and mineral supply.

We selected lithium supply as the primary mineral-based limiting factor for several reasons. In Preamble IV.C.6 we noted that cobalt, nickel, and manganese are important to today's leading battery chemistry formulations, but we also note that there is some flexibility in choice of cathode minerals, and in many cases, opportunity will exist to reduce cobalt and manganese content or to employ iron-phosphate cathode chemistries that do not utilize nickel, cobalt or manganese. Graphite is used as the anode of most current and near-term PEV battery chemistries, and all require lithium in the form of lithium carbonate or lithium hydroxide in the electrolyte and the cathode. The role of natural graphite in many cases can be served by artificial graphite or highly refined hard or amorphous carbon. However, lithium has no substitute in commercially produced automotive applications at this time (however, see the discussion of alternatives to lithium under development, later in this section). Although the common chemistries vary in their need for either lithium hydroxide or lithium carbonate, either can potentially be produced from available lithium sources.

Further, and as described in greater detail in Preamble IV.C.6, we considered the projections of cobalt, nickel, and lithium supply and demand published in 2022 by the International Energy Agency (IEA), which concluded that supply of cobalt and nickel should be sufficient to meet demand between 2020 and 2030 for the two most likely demand scenarios modeled, while lithium demand may begin to approach available supply after 2025 (for further discussion and citations see Preamble IV.C.6). By contrast, as also described in Preamble IV.C.6, projections made by DOE in November 2022 indicate that global supplies of cathode active material (and incidentally, lithium chemical products) are expected to be sufficient to meet expected global demand through 2035.

The observations described above, taken together, suggest that critical battery mineral supply is likely to be adequate to meet anticipated demand, in some cases by a significant margin. This data also suggests that, among the primary critical minerals needed for battery manufacturing, growth in demand for lithium would likely be the first to approach available supply, if a battery mineral shortage were to be encountered. Accordingly, we focused on lithium availability as a potential limiting factor on the rate of growth of PEV production, and thus the most appropriate basis for establishing a modeling constraint on PEV penetration into the fleet over the time frame of the proposed rule.

With regard to battery manufacturing capacity in the U.S., we considered estimates of announced manufacturer plans and currently installed capacity as reported in mid-2022 by S&P Global and in late 2022 by Argonne National Laboratory. These sources are discussed in more detail in Preamble IV.C.6. S&P Global indicated that U.S. battery manufacturing capacity will reach 382 GWh by 2025 (S&P Global 2022a), and 580 GWh by 2027. (S&P Global 2022b).

A later and more detailed estimate by Argonne National Laboratory reported 838 GWh of capacity by 2025, 896 GWh by 2027, and 998 GWh by 2030, the vast majority representing cell manufacturing capacity, and sufficient to supply final pack assembly for 10 to 13 million BEVs per year by 2030 (Argonne National Laboratory 2022).While it remains possible that some of this nameplate capacity may be implemented in stages to match suppliers' expectations of cell demand, we assumed that the rapidly increasing demand scenario that the industry widely anticipates will incentivize rapid buildout of the full announced capacity. In such a scenario, the primary lead time component in meeting new demand is likely to be planning and construction of the base plant, rather than outfitting production lines once the plant is built.

Although these forecasts suggest that planned manufacturing facility capacity could be a potential basis for a modeling constraint on battery production, this would not reflect the possibility that operating capacity could be constrained by mineral availability. We thus sought to condition these production capacities by comparing them to estimates of global lithium supply and demand.

Here it is relevant to note that, although the Inflation Reduction Act incentivizes use of domestically sourced and processed mineral products, it only ties these products to availability of the related tax incentives (primarily the Clean Vehicle Credit under 30D) and does not prohibit use of imported mineral products by manufacturers that cannot secure domestic sources. Thus, it is the global supply for lithium, not only domestically sourced supply, that potentially constrains battery production.

We then referred to proprietary projections of lithium chemical capacity obtained from Wood Mackenzie through a service subscription (Wood Mackenzie 2022). Forecast lithium production in tons per year was reported as lithium carbonate equivalent (LCE) which EPA converted to GWh of gross battery capacity using a widely accepted conversion factor. As a first-order, conservative approximation of lithium availability to supply U.S. demand, we first subtracted the Wood Mackenzie projections of U.S. lithium demand from their projections of global demand, to estimate a "rest of world" (ROW) lithium demand trajectory. We then calculated the difference between the ROW demand trajectory and the Wood Mackenzie high and low estimates of global lithium chemical production. This difference was taken to represent a hypothetical lithium production capacity that would be available to the U.S. market, assuming that ROW demand was satisfied first, and growing demand did not generate a demand response among lithium suppliers beyond what is already represented in the forecast. This is likely a conservative assumption, as market forces would ultimately play some role in determining distribution, and increased demand would likely result in higher prices and greater market certainty for investment in additional supply capacity. We also noted that the resulting availability curve would be most applicable to earlier years, as the data on which it was based does not represent likely industry response to increased lithium demand as the market continues to grow. For this reason, we do not depict the supply curves beyond 2027 due to the lack of modeled demand response in the underlying data.

Figure 3-10 shows the S&P and Argonne battery plant production capacity estimates plotted against the calculated lithium production capacity potentially available to the U.S. market (in estimated battery GWh equivalent).

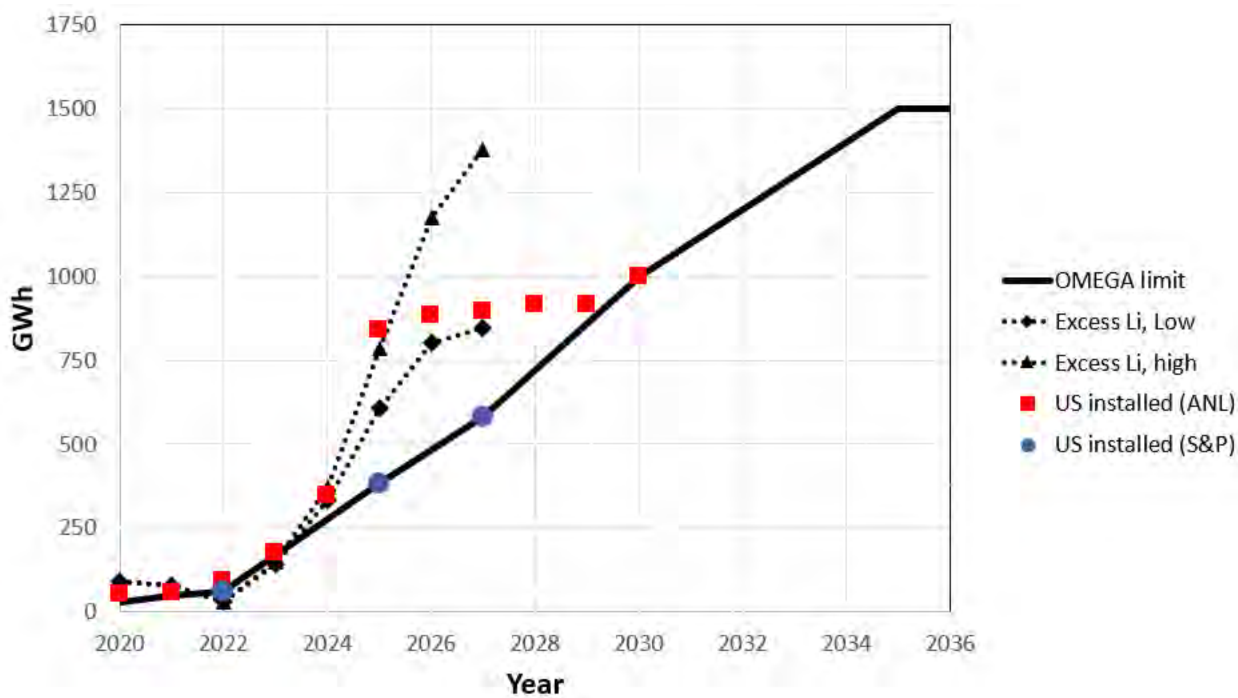

Figure 3-10: Limit on battery GWh demand implemented in OMEGA, compared to projected battery manufacturing capacity and excess lithium supply

We then examined this data to establish a conservative but reasonable limit on GWh battery supply for use by the OMEGA model. First, we noted that the S&P estimate of U.S. battery manufacturing plant production capacity, which due to its earlier date of origin is likely conservative and extends only to 2027, is well beneath the low estimate of hypothetical "excess" lithium supply. This suggests that lithium supply is more than sufficient to sustain the S&P estimate of U.S. plant operation at full capacity.

The ANL accounting of U.S. plant capacity is larger than the S&P accounting, reflecting the pace of newer announcements, although it does not distinguish between likely actual production and nameplate capacity. It exceeds the low estimate of excess lithium supply but is still well within the upper limit for most of its trajectory.

As a conservative bound on battery production capacity for the OMEGA model, we thus followed the S&P trajectory to 2027 at 580 GWh. This trajectory stays within lower expected lithium excess capacity for the first several years, when limited time is available for new capacity to come on-line.

Past 2027, estimates of "excess" lithium as a difference between ROW demand and a current accounting of global supply become less informative, because a demand response is not built into the supply data. Therefore, uncertainty about the supply-demand balance against ROW demand increases rapidly as the time horizon increases. In general, analysts believe that as demand for a mineral commodity remains strong over time, investment in mining operations and exploration will consistently increase, which leads to unknown or previously unprofitable geological sources to become available (Sun, Ouyang and Hao 2022). In resonance with this fact, we noted that it seems very unlikely from an investment point of view that manufacturers and battery suppliers would plan to construct plant capacity to come online in 2030 if it exceeds their expectation of availability of mineral products to supply the plant's production. Given the amount of lead time in the time frame past 2027 and the current level of activity in development of supply chain capacity across the world, we considered it reasonable to expect that the ANL estimate for 2030 at 998 GWh should be feasible to supply. We then continued a similar rate of increase to 2035 at 1500 GWh. Passing through these three defined points results in an almost linear growth rate that we then adopted as the annual battery GWh production limit for OMEGA modeling purposes. We flattened the limit at 1500 GWh after 2035 due to lack of data for that time period.

Here it is important to note, again, that our estimate of "excess" lithium available to the U.S., as the difference between currently anticipated global lithium supply and ROW demand, is likely a conservative estimate because it quantifies only currently known sources of lithium that will not be subject to demand elsewhere, and does not reflect the development of additional sources over time, nor the market forces that will ultimately determine where these supplies will be deployed.

The numeric values for the annual GWh limit input to OMEGA are provided in DRIA 2.6.4.2. More details on how OMEGA calculates BEV battery capacities that are summed to a fleet GWh production capacity is provided in DRIA 2.5.2.1.1.

3.1.3.3 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."

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.

- 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.

- In June 2022, the United States formed the Minerals Security Partnership, 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.

Preamble IV.C.6 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.

- 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.

- 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.

- 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.

- 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.

- 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.

Although currently there is no alternative to lithium in manufacturing automotive BEV batteries, several alternatives are under development that may provide an alternative, either in automotive batteries, or in non-automotive applications whose use of these alternatives would reduce competition for lithium in automotive applications. Citations for these examples may be found in a Memo to the Docket titled "DOE Communication to EPA Regarding Critical Mineral Projects."

- 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.

- 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.

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

Finally, a large amount of research and development is taking place to increase circularity and effective use of lithium and critical minerals. Beyond commercial technologies, continued research and development with industry and academia through the US Automotive 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.

- 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.

- $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.

3.2 Proposed Criteria and Toxic Pollutant Emissions Standards for Model Years 2027-2032

EPA is proposing changes to criteria pollutant emissions standards for both light-duty vehicles and medium duty vehicles (MDV). Light-duty vehicles include LDV, LDT, and MDPV. NMOG+NO_x changes for light-duty vehicles include a fleet average that declines from 2027-2032 in the early compliance program (or steps down in 2030 for GVWR > 6,000 lb. in the default program), the elimination of higher certification bins, a requirement for the same fleet average emissions standard to be met across four test cycles (25°C FTP, HFET, US06, SC03), a change from fleet average NMHC standards to one fleet average NMOG+NO_x standard in the -7°C FTP test, and three NMOG+NO_x provisions similar to requirements defined by the CARB Advanced Clean Cars II program. NMOG+NO_x. changes for MDV include a fleet average that declines from 2027-2032 in the early compliance program (or steps down in 2030 in the default program), the elimination of higher certification bins, a requirement for the same fleet average emissions standard to be met across four test cycles (25°C FTP, HFET, US06, SC03), and a new fleet average NMOG+NO_x standard in the -7°C FTP. EPA is proposing a requirement for spark ignition and compression ignition MDV with GCWR above 22,000 lb to comply with engine-dynamometer-based criteria pollutant emissions standards under the heavy-duty engine program instead of the chassis-dynamometer-based criteria pollutant emissions standards (88 FR 4296 2023). EPA is proposing to continue light-duty vehicle and MDV fleet average FTP NMOG+NO_x standards that include both ICE-based and zero emission vehicles in a manufacturer's compliance calculation. Performance-based standards that include both ICE and zero emission vehicles are consistent with the existing NMOG+NO_x program as well as the GHG program. EPA has considered the availability of battery electric vehicles as a compliance strategy in determining the appropriate fleet average standards. Given the cost-effectiveness of BEVs for compliance with both criteria pollutant and GHG standards, EPA anticipates that most (if not all) automakers will include BEVs in their compliance strategies. However, the standards continue to be a performance-based fleet average standard with multiple paths to compliance, depending on choices manufacturers make about deployment of a variety of emissions control technologies for ICE as well as electrification and credit trading.

EPA is proposing a PM standard of 0.5 mg/mi for light-duty vehicles and MDV that must be met across three test cycles (-7°C FTP, 25°C FTP, US06), a requirement for PM certification tests at the test group level, and a requirement that every in-use vehicle program (IUVP) test vehicle is tested for PM. The 0.5 mg/mi standard is a per-vehicle cap, not a fleet average.

EPA is proposing CO and formaldehyde (HCHO) emissions requirement changes for light-duty vehicles and MDVs including transitioning to emissions caps (as opposed to bin-specific standards) for all emissions standards, a requirement that CO emissions caps be met across four test cycles (25°C FTP, HFET, US06, SC03), and a CO emissions cap for the -7°C FTP that is the same for all light-duty vehicles and MDVs.

EPA is proposing a refueling standards change to require incomplete MDVs to have the same on-board refueling vapor recovery standards as complete MDVs. EPA is also proposing eliminating commanded enrichment as an AECD for power and component protection.

The proposal allows light-duty vehicle 25°C FTP NMOG+NO_x credits and -7°C FTP NMHC credits (converting to NMOG+NO_x credits) to be carried into the new program. It only allows MDV 25°C FTP NMOG+NO_x credits to be carried into the new program if a manufacturer selects the early compliance pathway. New credits may be generated, banked and traded within the new program to provide manufacturers with flexibilities in developing compliance strategies.

The proposed phase-in for criteria pollutant standards, including NMOG+NOx, PM, CO, HCHO, CARB ACC II NMOG+NOx provisions, and elimination of enrichment, is described in detail within the Preamble to the proposal in § III.C.1 and is briefly summarized in Table 3-2 below.

Table 3-2: All combinations of criteria pollutant phase-in scenarios available to manufacturers[a]

Model Year	≤ 8,500 lb. GVWR[b]	8,501-14,000 lb. GVWR Chassis Certification[b]	8,501-14,000 lb. GVWR Engine Certification[b]
2027	40%	40%	40%
2028	80%	80%	80%
2029	100%	100%	100%
2030+	100%	100%	100%

Model Year	≤ 8,500 lb. GVWR[b]	8,501-14,000 lb. GVWR Chassis Certification	8,501-14,000 lb. GVWR Engine Certification[b]
2027	40%	0%	40%
2028	80%	0%	80%
2029	100%	0%	100%
2030+	100%	100%	100%

Model Year	≤ 8,500 lb. GVWR[b]	8,501-14,000 lb. GVWR Chassis Certification[b]	8,501-14,000 lb. GVWR Engine Certification
2027	40%	40%	0%
2028	80%	80%	0%
2029	100%	100%	0%
2030+	100%	100%	100%

Model Year	≤ 8,500 lb. GVWR[b]	8,501-14,000 lb. GVWR Chassis Certification	8,501-14,000 lb. GVWR Engine Certification
2027	40%	0%	0%
2028	80%	0%	0%
2029	100%	0%	0%
2030+	100%	100%	100%

Model Year	≤ 6,000 lb. GVWR	6,001-8500 lb. GVWR	8,501-14,000 lb. GVWR Chassis Certification[b]	8,501-14,000 lb. GVWR Engine Certification[b]
2027	40%	0%	40%	40%
2028	80%	0%	80%	80%
2029	100%	0%	100%	100%
2030+	100%	100%	100%	100%

Model Year	≤ 6,000 lb. GVWR	6,001-8500 lb. GVWR	8,501-14,000 lb. GVWR Chassis Certification	8,501-14,000 lb. GVWR Engine Certification[b]
2027	40%	0%	0%	40%
2028	80%	0%	0%	80%
2029	100%	0%	0%	100%
2030+	100%	100%	100%	100%

Model Year	≤ 6,000 lb. GVWR	6,001-8500 lb. GVWR	8,501-14,000 lb. GVWR Chassis Certification[b]	8,501-14,000 lb. GVWR Engine Certification
2027	40%	0%	40%	0%
2028	80%	0%	80%	0%
2029	100%	0%	100%	0%
2030+	100%	100%	100%	100%

Model Year	≤ 6,000 lb. GVWR	6,001-8500 lb. GVWR	8,501-14,000 lb. GVWR Chassis Certification	8,501-14,000 lb. GVWR Engine Certification
2027	40%	0%	0%	0%
2028	80%	0%	0%	0%
2029	100%	0%	0%	0%
2030+	100%	100%	100%	100%

[a] Specific applicable phase-in depends upon a manufacturer's decisions regarding default or early compliance for vehicles above 6,000 pounds GVWR. See § III.C of the Preamble to the proposed rule

[b] Early compliance.

3.2.1 <u>Proposed $NMOG+NO_X$ standards</u>

EPA is proposing new $NMOG+NO_X$ standards for MY2027 and later. The standards are structured to take into account this increased vehicle electrification that will be occuring over the next decade.

The current Tier 3 fleet average $NMOG+NO_X$ emissions standards were fully phased-in for Class 2b and Class 3 (structured together as MDV within this proposal) in 2022 at 178 and 247 mg/mi, respectively. Tier 3 standards for light-duty vehicles, including LDT3 and LDT4 trucks and medium-duty passenger vehicles (MDPVs), will be fully phased into the Tier 3 30 mg/mi fleet average $NMOG+NO_X$ standard in 2025. Tier 3 standards are feasible without vehicle electrification. In the absence of our proposed $NMOG+NO_x$ standards, as sales of PEVs continue to increase, there would be an opportunity for the remaining ICE portion of light-duty vehicles and MDVs to reduce emission control system content (i.e., system costs) and comply with less stringent $NMOG+NO_x$ standard bins under Tier 3. If this were to occur, it would have the effect of increasing $NMOG+NO_x$ emissions from the ICE portion of the light-duty vehicle and MDV fleet and delay the overall fleet emission reductions of $NMOG+NO_x$ that would have occurred from increased penetration of PEVs into the light-duty vehicle and MDV fleets.

The structure of the proposed $NMOG+NO_X$ standards has been designed to cap the $NMOG+NO_x$ contribution of ICE vehicles at approximately Tier 3 levels for light-duty vehicles and at approximately 100 mg/mi $NMOG+NO_x$ for MDV.. The feasibility of ICE MDV meeting 100 mg/mi $NMOG+NO_X$ by 2027 is discussed in further detail within Chapter 3.2.1.3. The year-over-year reductions in 2027 and later light-duty and MDV $NMOG+NO_X$ standards from an average of 30 mg/mi and 100 mg/mi, respectively, thus would occur primarily from increased year-over-year electrification of new vehicle sales and the resulting averaging of zero emission vehicles with ICE vehicles within the fleet average light-duty and MDV $NMOG+NO_X$ standards.

The Clean Air Act (CAA) requires 4 years of lead time and 3 years of standards stability for heavy-duty vehicles. There are three categories of vehicles that are currently regulated as light-duty vehicles but are defined within the CAA as heavy-duty vehicles for purposes of lead time and standards stability: the heavy-light-duty truck categories (LDT3 and LDT4) and MDPV.[27] Furthermore, MDVs are also defined as heavy-duty vehicles under the CAA. EPA is proposing several alternative pathways for these three categories of vehicles for compliance with the proposed $NMOG+NO_x$ standards. The Agency's early compliance $NMOG+NO_x$ program would apply to all LDV, LDT, MDPV, and MDV vehicles beginning in 2027 in order to coincide with the timing of increased electrification of these vehicles. However, mandatory regulations beginning in 2027 would not provide 4 years of lead time as required for vehicles defined as heavy-duty under the CAA. To address this issue, we are proposing two schedules for compliance with $NMOG+NO_x$ standards for LDT3, LDT4, MDPV, and MDV.

The early compliance pathway (Table 3-3) has LDT3, LDT4 and MDPV meeting identical and gradually declining fleet average $NMOG+NO_X$ emissions standards to those for LDV, LDT1

[27] Light-duty truck 3 (LDT3) is defined as any truck with more than 6,000 pounds GVWR and with an ALVW of 5,750 pounds or less. Light-duty truck 4 (LDT4) is defined as any truck is defined as any truck with more than 6,000 pounds GVWR and with an ALVW of more than 5,750 pounds. See 40 CFR 86.1803-01 – Definitions. For current and proposed MDPV definitions, see § III.D of the Preamble to this proposed rule.

and LDT2 (see §III.C.1.iii in the Preamble for the proposed rule).[28] It also includes separate, gradually declining fleet average NMOG+NO_X emissions standards for MDV with less than 22,000 pounds GCWR (see §III.C.1.iv in the Preamble for the proposed rule). This pathway for early compliance with NMOG+NO_X emissions standards for LDT3, LDT4, MDPV and/or MDV includes additional flexibilities (see see §III.C.9 in the Preamble for the proposed rule).

The second, and default, NMOG+NO_x compliance path (Table 3-4) has LDV, LDT1, and LDT2 meeting a gradually declining fleet average NMOG+NO_x standards from 2027 through 2032. Vehicles in the LDT3, LDT4, and MDPV categories would continue to meet Tier 3 standards through the end of MY 2029 and then would proceed to meeting a 12 mg/mi NMOG+NO_x standard in a single step in MY 2030 in order to comply with CAA provisions for 4 years of lead time and 3 years of standards stability. Similarly, MDVs would continue to meet Tier 3 standards through the end of MY 2029 and then MDVs with less than 22,000 lb. GCWR would proceed to meeting a 60 mg/mi NMOG+NO_x standard in a single step in 2030 in order to comply with CAA provisions for 4 years of lead time and 3 years of standards stability.

We are also proposing a similar choice between early compliance and default compliance pathways for MDVs with high GCWR, which are defined as being at or above 22,000 lb (see III.C.2 and III.C.5 in the Preamble to the proposed rule). Under the early compliance pathway, high GCWR MDVs would comply with MY 2027 and later heavy-duty engine criteria pollutant emissions standards beginning with MY 2027 (see section III.C.5 in the Preamble for the proposed rule). Manufacturers with high GCWR MDVs choosing the early compliance pathway would have additional flexibilities with respect to GHG compliance. They could delay entry into the MDV GHG work factor-based fleet average standards until the beginning of MY 2030 (see § III.B.3 in the Preamble for the proposed rule).

Under the default compliance path (Table 3-4), high GCWR MDVs would continue to comply with Tier 3 standards until the end of MY 2029 and then would comply with MY 2027 and later heavy-duty engine criteria pollutant emissions standards beginning with MY 2030 in order to comply with CAA provisions for 4 years of lead time. Under this default compliance path, high GCWR MDVs would comply with fleet average MDV GHG emissions beginning with MY 2027 (see § III.B.3 in the preamble for the proposed rule).

[28] Note that the LDV, LDT1 and LDT2 classifications are defined in 40 CFR 86.1803-01 – Definitions.

Table 3-3: LDV, LDT, MDPV and MDV fleet average, chassis dynamometer FTP NMOG+NO_X standards under the early compliance pathway

Model Year	LDV, LDT1, LDT2, LDT3†, LDT4† & MDPV† NMOG+NO_X (mg/mi)	MDV† NMOG+NO_X (mg/mi)	
		Class 2b	Class 3
2026	30*	178*	247*
2027	22	160	
2028	20	140	
2029	18	120	
2030	16	100	
2031	14	80	
2032 and later	12	60	

* Tier 3 standards provided for reference

† NMOG+NOX credit generated under Tier 3 can be carried forward for 5 years after it is generated. MDV chassis dynamometer NMOG+NO_X standards only apply for vehicles under 22,000 pounds GCWR.

Table 3-4: LDV, LDT, MDPV and MDV fleet average, chassis dynamometer FTP NMOG+NO_X standards under the default compliance pathway

Model Year	LDV, LDT1 & LDT2 NMOG+NO_X (mg/mi)	LDT3, LDT4 & MDPV NMOG+NO_X (mg/mi)	MDV† NMOG+NO_X (mg/mi)	
			Class 2b	Class 3
2026	30*	30*	178*	247*
2027	22	30*	178*	247*
2028	20	30*	178*	247*
2029	18	30*	178*	247*
2030	16	12	60	
2031	14	12	60	
2032 and later	12	12	60	

* Tier 3 standards provided for reference

† MDV chassis dynamometer NMOG+NO_X standards only apply for vehicles under 22,000 pounds GCWR.

3.2.1.1 Proposed NMOG+NO_X bin structure for light-duty and MDVs

The propsoed bin structure being proposed for LDV, LDT, MDPV and MDV below 22,000 pounds GCWR is shown in Table 3-6. The upper two bins are only available to MDV.

For LDV, the revised bin structure removes the highest Tier 3 bins (bin 160 and bin 125) and adds several new bins (bin 60, bin 40, bin 10). For MDV, the revised bin structure moves away from separate bins for class 2b and class 3 vehicles, adopting LDV bins with higher bins only available to MDV.

Table 3-5: Proposed LDV, LDT, MDPV and MDV† $NMOG+NO_X$ bin structure

LDV bin	$NMOG+NO_X$ (mg/mi)
Bin 160*	160
Bin 125*	125
Bin 70	70
Bin 60	60
Bin 50	50
Bin 40	40
Bin 30	30
Bin 20	20
Bin 10	10
Bin 0	0

3.2.1.2 Light-duty $NMOG+NO_X$ standards and test cycles

EPA is proposing increasingly stringent light-duty vehicle $NMOG+NO_x$ standards (Table) for the sales weighted average inclusive of all LDV, LDT and MDPV (e.g, ICE vehicles, BEVs, PHEVs, fuel cell, vehicles, etc.). (Table 3-7). For a detailed description of the proposed phase-in of the standards by vehicle category, please refer to § III.C.1 in the Preamble to the proposed rule.

EPA recognizes that vehicles will differ with respect to their levels of $NMOG+NO_x$ emissions control depending on degree of electrification, choice of fuel, ICE technology, and other differences. The proposed fleet average standards are feasible in light of anticipated technology penetration rates commensurate with the GHG technology implementation during this same time period and increasing electrification of light-duty vehicles. The declining fleet average standards over the FTP cycle ensure that $NMOG+NO_x$ continues to decrease over time for the light-duty fleet. The elimination of the two highest bins (Table 3-7) caps the maximum $NMOG+NO_x$ emissions from an individual new vehicle model. EPA anticipates that electrified technology, including BEVs, will play a significant role within the compliance strategies for meeting the fleet average $NMOG+NO_x$ standards for each manufacturer. However, EPA anticipates that manufacturers may use multiple technology solutions to comply with fleet average $NMOG+NO_x$ standards. For example, a manufacturer may choose to offset any ICE increases with increased BEV sales, or could alternatively improve engine and exhaust aftertreatment designs to reduce emissions for ICE vehicles while planning for a more conservative percentage of BEV sales as part of their compliance with the declining fleet average $NMOG+NO_x$ standards (Table 3-8).

Since technologies are available to further reduce $NMOG+NO_x$ emissions relative to the current fleet, and since more than 20 percent of MY 2021 Bin 30 vehicle certifications already show an FTP certification value under 15 mg/mi $NMOG+NO_x$, achieving reduced $NMOG+NO_x$ emissions through improved ICE technologies is feasible and reasonable (see Chapter 3.2.1.5. Regardless of the compliance strategy chosen, overall, the fleet will become significantly cleaner.

EPA is proposing that the same bin-specific numerical standards be applied across four test cycles: 25°C FTP (40 CFR 1066.801(c)(1)(i) 2023) (40 CFR 1066.815 2023), HFET (40 CFR 1066.840 2023), US06 (40 CFR 1066.831 2023) and SC03 (40 CFR 1066.835 2023). This means that a manufacturer certifying a vehicle to comply with Bin 30 $NMOG+NO_x$ standards would be required to meet the Bin 30 emissions standards for all four test cycles. Meeting the same

$NMOG+NO_x$ standards across four cycles is an increase in stringency from Tier 3, which had one standard for the higher of FTP and HFET, and a less stringent composite based standard for the SFTP (weighted average of 0.35*FTP + 0.28*US06 + 0.37*SC03).

Present-day engine, transmission, and exhaust aftertreatment control technologies allow closed-loop air-to-fuel (A/F) ratio control and good exhaust catalyst performance throughout the US06 and SC03 cycles. As a result, higher emissions standards over these cycles are no longer necessary. Approximately 60 percent of the test group / vehicle model certifications from MY 2021 have higher $NMOG+NO_x$ emissions over the FTP cycle as compared to the US06 cycle, supporting the conclusion that a single standard is feasible and appropriate.

EPA is proposing to replace the existing -7°C FTP NMHC fleet average standard of 300 mg/mi for passenger cars and LDT1, and 500 mg/mi fleet average standard for LDT2 through LDT4 and MDPV, with a single $NMOG+NO_x$ fleet average standard of 300 mg/mi for LDV, LDT1 through 4 and MDPVs to harmonize with the combined $NMOG+NO_x$ approach adopted in Tier 3 for all other cycles (i.e., 25°C FTP, HFET, US06, and SC03 cycles). EPA emissions testing at -7°C FTP showed that a 300 mg/mi standard is feasible with a large compliance margin for $NMOG+NO_x$. EPA testing of a 2019 F150 5.0L, a 2021 Corolla 2.0L, and a 2021 F150 HEV at -7°C FTP showed that a 300 mg/mi standard could be met with a large compliance margin for both NMHC and $NMOG+NO_X$. For example, $NMOG+NO_X$ was 189+25, 124+3, and 47+70 for a 2019 F150 5.0L, a 2021 Corolla 2.0L, and a 2021 F150 HEV, respectively. EPA did not include EVs in the assessment of the proposed fleet average standard and therefore EVs and other zero emission vehicles are not included and not averaged into the fleet average -7°C FTP $NMOG+NO_x$ standards. Since -7°C FTP and 25°C FTP are both cold soak tests that include TWC operation during light-off and at operating temperature, it is appropriate to apply the same Tier 3 useful life to both standards.

The proposed standards apply equally at high altitude, rather than including compliance relief provisions from Tier 3 for certification at high altitude. Modern engine management systems can use idle speed, engine spark timing, valve timing, and other controls to offset the effect of lower air density on exhaust catalyst performance at high altitudes.

Table 3-6: LDV, LDT* and MDPV NMOG+NO_X NMOG+NO_X fleet average FTP standards

Model Year	NMOG+NOX (mg/mi)
2027	22
2028	20
2029	18
2030	16
2031	14
2032	12
*Manufacturers choosing the early compliance pathway	

Table 3-7: LDV, LDT* and MDPV* NMOG+NO_X fleet average FTP standards

Model Year	LDV, LDT1 & LDT2 NMOG+NOX (mg/mi)	LDT3, LDT4 & MDPV NMOG+NOX (mg/mi)
2026	30**	30**
2027	22	30**
2028	20	30**
2029	18	30**
2030	16	12
2031	14	12
2032 and later	12	12
* Manufacturers choosing the default compliance pathway ** Tier 3 standards provided for reference		

3.2.1.3 NMOG+NOx Standards for MDV at or below 22,000 lb GCWR

The proposed MDV (medium duty vehicles, 8,501 to 14,000 lb. GVWR) NMOG+NOx standards for vehicles under 22,000 lb. GCWR are shown in Table 3-8 and Table 3-9 for the early compliance and default compliance pathways, respectively. Certification data show that for MY 2022-2023, 75 percent of sales-weighted Class 2b/3 gasoline vehicle certifications were below 120 mg/mi in FTP and US06 tests. Diesel-powered MDVs designed for high towing capability (i.e., GCWR over 22,000 lb.) were higher (75 percent were below 180 mg/mi) but they are not being used to inform the proposed MDV standard because the Agency is proposing the requirement that MDVs (diesel and gasoline) with GCWR (gross combined weight rating) above 22,000 lb. comply with criteria pollutant emissions standards under the HD engine program.[29] As described in Chapter 3.2.1.5, MDVs with GCWR below 22,000 lb. have comparable emissions performance to LDVs and LDTs. The year-over-year fleet average FTP standards for MDV below 22,000 lb. GCWR and the rationale for the manufacturer's choice of early compliance and default compliance pathways is described in Section III.C.1. For further discussion of MDV NMOG+NOx feasibility, please refer to Chapter 3.2.1.5.

The proposed MDV NMOG+NOx standards are based on applying existing light-duty vehicle technologies, including electrification, to MDV. As with the light-duty vehicle categories, EPA anticipates that there will be multiple compliance pathways, such as increased electrification of

[29] See § III.C.5 of the Preamble to this proposed rule.

vans together with achieving 100 mg/mile NMOG+NOx for ICE-power MDV. Present-day MDV engine and aftertreatment technology allows fast catalyst light-off after cold-start followed by closed-loop A/F control and excellent exhaust catalyst emission control on MDV, even at the adjusted loaded vehicle weight, ALVW [(curb + GVWR)/2] test weight, which is higher than loaded vehicle weight, LVW (curb + 300 lb.) used for testing light-duty vehicles. The proposed MDV standards begin to take effect in 2030, consistent with the CAA section 202(a)(3)(C) lead time requirement for these vehicles.

Table 3-8: MDV fleet average NMOG+NOx standards under the early compliance pathway†

Model Year	$NMOG+NO_X$ (mg/mi)	
	Class 2b	Class 3
2026	178*	247*
2027	160	
2028	140	
2029	120	
2030	100	
2031	80	
2032 and later	60	

† Please refer to § III.C.1 of the Preamble to the propsed rule for further discussion of the early compliance and default compliance pathways
* Tier 3 standards provided for reference

Table 3-9: MDV fleet average chassis dynamometer FTP NMOG+NOx standards under the default compliance pathway*

Model Year	MDV† NMOG+NOx (mg/mi)	
	Class 2b	Class 3
2026	178**	247**
2027	178**	247**
2028	178**	247**
2029	178**	247**
2030	60	
2031	60	
2032 and later	60	

* Please refer to § III.C.1 of the Preamble to the propsed rule for further discussion of the early compliance and default compliance pathways
** Tier 3 standards provided for reference
† MDV chassis dynamometer NMOG+NOx standards only apply for vehicles under 22,000 lb. GCWR.

If a manufacturer has a fleet mix with relatively high sales of MDV BEV, that would ease compliance with MDV NMOG+NOx fleet average standards for MDV ICE-powered vehicles. If the manufacturer has a fleet mix with relatively low BEV sales, then improvements in NMOG+NOx emissions control for ICE-powered vehicles would be required to meet the fleet average standards. Improvements to NMOG+NOx emissions from ICE-powered vehicles are feasible with available engine, aftertreatment, and sensor technology, and has been shown within an analysis of MY 2022-2023 MDV certification data (see Chapter 3.2.1.5). Fleet average

NMOG+NOx will continue to decline to well below the final Tier 3 NMOG+NOx standards of 178 mg/mi and 247 mg/mi for Class 2b and 3 vehicles, respectively.

The proposed standards require the same MDV numerical standards be met across all four test cycles, the 25°C FTP, HFET, US06 and SC03, consistent with the proposed approach for light-duty vehicles described in Section III.C.1.ii. This would mean that a manufacturer certifying a vehicle to bin 60 would be required to meet the bin 60 emissions standards for all four cycles. Meeting the same NMOG+NOx standard across four cycles is an increase in stringency from Tier 3, which had one standard over the FTP and less stringent bin standards for the HD-SFTP (weighted average of 0.35*FTP + 0.28*HDSIM + 0.37*SC03, where HDSIM is the driving schedule specified in 40 CFR 86.1816-18(b)(1)(ii)). Current MDV control technologies allow closed-loop A/F control and high exhaust catalyst emissions conversion throughout the US06 and SC03 cycles, so compliance with higher numerical emissions standards over these cycles is no longer needed. Manufacturer submitted certification data and EPA testing show that Tier 3 MDV typically have similar NMOG+NOx emissions in US06 and 25°C FTP cycles, and NMOG+NOx from the SC03 is typically much lower. Testing of a 2022 F250 7.3L at EPA showed average NMOG+NOx emissions of 56 mg/mi in the 25°C FTP and 48 mg/mi in the US06. Manufacturer-submitted certifications show that MY 2021+2022 gasoline 2b/3 trucks achieved, on average, 69/87 mg/mi in the FTP, and 75/NA mg/mi in the US06, and 18/25 mg/mi in the SC03.

Several Tier 3 provisions would end with the elimination of the HD-SFTP and the combining of bins for Class 2b and class 3 vehicles. First, Class 2b vehicles with power-to-weight ratios at or below 0.024 hp/lb. could no longer replace the full US06 component of the SFTP with the second of three sampling bags from the US06. Second, Class 3 vehicles would no longer use the LA-92 cycle in the HD-SFTP calculation but would rather have to meet the NMOG+NOx standard in each of four test cycles (25°C FTP, HFET, US06 and SC03). Third, the SC03 could no longer be replaced with the FTP in the SFTP calculation.

The proposed standards do not include relief provisions for MDV certification at high altitude. Modern engine systems can use idle speed, engine spark timing, valve timing, and other controls to offset the effect of lower air density on catalyst light-off at high altitudes.

EPA is also proposing a new -7°C FTP NMOG+NOx fleet average standard of 300 mg/mi for gasoline and diesel MDV. EPA testing has demonstrated the feasibility of a single fleet average -7°C FTP NMOG+NOx standard of 300 mg/mi across light-duty vehicles and MDV. EPA did not include EV's in the assessment of the proposed fleet average standard and therefore EVs and other zero emission vehicles are not included and not averaged into the fleet average -7°C FTP NMOG+NOx standards. Since -7°C FTP and 25°C FTP are both cold soak tests that include TWC operation during light-off and at operating temperature, it is appropriate to apply the same Tier 3 useful life to both standards. Additional discussion on the feasibility of the proposed standards can be found in Chapter 3.2.4.

3.2.2 Proposed PM standards for light-duty and MDV at or below 22,000 pounds GCWR

Details of the proposed PM standards, including test cycles used for compliance, phase-in, the certification process, demonstration of in-use compliance, and OBD are discussed in further detail in § III.C.3 of the Preamble to the proposed rule. Details regarding PM emissions control feasibility and GPFs are summarized in Chapter 3.2.5. For reference, the proposed light-duty PM standards are shown in Table 3-10; and PM standards for MDV at or below 22,000 pounds GVWR are shown in Table 3-11.

Table 3-10: Propsed light-duty PM standards

Test Cycle	Tier 3 Standards (mg/mi)	Proposed PM Standard (mg/mi)
25°C FTP	3	0.5
US06	6	0.5
-7°C FTP	Not applicable	0.5

Table 3-11: Proposed PM standards for MDV at or below 22,000 pounds GCWR

Test Cycle	Tier 3 Standards (mg/mi)	Proposed PM Standard (mg/mi)
25°C FTP	8 (Class 2b) 10 (Class 3)	0.5
US06	10 (Class 2b) over SFTP 7 (Class 3) over SFTP	0.5
-7°C FTP	Not applicable	0.5

3.2.3 Proposed CO and formaldehyde (HCHO) standards

A detailed description of EPA's proposed CO and formaldehyde (HCHO) standards can be found in § III.C.4 of the Preamble to the proposed rule. For reference, the proposed light-duty standards are shown in Table 3-12; and standards for MDV at or below 22,000 pounds GVWR are shown in Table 3-13.

Table 3-12: Light-duty CO and HCHO standards

CO cap for 25°C FTP, HFET, US06, SC03 (g/mi)	1.7
HCHO cap for 25°C FTP (mg/mi)	4
CO cap for -7°C FTP (g/mi)	10.0

Table 3-13: CO and HCHO standards for MDV at or below 22,000 pounds GCWR

CO cap for 25°C FTP, HFET, US06, SC03 (g/mi)	3.2
HCHO cap for 25°C FTP (mg/mi)	6
CO cap for -7°C FTP (g/mi)	10.0

3.2.4 Current ICE-based vehicle NMOG+ NO_X emissions

At the time of this proposal Tier 3 emissions standards for light-duty vehicles have not yet fully phased-in. The current Tier 3 standards will be fully phased-in by MY 2025 and will result in a fleet average standard for passenger cars and light trucks of 30 mg/mi FTP NMOG+NO_X. This means on average, the light-duty fleet will be certified to Tier 3 Bin 30 in MY 2025. While the declining FTP NMOG+NO_X fleet average in this proposal is fully feasible with the introduction of zero emission vehicles such as BEV's, continued reductions in ICE-based vehicle emissions could provide an alternative pathway to compliance or at a minimum offset the number of ZEV's a vehicle manufacturer may require to produce to meet the standards. EPA reviewed the MY 2021 test car data (U.S. EPA 2022b) and identified nineteen vehicles with FTP emissions performance data currently below 15 mg/mi, two of which are at or below 10 mg/mi (Table 3-14).

Table 3-14: Examples of NMOG+NO_X cert emissions

Manufacturer	Model		Certified NMOG +NO_X (g/mi)
	Vehicles Certified at 10 mg/mi or less		
Audi	Q3		0.008
Hyundai	Sonata Hybrid		0.01
	Vehicles Certified at less 15 mg/mi		
BMW	X3 xDrive30e		0.014
BMW	X5 xDrive45e		0.011
BMW Mini	John Cooper Works Conv		0.014
GMC	Terrain AWD		0.013
Buick	Encore AWD		0.012
Honda	CRV AWD		0.012
Hyundai	Tuscon		0.012
Jaguar	Range Rover Sport		0.012
Kia	Soul		0.011
Kia	Forte 5		0.011
Nissan	Sentra SR		0.012
Subaru	Outback		0.014
Lexus	NX 300h AWD		0.012
Lexus	UX 200		0.014
Toyota	Corolla XSE		0.013
Volkswagen	Tiguan AWD		0.014
Volkswagen	Jetta GLI		0.012

The Agency also analyzed emissions certification data MY 2022 and MY 2023 MDV emissions families. The emissions family certification data are graphically represented in Figure 3-11 for gasoline and diesel MDV vans and pickups using a "box-and-whisker" plot (Frigge, Hoaglin and Iglewicz 1989) (Tukey 1977) (Benjamini 1988). The upper and lower boxes correspond to the first and third quartiles (the 25th and 75th percentiles), respectively, of the NMOG+NO_X emissions data for each MDV category. The horizontal line between each set of upper and lower boxes represents median emissions and the "x" represents mean emissions. The upper vertical line or "whisker" extends from the median to the highest value that is within 1.5X inner quartile range (IQR) of the median, where IQR is the distance between the first and third quartiles. The lower "whisker" extends from the median to the lowest value within 1.5X IQR of the median. A certification emissions data point was considered an outlier if it exceeded a distance of 1.5 times the IQR below the 1st quartile or 1.5 times the IQR above the 3rd quartile and is represented as a “dot” in the “box-and-whisker” plot. The analysis found significant compliance headroom for MDVs below the current Tier 3 NMOG+NO_X emissions standards for Class 2b and Class 3 MDVs, with median NMOG+NO_X emissions of approximately 100 mg/mi for gasoline pickups, approximately 80 mg/mi for gasoline vans, and approximately 130 mg/mi for diesel vans. Median emissions for diesel pickups were approximately 170 mg/mi, however all MY2022 and 2023 diesel pickups were above the 22,000 pound threshold for the proposed MDV NMOG+NO_X standards and would instead need to comply with 2027 and later heavy-duty emissions standards, with use of engine-dynamometer regulatory cycles for demonstrating compliance.

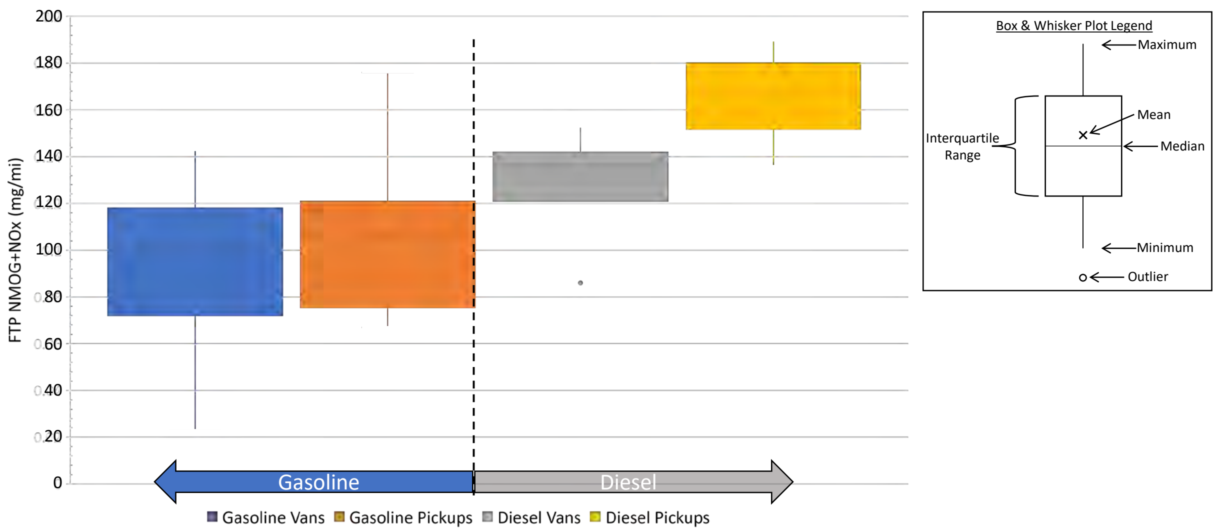

Figure 3-11: MY2022-2023 MDV box and whisker plot showing the interquartile range of certification NMOG+NO_X data

EPA recognizes that compliance headroom is a concern for vehicle manufacturers. Vehicle manufacturing variation, test to test variations, and test location variables all contribute to a manufacturer's desire to have 40 to 50 percent compliance headroom when submitting data and vehicles to EPA for certification. However, given the low emissions performance demonstrated by current MY 2021 LD vehicles and MY2022 and MY2023 MDVs, EPA believes that manufacturers will be able to utilize the lower bins proposed in this NPRM and maintain their target compliance headroom. Certification of ICE-based vehicles to the lower bins in combination with the introduction of an increasing number of PEVs into the fleet average provides a feasible compliance pathway to meet the proposed declining FTP NMOG+NO_X fleet averages for both LD vehicles and MDVs.

3.2.4.1 Current ICE Emissions at -7°C FTP

Table 3-15: Light-Duty Gasoline Vehicles – 7C FTP Emissions (mg/mi)

Engine	Vehicle Class	NMOG	NO_X	NMOG+NO_X
3.9L Ferrari	LDV	154.1	53.1	207.2
6.3L Ferrari	LDV	220.2	38	258.2

Table 3-16: Light-Duty Diesel Vehicles -7C FTP Emissions

Engine	Vehicle Class	NMOG	NO_X	NMOG+NO_X
2.8L GM	LDT2/3	45	134	179
3.0L Ram	LDT3/4	58	229	287
3.0L GM	LDT3/4	80	134	214
1.5L Ford	LDT1/2	14	33	47
average				182

3.2.4.2 Feasibility of a single numerical standard for FTP, HFET, SC03 and US06

Table 3-15 below provides a comparison of FTP, HWFE, SC03 and US06 test results for several vehicles that represent a broad spectrum of vehicle types and conventional powertrain technologies. For most of the vehicles identified the FTP results are higher than the HWFE, SC03 and US06 test results showing that a single standard is feasible and already being met by some manufacturers. There are several examples where SC03 or US06 results are higher than the FTP results. The data shows that the FTP and the US06 are the most stringent standards because the of the FTP cold start and the US06 because of higher power requirements and potential enrichment. The HWFE and SC03 cycles are less stringent due to the lack of cold start and lower power demands.

Table 3-17: Comparison of FTP, HFET, SCO3, US06 cert test results for LD vehicles

		Manufacturer Reported NMOG+NO_X Values			
Manufacturer	Vehicle	FTP (g/mi)	HWFE (g/mi)	SC03 (g/mi)	US06 (g/mi)
BMW	X4 xDrive 30i	0.02	0.008	0.008	0.014
BMW	I3s REX	0.014	0.02	0.012	0.011
BMW	540i xDrive	0.036	0.02	0.031	0.029
Ford	Corsair	0.035	0.009	0.09	0.03
Ford	Ranger	0.052	0.033	0.05	0.09
Ford	Explorer	0.038	0.025	0.03	0.03
Ford	F150	0.026	0.014	0.017	0.041
GM	Terrain	0.013	0.001	0.011	0.005
GM/Cadillac	XT6	0.026	0.002	0.008	0.005
GMC	K10 Sierra 4WD	0.026	0.005	0.014	0.008
Hyundai	Genesis	0.038	0.014	0.013	0.056
Hyundai	Elantra	0.037	0.015	0.028	0.072
Kia	Sportage	0.036	0.017	0.036	0.024
Kia	Sorento	0.032	0.016	0.03	0.039
Nissan	Altima	0.015	0.006	0.019	0.017
Porsche	Cayenne Turbo	0.072	0.034	0.05	0.05
Volkswagen	Audi Q3	0.008	0.002	0.009	0.012
Volkswagen	Tiguan AWD	0.017	0.002	0.009	0.008
Volkswagen	Jetta GLI	0.017	0.003	0.016	0.009
Average		0.029	0.013	0.025	0.030

As the result of this proposed change, EPA expects light-duty vehicles to have lower emissions over a broader area of vehicle operation. Present-day engine, transmission, auxiliary and aftertreatment control technologies allow closed-loop A/F control and good emissions conversion throughout the HWFE, US06 and SC03 cycles; as a result, higher emissions standards over these cycles are no longer justified. Overall, approximately 60 percent of the of test group / vehicle model certifications from MY 2021 have higher NMOG+NO_X emissions in the FTP as compared to the US06, supporting the conclusion that a single standard is feasible and appropriate.

3.2.4.3 Off-Cycle emission controls

When the agency proposed and subsequently finalized the SFTP standards in 1996, with phase-in beginning with MY 2000 (61 FR 54852 1996), the agency acknowledged a potential need for unique operation related to high loads and speeds that would typically result in increased emissions from SI engines. This acknowledgement was reflected in both the standard levels set for the US06 test cycle but also in accompanying AECD language indicating allowances for control features that deviate from behaviors demonstrated over the test cycles. These allowances are specific to an operating mode in SI engines called enrichment when the control system changes the A/F ratio such that more fuel than air is commanded in an attempt to either make additional power or to lower the exhaust gas temperatures. Unfortunately, during these enrichment episodes, it is difficult to maintain effective control of HC, CO, PM and NO_X. Engines operate almost like they have no exhaust emission controls, particularly in the case of HC/NMOG, CO, PM and air toxic emissions, and largely engine out emission levels are exhausted without the catalyst largely performing any effective reduction in the high engine out emission levels. In fact, studies suggest that during these enrichment episodes, substantial increases in PM, ammonia and air toxic emissions have been observed.

At the time of the development of the SFTP FRM, the technology level of vehicle controls and hardware was very different from today. The operator generally was in full control of the engine and transmission areas operation because engines possessed very little engine speed and load controlling or limiting operation, and most transmissions were either hydraulically controlled automatic transmissions responding to mechanical parameter inputs or manual transmissions responding to driver decisions on gear selection or clutch engagement. At that time, throttles still used direct mechanical connection to an accelerator pedal. In MY 1996, most automatic transmissions had four forward gear ratios.

Since that time, the evolution of powertrain control technology has resulted in full control of almost every aspect of engine and transmission control via complex and precise electronic software, feedback sensors and other hardware. Every new vehicle today has incorporated electronic throttle control that allows the electronic engine management system to control the throttle with the operator simply "requesting" an engine power level but ultimately the electronics decide how to safely operate the engine and in the case of automatic transmissions, which gear to select within the transmission.

These technological advancements have also improved vehicle safety by electronically limiting acceleration; limiting top speed; and by implementing traction control, antilock braking systems and vehicle stability control. Electronic powertrain management has also been used extensively by all auto manufacturers to protect engines and drivelines from excessive torque or RPM that could potentially damage drivetrain components. Many manufacturers use "torque limiting" controls to improve durability of various hardware components and systems.

Automatic transmissions have also similarly evolved to allow precise electronic control of gear selection, shift points, torque convertor lockup and other operational parameters. By 2021, most transmissions have more than seven gear rations (see Chapter 3.1.1) with both a wider range of ratios and smaller steps between ratios than the previous four and five speed automatic transmissions of two decades ago. Some of these control improvements are related to expectations by the driver/customer regarding shift quality, powertrain noise, and other drive-quality attributes. However, these controls and hardware designs have also resulted in improved acceleration performance, improved fuel economy and lower GHG emissions made possible via multi-gear (more than 7 forward gears) transmissions and related complimentary engine and electronic transmission controls that optimize and capitalize on the synergies of the engine and transmission as a system. Additionally, many of the few remaining manual transmissions have been replaced with electronically controlled, automated dual-clutch transmissions (DCT).

Modern engines have also added technologies such as VVT, cylinder deactivation, turbo boost control and other technologies that effectively allow the manufacturer designed controls, when used in conjunction with electronic throttle and transmission control to operate the engine in nearly any manner they determine to be optimal for the customer and manufacturer drivability expectations and durability goals.

The agency believes that these same technologies, only available in recent years, could also be used for limiting operation in areas described previously as requiring enrichment that result in substantial increases in emission levels in normal operation including high acceleration rates, high loads. The reasons for the original allowances for enrichment discussed in the SFTP FRM can easily be addressed in modern engine and transmissions by utilizing existing controls to limit or avoid operation in areas that require enrichment for any normal vehicle operation. Vehicles can "drive" through these areas but quickly exit by changing the engine airflow control, ignition timing, valvetrain settings, speed, or other parameters that would avoid this unnecessary increase in emissions.

This is consistent with strategies used for other purposes including durability, customer drivability issues and even performance features such as short durations of overboost for extra horsepower and gear hold on grades, etc. Manufacturers have also implemented controls that limit the engine and transmission operating range during initial break-in periods ((Streeter 2021)) and also during high coolant temperatures or coolant loss. Limiting or controlling areas of engine operation using electronic powertrain controls is common for many manufacturer goals, with the exception of limiting criteria pollutant emissions increases unless explicitly required to by emissions regulations.

The agency has required a similar concept in heavy-duty diesel engines to limit emission increases. Diesel engines are required to go into modes that restrict engine output when the operator does not have DEF[30] available in the storage tank required for the SCR system to control emissions. The operator might request more acceleration or power but the controls will limit the speed and loads allowed to be put on the engine in order to limit emission increases.

Another agency requirement for diesel emission control designs that have occasional but irregular emission increases, similar to the discussion above regarding enrichment episodes in SI engines, is the infrequent regeneration adjustment factor (IRAF). Because the design of the diesel emission control requires occasional increases in emissions, the agency has required manufacturers to quantify that increase and adjust the emission compliance levels to account for those design-based increases. The SI engine design decisions for hardware and controls also directly influence the degree to which emission increases will occur for the purposes of temperature protection and power. The agency could consider the IRAF approach to also apply

[30] Diesel emissions fluid (or DEF) is aqueous urea injected into the exhaust as a reductant for selective catalytic reduction (SCR) of NO_X emissions. SCR is used for NO_X emissions control in diesel engines and other engines using net lean combustion strategies.

to SI emission increases in real world operation and require a similar adjustment to the compliance level. A similar discussion was included in the HD2027 rule for SI engines.

It is important to note that with the introduction and expanded use of gas particulate filters, the agency will propose a similar adjustment as the diesel IRAF for any increase in emissions related to similar regeneration strategies.

The regulations of 40 CFR §86.1809 prohibit the use of strategies that unnecessarily reduce emission control effectiveness exhibited during the Federal or Supplemental Federal emissions test procedures (FTP or SFTP) when the vehicle is operated under conditions which may reasonably be expected to be encountered in normal operation and use. Unless the need for the strategy or Auxiliary Emission Control Device (AECD) is justified in terms of protecting the vehicle against damage or accident (ref.40 CFR §86.1803-01

Most vehicles today incorporate AECDs which utilize enrichment (i.e., commanding air/fuel ratio less than the stoichiometric air/fuel ratio) for the purpose of protecting components in the exhaust system from thermal damage during normal operation and use. EPA considers normal operation and use to include all operation within the vehicles design parameters for example: driving at sustained high speeds, maximum acceleration at wide open throttle, operating at the max gross vehicle weight rating, trailer towing within the rated trailer tow limits. Normal operation and use does not include conditions of component failure or engine overheating protection mode where the check engine light or other warning systems are active. EPA is also aware that some vehicles incorporate similar strategies for the purpose of increasing the power output of the engine and such strategies significantly reduce the effectiveness of three-way catalytic converters, which require the exhaust gas composition to be precisely controlled via engine operation near the stoichiometric air-to-fuel ratio.

Technologies exist today which can prevent thermal damage of exhaust system components without the use of commanded enrichment during normal operation and use, and modern vehicles have sufficient power without the use of commanded enrichment. The use of commanded enrichment only has the potential to increase power by approximately 5 percent on a naturally aspirated engine but significantly reduces the effectiveness of three-way catalytic converter systems, resulting in increases of NMOG, CO and air toxics, in some cases by orders of magnitude. Even for particularly challenging operating conditions, for example sustained high-load conditions that may be encountered by highly loaded vehicles or vehicles towing heavy trailer loads, measures can be taken via both the engine management system and within the design of powertrain components to allow operation closer to a stoichiometric air-to-fuel ratio. Specific examples include reducing torque demand via electronic throttle control, changing electronic transmission shift control, and improvements to the cooling system , exhaust valve materials and exhaust system component design. Analyses of the impacts of operating with and without power enrichment were conducted as part of the Regulatory Impact Analysis (U.S. EPA 2022)[31] for the recently finalized 2027 and later heavy-duty vehicle and engine standards (88 FR 4296 2023). As summarized within Chapter 3.2.2.2 of the HD-RIA, EPA conducted testing of a light-heavy-duty gasoline spark-ignition engine over the Heavy-duty Supplemental Emissions Test (SET) (Title 40 CFR § 600.311–12 2021), which includes sustained high-load operation. Power and torque results for this testing are shown in Table 3-15 for the SET A, B and C

[31] This will be referred to as the "HD-RIA" to differentiate from the RIA for this proposal.

setpoints. Sustained operation at near-stoichiometric air-to-fuel ratio conditions during testing over the SET resulted in power that was approximately 5 percent less and torque that was approximately 4 percent less when compared to allowing power enrichment.

Table 3-18: SET Operation Mode Power Comparison

	Power (kW)			Torque (Nm)		
	SET Set Points*			SET Set Points*		
	A	B	C	A	B	C
Power Enrichment Allowed	211	187	145	546	572	547
Enrichment for Catalyst Protection with No Power Enrichment	211	182	141	542	554	524
Stoichiometric Operation, Catalyst Protection via Load Reduction	201	179	137	522	551	526
* The A, B and C engine speeds are setpoints defined within the SET procedures (Title 40 CFR § 600.311–12 2021).						

Contract work conducted by Southwest Research Institute for EPA using a modern, 6.4L heavy-duty gasoline engine[32] demonstrated the use of close-coupled exhaust catalysts and a combination of down-speeding and near-stoichiometric operation that achieved adequate component protection for the catalyst, low NMHC and NO_X emissions, and reduced GHG emissions (Southwest Research Institute 2022).

EPA is proposing in this rulemaking to eliminate the allowance of the use of commanded enrichment as an AECD for either power enrichment or component protection during normal operation and use with exceptions for conditions of imminent component failure or engine overheating protection modes specifically where the check engine light, MIL, or other warning systems are triggered.

Additionally, EPA is proposing that vehicle emission control strategies used for both gasoline and diesel vehicles and demonstrated over the emission test cycles also perform at similar effectiveness levels over normal vehicle operation. This includes operation at higher legal speeds observed on public roads but also under loaded conditions that vehicles are designed and advertised to perform for consumers. If a vehicle is designed to carry high loads or tow trailers by the manufacturer and such operation does not conflict with manufacturer's recommendations and/or does not potentially void warranty coverage, that operation is considered normal vehicle operation for purposes of expectation of similar emission control system design effectiveness.

3.2.5 Particulate Matter Emissions Control

The proposed PM standard and phase-in are presented in Preamble Section III.C.3. An overview of GPF technology is provided in Chapter 3.2.2.1. GPF benefits are introduced in Chapter 3.2.2.2. The importance of the three PM certification test cycles is described in Chapter 3.2.2.3. A demonstration of the feasibility of the PM standard for light-duty vehicles and MDVs is provided in Chapter 3.2.2.4. Finally, GPF cost is discussed in Chapter 3.2.2.5.

[32] Note that this 6.4L heavy-duty gasoline engine used in RAM Class 4 applications shares an engine family with engines used in RAM MDV pickup truck applications.

3.2.5.1 Overview of GPF technology

Gasoline particulate filter (GPF) technology is not new. It has been used in series production on all new pure GDI vehicle models (type approvals) in Europe since 2017 (WLTC and RDE test cycles) and on all pure GDI vehicles in Europe since 2019 (WLTC and RDE test cycles) to meet a $6x10^{11}$ #/km solid particle number (PN) standard. All gasoline vehicles in China have had to meet the same $6x10^{11}$ #/km solid PN limit in the WLTC test since 2020, and in the WLTC and RDE starting in 2023. In India, BS6 stage 2 requires gasoline vehicles to also meet the $6x10^{11}$ #/km solid PN limit in the MIDC (Indian version of NEDC) and RDE starting in April 2023. U.S., European, and Asian manufacturers have extensive experience with applying GPF technology to series production vehicles and several manufacturers assemble vehicles with GPF in the U.S. for export to other markets.

GPFs being used in Europe and Asia and expected to be used in the U.S. to meet the proposed 0.5 mg/mi PM standard across 25°C FTP, US06, and -7°C FTP cycles, use a ceramic honeycomb structure with alternating channels plugged at their inlet and outlet ends (Figure 3-12). GPFs use Cordierite for its low coefficient of thermal expansion and thermal shock tolerance. GPF substrates typically have 45-65 percent porosity, 10-25 µm median pore size, 6-12 mil (1 mil = 1/1000 inch) wall thickness, and 200-300 cpsi (cells per square inch) cell density. GPF substrates can be manufactured in various diameters, lengths, and shapes (e.g., round or oval).

Wall flow filters allow exhaust gases to flow through porous filter walls while particulates are captured in or on the wall (Figure 3-12). Gasoline engine-out particulates (typically from <10 to 300 nm) are smaller than GPF mean pore size (typically 10-25 µm), but particles are captured at high filtration efficiencies across the engine-out size range by Brownian diffusion (small particles), interception (intermediate particles), and inertial impaction (large particles).

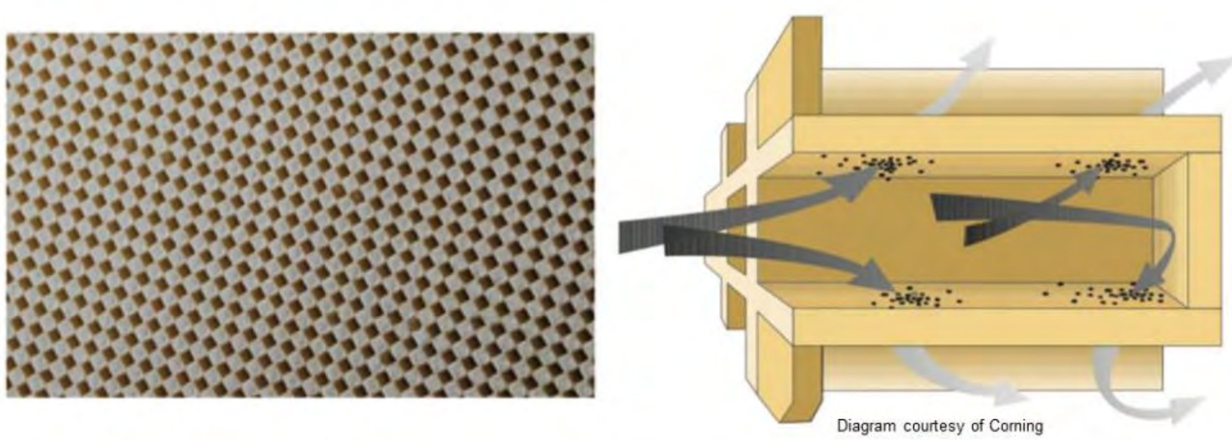

Figure 3-12: Wall-flow GPF design.

A clean GPF initially captures particulates within its pore structure (depth filtration mode); at high levels of soot loading, additional particulates form a soot layer (soot cake) on the top of the wall (soot cake or surface filtration mode). Filtration efficiency improves rapidly with initial soot and ash loading (Lambert, et al. 2017), then levels off at high soot loading. GPF backpressure increases with soot and ash loading. Operation at low levels of soot loading are more challenging for PM filtration because the GPF cannot rely on stored soot to assist with filtration.

Both bare and catalyzed GPFs are used in series production. Catalyzed GPFs typically use a washcoat containing Pd and Rh for TWC-type activity. Catalyzed GPFs reduce the temperature needed to oxidize stored soot and convert criteria emissions like a TWC does. A catalyzed GPF and can replace one of the TWCs on a vehicle, potentially reducing system cost. Optimizing filtration, backpressure, and gaseous emissions light-off, however, can be more challenging with a catalyzed GPF.

Accumulated soot in a GPF is oxidized to CO_2 and H_2O in the presence of sufficient temperature and oxidants (mostly O_2 in gasoline engines). Significant rates of GPF regeneration are observed above 600°C for a bare GPFs (Borger, et al. 2018) and above 500°C for a catalyzed GPFs (Saito, et al. 2011). In most applications, normal vehicle operation results in sufficiently high temperature, and deceleration fuel cut-off (DFCO) supplies the GPF with sufficient O_2, resulting in passive regeneration. If a vehicle is only operated at very low load conditions or is not allowed to warm up, a differential pressure sensor on the GPF can sense imminent GPF overloading and initiate an active regeneration in which engine settings are adjusted to increase GPF temperature and supply it with sufficient O_2. Active GPF regeneration strategies are discussed in (van Nieuwstadt, et al. 2019).

GPFs are sometimes installed close to the engine in a "close-coupled" position, immediately following the TWC, to promote passive regeneration and fast light-off of a catalyzed GPF. Other times GPFs are installed farther from the engine, in an "underfloor" location, for packaging reasons. The lower exhaust gas temperature in underfloor GPFs also reduces backpressure for a given GPF size and geometry because cooler exhaust has higher density.

GPF size, design, and installation relative to the engine must be considered for the GPF to have sufficient PM filtration efficiency, sufficiently low backpressure, sufficient ash loading capacity, fast light-off if the GPFs washcoat is relied upon for gaseous criteria emissions conversion, and good regeneration characteristics. Unlike soot that is oxidized after being captured by the GPF, ash accumulates on the GPF, typically for the life of the vehicle. Thus, ash capacity is one factor that determines GPF size for a given application.

GPFs are like diesel particulate filters (DPF) in certain respects. Both GPFs and DPFs are wall-flow filters that use a ceramic honeycomb substrate with alternating channels plugged at their inlet and outlet ends to filter particulates. But GPFs operate at higher exhaust gas temperatures, lower soot loadings, lower exhaust gas O_2 and NO_2 concentrations, and only see elevated exhaust gas O_2 concentrations during DFCO events. High exhaust gas temperature tends to keep GPFs at lower soot loading through frequent passive regeneration, making high filtration efficiency harder to achieve in GPFs, especially in applications that frequently operate at high load. Low soot loading of GPFs results in lower backpressure than DPFs. GPFs require low heat capacity to make use of relatively short bursts of elevated O_2 during DFCO events, so Cordierite has become the GPF substrate material of choice. DPFs require higher heat capacity to accommodate larger and less frequent regeneration events involving larger amounts of soot and high flow rates of exhaust O_2 making silicon-carbon a popular DPF substrate material.

GPFs have an excellent record with respect to robust operation and durability since their introduction into mass production in Europe and China. The first GPFs introduced into series production have not experienced the failures that troubled early DPFs introduced into series production, in part because the higher exhaust gas temperatures seen by GPFs promote frequent passive regeneration, avoiding larger, less frequent regeneration events seen by DPFs that store larger amounts of soot and have high exhaust O_2 flow under all conditions.

GPF technology has been studied extensively for more than a decade and there exists extensive literature on GPF. GPF technology review articles include (Saito, et al. 2011), (Joshi and Johnson 2018), (Boger and Cutler 2019).

3.2.5.2 GPF benefits

GPF technology offers benefits of reduced PM emissions, BC emissions, and PAH reductions. This section begins by showing measured reductions in PM mass, black carbon (BC), and polycyclic aromatic hydrocarbon (PAH) using a MY 2011 F150 and a MY 2019 GPF. The second part of this section presents reductions in PM mass emissions resulting from the addition of MY 2019 and MY 2022 GPFs to three newer vehicles (MY 2019 F150, MY 2021 F150 HEV, and MY 2022 F250.

3.2.5.2.1 PM mass, BC, and PAH emissions reductions over a composite drive cycle

The test vehicle was a MY 2011 F150 and the GPF was an underfloor catalyzed MY 2019 GPF. Additional details of the vehicle, GPF, and test setup are described in Section 3.2.2.5 and in (Bohac and Ludlam, Characterization of a Lightly Loaded Underfloor Catalyzed Gasoline Particulate Filter in a Turbocharged Light Duty Truck 2023). Emissions were quantified over a composite test cycle, comprised of vehicle operation at 60 mph cruise control, 25°C FTP, HFET, and US06. Results are shown in total emissions mass per total distance of the test cycle. Tailpipe emissions were quantified a) without a GPF, b) with the GPF in a lightly loaded state with the GPF predominantly in the depth filtration mode (Konstandopoulos 2008) (0.1-0.6 g/L, grams soot per liter of GPF substrate volume), and c) with the GPF predominantly in the soot-cake or surface filtration mode (Konstandopoulos 2008) (1.7-2.0 g/L).

Composite cycle PM emissions are shown in Figure 3-13. PM was reduced by 94 percent with the GPF in a lightly loaded state and 98 percent with the GPF in a heavily loaded state. Additional results and discussion, including cycle-specific PM reductions, can be found in (Bohac, Ludlam and Martin, et al. 2022).

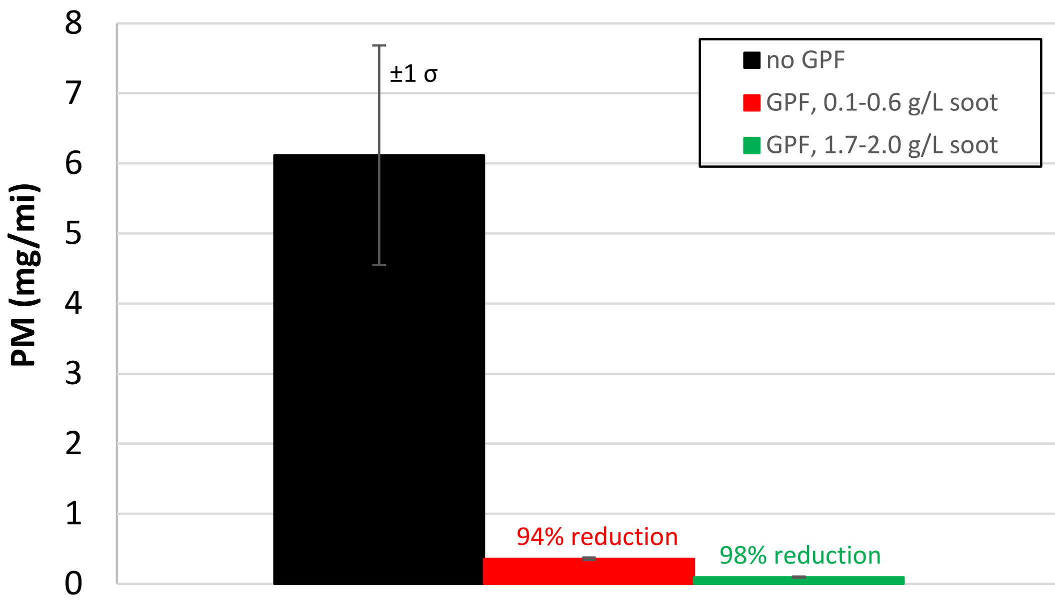

Figure 3-13: Composite cycle PM reduction at low and high GPF soot loading.

EC emissions without a GPF and with the GPF in a lightly loaded state (0.1-0.6 g/L soot loading) are shown in Figure 3-14. EC was reduced by 100.0 percent in the 60 mph, 25°C FTP, and HFET cycles, and was reduced by 98.5 percent in the US06 cycle. EC measurements were performed using 47 mm quartz fiber filters (Pall Tissuquartz 7202) and a Sunset Laboratory model 5L OCEC Analyzer running National Institute for Occupational Safety and Health (NIOSH) method 870.

Exhaust elemental carbon (EC) emissions quantified in this study and airborne black carbon (BC) studied by climate scientists have different operationally defined definitions, but they are closely related and often used as surrogates (Bond, Doherty and Fahey 2013).

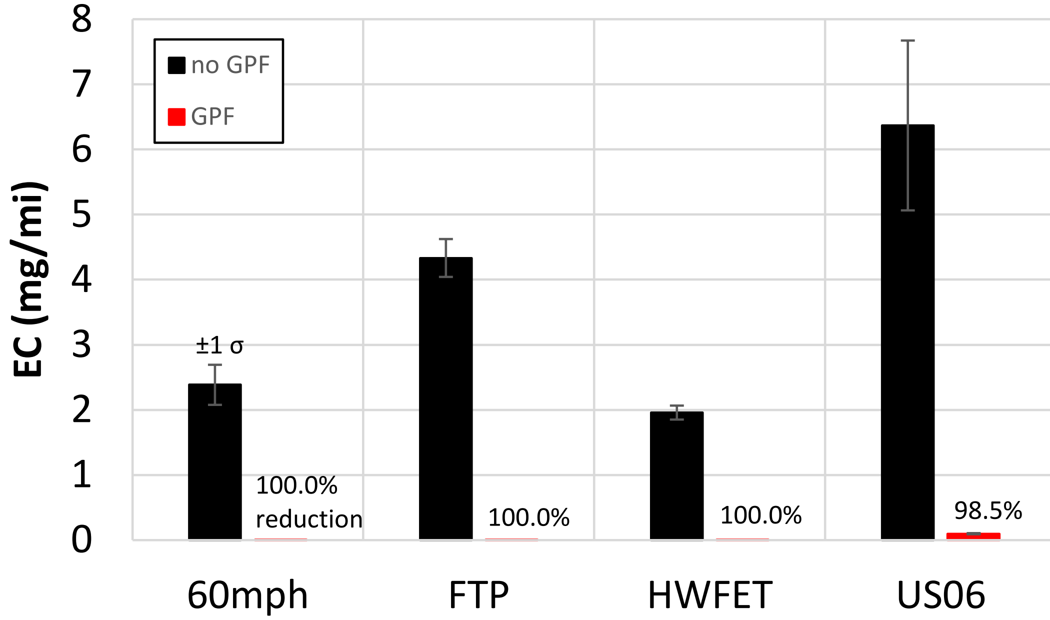

Figure 3-14: Cycle-specific EC reduction.

Another significant benefit of GPF technology is the reduction of PAH emissions. To quantify PAH emissions reductions, filter-collected PAH were sampled onto 47 mm quartz fiber filters (Pall Tissuquartz 7202) and gas-phase PAH were sampled using sorbent tubes (Carbotrap C+F). PAHs on filter punches and sorbent tubes were thermally desorbed, cryofocused, and speciated (Agilent 6890/5973 GCMS operated in selected ion mode). 26 PAHs ranging from naphthalene to coronene were quantified. Additional sampling and analysis details can be found in (Bohac, Ludlam and Martin, et al. 2022).

PAH emissions reductions are shown in Figure 3-15. Measurements were performed with the GPF in lightly loaded state (0.1-0.6 g/L soot loading) and in a heavily loaded state (1.7-2.0 g/L soot loading). Filter-collected PAH emissions (those collected by the PM sampling filter) were reduced by over 99 percent and gas-phase PAH emissions (those passing through the PM sampling filter) were reduced by about 55 percent. The percentage reduction in gas-phase PAH emissions may be less for bare GPFs.

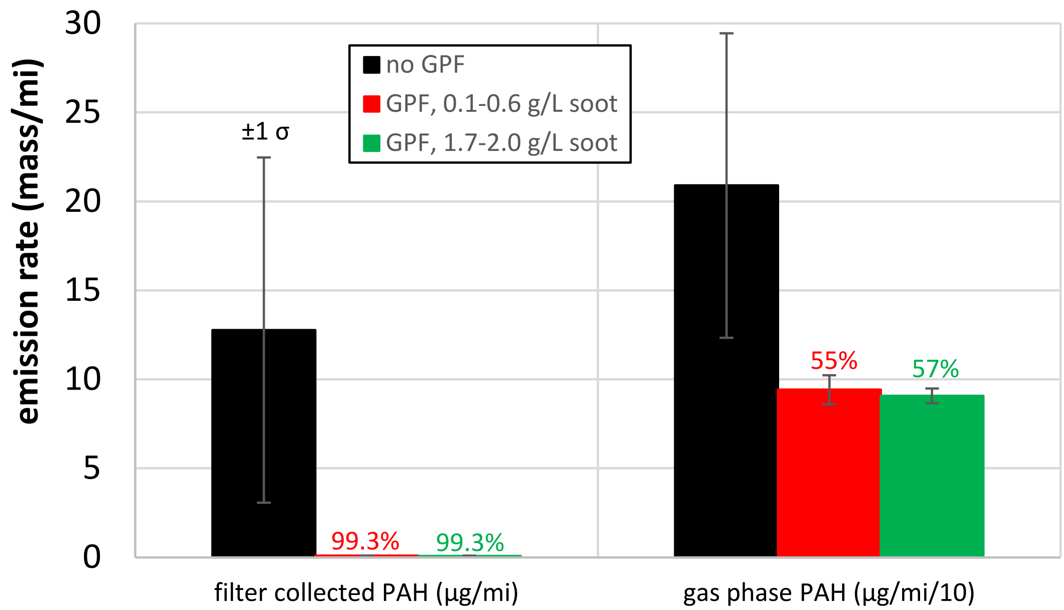

Figure 3-15: Composite cycle PAH reduction at low and high GPF soot loading. Sum of 26 filter collected PAHs shown on the left and sum of 26 gas phase PAHs shown on the right.

As shown in Figure 3-16, filter-collected PAHs ranged from 2-ring naphthalene to 7-ring coronene for no GPF and GPF test cases. High rates of PAH reduction were seen across all 26 PAHs.

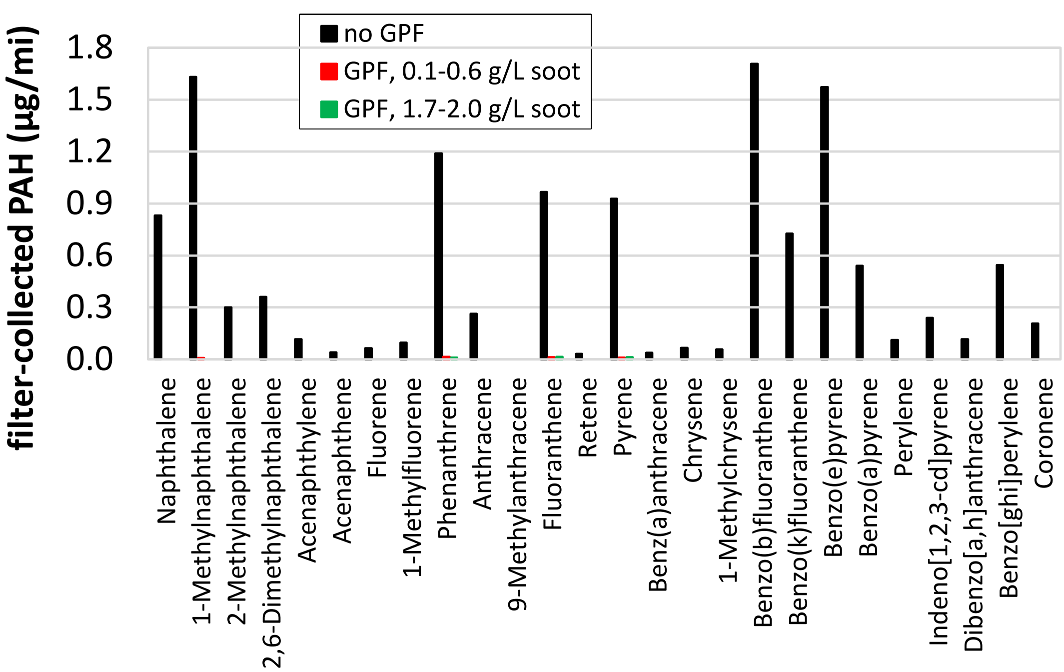

Figure 3-16: Filter-collected PAH emissions rates with no GPF, lightly loaded GPF, and heavily loaded GPF.

Composite cycle cancer potency weighted toxicity of 20 filter-collected PAHs for which cancer toxicities are quantified by the EPA 2014 National Toxics Assessment (OAQPS 2014) was reduced by 99.8 percent (Figure 3-17).

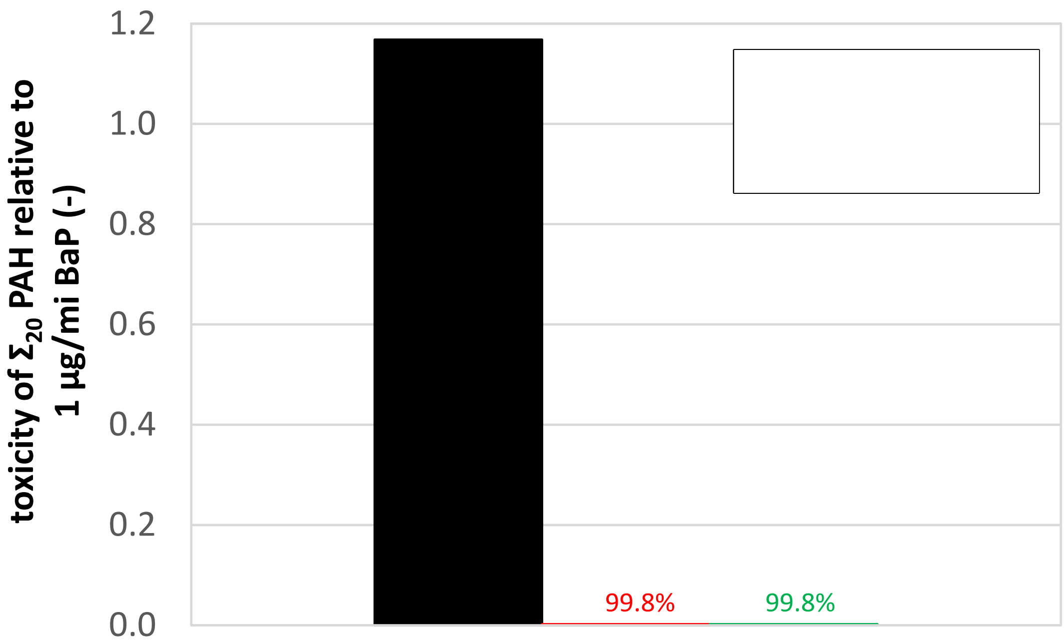

Figure 3-17: Cancer potency weighted toxicity of 20 filter-collected PAHs with no GPF, lightly loaded GPF, and heavily loaded GPF.

3.2.5.2.2 Cycle-specific reduction in PM mass emissions from GPF application to three vehicles

Reductions in cycle-specific PM mass emissions resulting from the adoption of GPF technology is discussed in this subsection. Three vehicle examples are presented: a MY 2019 F150 5.0L, a MY 2021 F150 HEV 3.5L Powerboost, and MY 2022 F250 7.3L.

The first test vehicle is a MY 2019 F150 5.0L that was tested stock and with a MY 2019 European Ford Mustang 5.0L aftertreatment system. PM emissions are shown in Figure 3-18. This GPF system reduced PM emissions by 91 percent, 90 percent, and 77 percent in the -7°C FTP, 25C FTP, and US06 cycles, respectively. The testing was conducted with the GPFs in a lightly loaded state. The lightly loaded state was achieved by running a sawtooth GPF regeneration cycle after several tests were completed. Older technology GPFs like the one used in on this test have lower filtration efficiency at low soot loading than newer GPFs used on the other two test vehicles described in this subsection. Figure 3-18 shows that filtration efficiency was lowest in the US06, which was caused by the passive regeneration that occurs in this cycle. Additional details of the vehicle and GPFs are provided in Section 3.2.2.4.

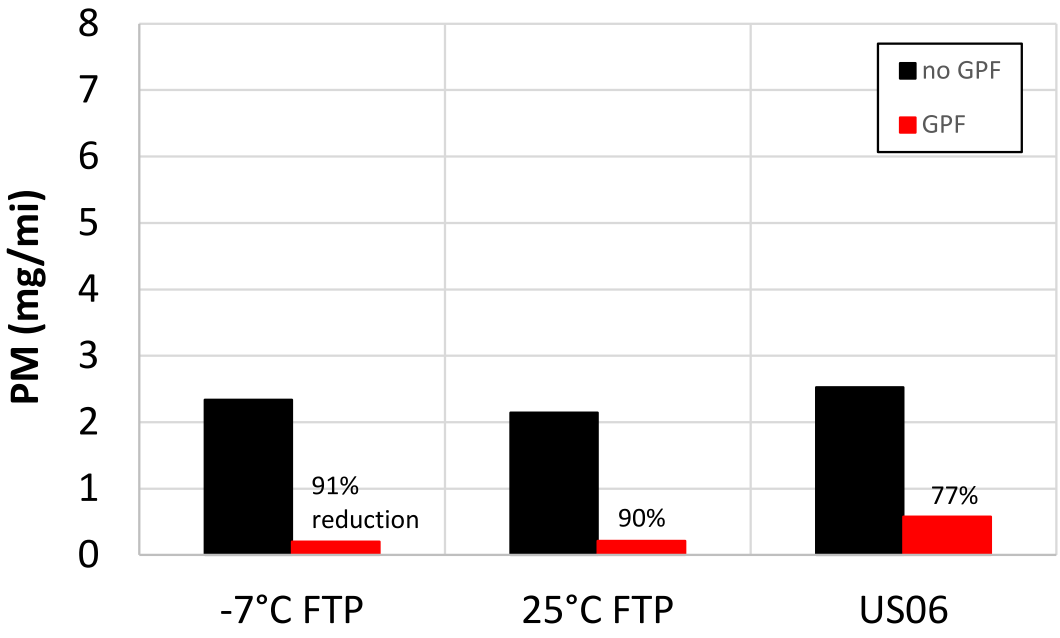

Figure 3-18: PM emissions from a MY 2019 F150, with and without a MY 2019 GPF.

The second test vehicle is a MY 2021 F150 HEV Powerboost that was tested with and without a MY 2022 bare underfloor GPF. PM emissions are shown in Figure 3-19. The MY 2022 GPF reduced PM emissions by 99 percent, 96 percent, and 96 percent in the -7°C FTP, 25C FTP, and US06 cycles, respectively. The GPF was fully regenerated immediately before each day of testing using a sawtooth GPF regeneration cycle. The GPF results shown here are worst case with respect to PM filtration because testing was preceded by a GPF regeneration, so the GPF was evaluated with almost no soot. Filtration efficiency of the MY 2022 GPF was significantly better than what was achieved with the MY 2019 GPF shown in Figure 3-18, especially in the US06. Additional details of the vehicle and GPFs are provided in Section 3.2.2.4.

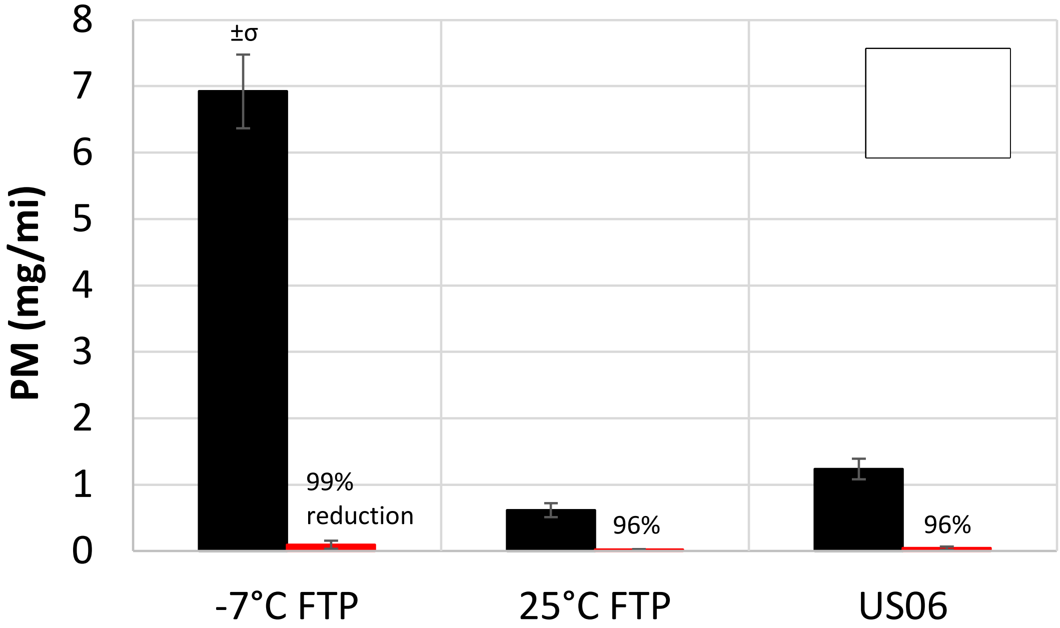

Figure 3-19: PM emissions from a MY 2021 F150 HEV, with and without a MY 2022 GPF.

The third test vehicle is a MY 2022 F250 7.3L that was retrofit with two MY 2022 GPFs, one for each engine bank. PM emissions are shown in Figure 3-20. The MY 2022 GPFs reduced PM emissions by 98 percent, 78 percent, and 98 percent in the -7°C FTP, 25C FTP, and US06 cycles, respectively. The GPF was fully regenerated immediately before each day of testing using a sawtooth GPF regeneration cycle. The GPF results shown are worst case with respect to PM filtration because testing was preceded by a GPF regeneration, so the GPF was tested with almost no soot.

Filtration efficiency of the MY 2022 GPFs on the MY 2022 F250 was nearly identical to the filtration efficiency of the MY 2022 GPF on the MY 2021 F150 HEV in the -7°C FTP and US06 cycles. Filtration efficiency in the 25C FTP test was higher on the MY 2021 F150 HEV than on the MY 2022 F250, but the extremely low GPF-equipped levels of PM, around 0.04 to 0.06 mg/mi makes precise PM mass measurements more challenging.

Tailpipe PM was significantly lower with the MY 2022 GPFs as compared to the MY 2019 GPF, especially in the US06 cycle where passive GPF regeneration occurs. Additional details of the vehicle and GPFs are provided in Section 3.2.2.4.

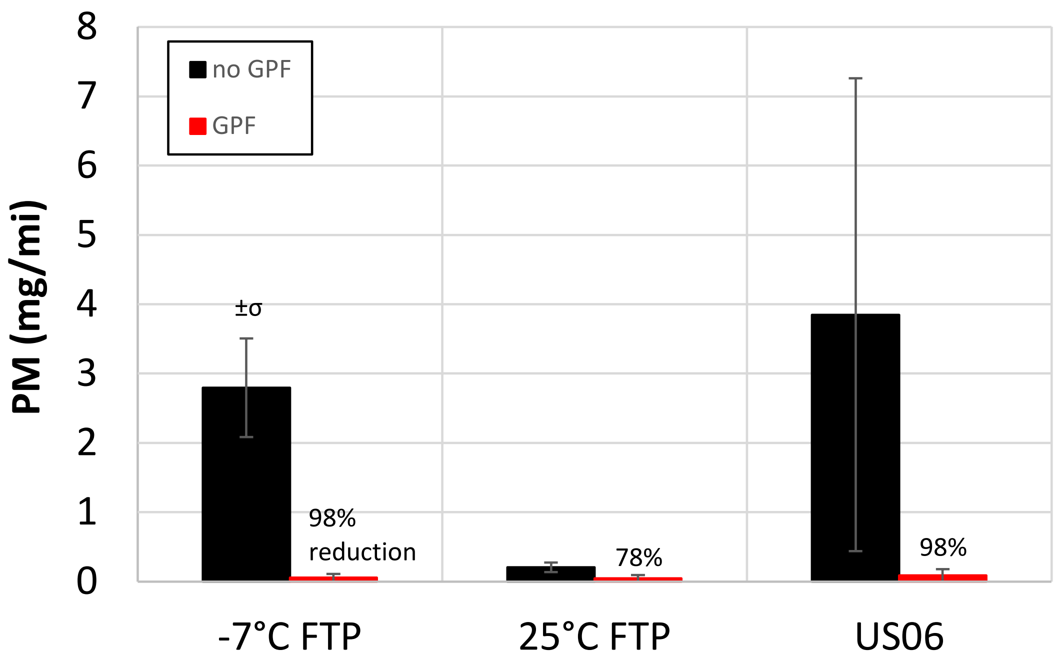

Figure 3-20: PM emissions from a MY 2022 F250, with and without MY 2022 GPFs.

3.2.5.3 Importance of test cycles

The -7°C FTP test is essential to the proposed PM standard because -7°C[33] is an important real-world temperature with significant uncontrolled PM emissions. Based on EPA testing, PM emissions in the -7°C FTP are significantly higher than those demonstrated during a 25°C FTP test (e.g., Figure 3-18, Figure 3-19, Figure 3-20, and Preamble Figure 11 in Chapter 3). In addition to controlling high cold weather PM emissions that were uncontrolled in Tier 3, the -7°C FTP test differentiates Tier 3 levels of PM from GPF-level PM.

PM is elevated in the -7°C FTP test because heavy species in gasoline have very low vapor pressure at cold temperatures, making them difficult to vaporize on cold engine surfaces. For example, as shown in Figure 3-21, the vapor pressure of toluene and n-decane, two representative heavy species of gasoline, are reduced by 6.5X and 12X, respectively, as temperature decreases from 25° to -7°C. Early examples of peer-reviewed literature showing cold ambient temperature (including -7°C) increases PM mass and solid PN from a GPF-equipped vehicle include (T. W. Chan 2013) and (T. W. Chan 2014).

[33] -7°C is approximately 20°F, a temperature common through much of the United States during winter months.

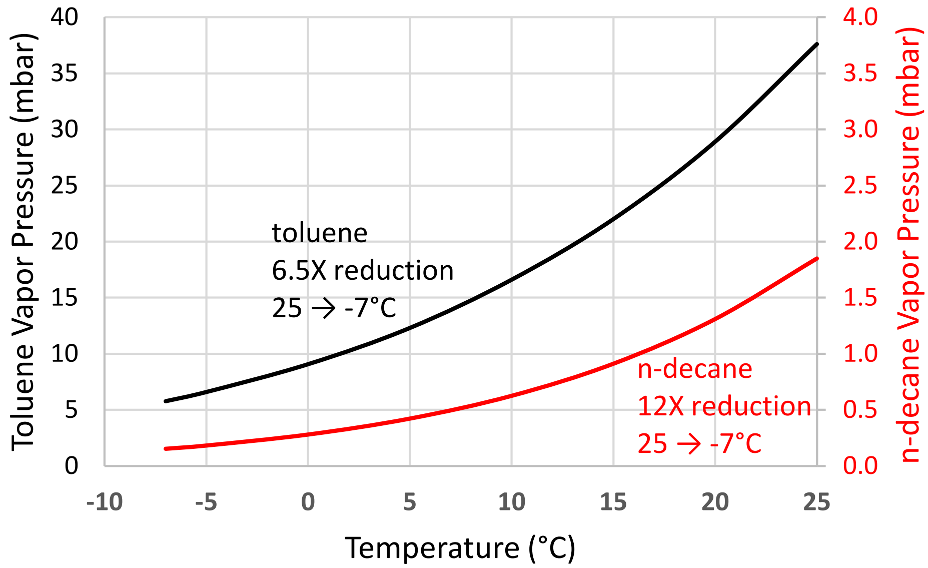

Figure 3-21: Vapor pressure of toluene and n-decane as a function of temperature.

The 25°C FTP test is retained from prior standards because it ensures that vehicles are designed and calibrated to operate clean over a range of ambient temperatures. The US06 test is important because 1) it represents higher load real-world driving, and 2) it ensures low tailpipe PM during and after a GPF regeneration, when soot loading is low and makes PM filtration more challenging. The relatively poor filtration of earlier GPF designs, during and immediately after regeneration, e.g., in a US06 cycle, has been discussed in the literature for some time, e.g., (T. W. Chan 2016).

In sum, the combination of -7°C FTP, 25°C FTP, and US06 standards ensures that a vehicle has good PM control over the broadest area of vehicle operation and environmental conditions.

In Tier 3, most Class 2b vehicles used the US06 cycle, while low power to weight Class 2b vehicles and all class 3 vehicles used the LA92 cycle in the SFTP calculation. The proposed rule requires all LD vehicles and MDVs to certify using the same cycles: -7°C FTP, 25°C FTP, and US06. Requiring the US06 for all class 2b/3 vehicles ensures that GPF regeneration occurs during the test cycle and requires high GPF filtration under all operating conditions, even during and after a GPF regeneration. Without the US06 test, GPF regeneration may not occur during any certification test cycle, allowing for high PM emissions during high load operation such as trailer towing. If a class 2b/3 vehicle cannot follow the US06 trace, it must be run at maximum effort, and in this case the test will not be voided.

3.2.5.4 Demonstration of the feasibility of the standard

3.2.5.4.1 Setup and Test Procedures

A demonstration of the feasibility of the PM standard for light-duty vehicles and MDVs is described in this section. Testing was performed using five chassis dynamometer test cells at three organizations (EPA, ECCC, FEV) and five test vehicles in stock and GPF configurations. Test vehicles included light-duty vehicles and MDVs powered by naturally aspirated and turbocharged PFDI (port and direct fuel injection), DI (direct injection), and PFI (port fuel injection) gasoline engines. GPF-equipped vehicles used series-production GPFs from MY 2019 and MY 2022 GPF. GPFs used catalyzed and bare substrates, and they were installed in close-coupled and underfloor configurations.

The five chassis dynamometer test cells used in the demonstration included three test cells at EPA National Vehicle and Fuel Emissions Laboratory (NVFEL), one test cell at ECCC, and one test cell at FEV. -7°C FTP tests were performed at EPA (one test cell), ECCC, and FEV. 25°C FTP and US06 tests were performed at EPA (three test cells), ECCC, and FEV. Three test vehicles were tested at all organizations, while two vehicles were only tested at EPA.

All five test cells used in the demonstration were designed to be compliant with 40 CFR Part 1065 and 1066. In each test cell, vehicle exhaust gas is diluted in a constant volume sampler (CVS) full-flow dilution tunnel system. Heated particulate filter samplers draw dilute exhaust through a coarse particle separator (~2.5 µm cut at sampling conditions) and 47 mm PTFE membrane filters [e.g., Measurement Technology Laboratories (MTL) PT47DMCAN].

PM filters were conditioned at 22±1°C, 9.5±1°C dew point for a minimum of 1 hour before being weighed, before and after being loaded with PM. Filters were weighed using a microbalance (e.g., Mettler-Toledo XPU2) while being surrounded by strips of Po210 (e.g., 5 strips of 500 µCi each) for static charge removal. EPA used an MTL A250 robotic autohandler for filter weighing; ECCC and FEV labs used manual filter weighing.

To increase sample filter loading and increase signal to noise ratio for GPF-equipped tests, test cell sampling settings were adjusted relative to test settings typically used to measure Tier 3 levels of PM emissions, within boundaries defined by the CFR. For GPF-equipped tests, 1) Dilution factor (DF) was set to the lower/middle part of the CFR-allowable range of 7-20. 2) 25°C FTP and -7°C FTP tests were mostly run using a single filter, as allowed by §1066.815(b)(5). 3) In many tests, filter flow was increased from a typical setting of ~58 slpm to ~65.25 slpm in phases 1&2 and ~87 slpm in phases 3&4 to increase filter loading and maintain proper phase weighting using flow weighting, while staying below the maximum allowable filter face velocity (FFV) of 140 cm/s as specified by §1066.110(b)(2)(iii)(C). 4) Many of the 25°C FTP and -7°C FTP tests were run as 4-phase FTP tests as opposed to 3-phase FTP tests, although in hindsight, phase 4 didn't add much PM mass to the sampling filter and may not be worth the extra test time. Additionally, to further increase PM filter loading, some of the GPF-equipped tests used double sampled US06 tests, which is not included in the CFR. In retrospect, a standard single sampled US06 would have likely been sufficient. Additional testing is being conducted to confirm this.

Tier 3 certification fuel was used for 25°C FTP and US06 testing, and Tier 3 winter certification fuel was used for -7°C FTP testing at all three organizations. Engine oil was conditioned in each vehicle for a minimum of 600 miles prior to emissions sampling to stabilize the oil (Christianson, Bardasz and Nahumck 2010).

The newest of the five test vehicles was an MDV Tier 3 bin 200 MY 2022 Ford F250 with a naturally aspirated 7.3L V8 PFI engine. It was tested at an ETW of 8000 lb. The F250 was tested in stock and GPF configurations. Vehicle mileage at the start of testing was 2700 miles. For GPF testing, series-production MY 2022 GPFs, one for each bank, were installed downstream of the stock TWCs where the resonator is normally mounted. The GPF used bare substrates of ϕ6.443” x 6” (3.21 L each), 200 cpsi, 8 mil wall thickness. GPFs were aged through 1500 miles of road driving prior to emissions sampling. GPF pressure drop and temperatures were recorded.

The second newest test vehicle was a LDT4 Tier 3 bin 70 MY 2021 Ford F150 HEV with a turbocharged (Ecoboost) 3.5L V6 PFDI engine. It was tested at an ETW of 6000 lb. The F150 HEV was only tested in GPF configuration. Vehicle mileage at the start of testing was 5000 miles. A series-production MY 2022 GPF was installed after the Y-pipe in place of the resonator. The GPF used a bare substrate of ϕ6.443” x 6” (3.21 L), 200 cpsi, 8 mil wall thickness. The GPF was aged through 1500 miles of road driving prior to emissions sampling. GPF pressure drop and temperatures were recorded.

The third newest test vehicle was an LDV Tier 3 bin 30 MY 2021 Toyota Corolla with a naturally aspirated 2.0L I4 PFDI engine. It was tested at an ETW of 3375 lb. The Corolla was only tested in stock (no GPF) configuration. Vehicle mileage at the start of testing was 5800 miles.

The fourth newest test vehicle was an LDT4 Tier 3 bin 125 MY 2019 Ford F150 with a naturally aspirated 5.0L V8 PFDI engine. It was tested at an ETW of 5000 lb. The 2019 F150 was tested in stock and GPF configurations. Vehicle mileage at the start of testing was 6700 miles. For GPF testing, a series-production aftertreatment system from a MY 2019 European Ford Mustang 5.0L replaced the stock aftertreatment system on the F150. The Mustang aftertreatment system uses a cc1 (close-coupled, position 1) TWC and a cc2 catalyzed GPF for each bank of the engine. The stock aftertreatment system uses a cc1 TWC and a cc2 TWC for each bank. The Mustang GPFs are ϕ5.2” x 3.3” (1.15 L each), 300 cpsi, 12 mil wall thickness. The Mustang aftertreatment system was aged through 1500 miles of road driving prior to emissions sampling. GPF pressure drop and temperatures were recorded.

The oldest test vehicle was an LDT4 Tier 2 bin 4 MY 2011 Ford F150 with a turbocharged (Powerboost) 3.5L V6 DI engine. It was tested at an ETW of 5500 lb. The 2011 F150 was tested in stock and GPF configurations. Vehicle mileage at the start of testing was 21,100 miles. For GPF testing, a series-production MY2019 GPF was installed after the Y-pipe in place of the resonator. The GPF used a catalyzed substrate of ϕ5.66” x 4” (1.65 L), 300 cpsi, 12 mil wall thickness. The GPF was aged through 600 miles of dynamometer driving prior to emissions sampling. GPF pressure drop and temperatures were recorded.

GPF operation was characterized over a range of soot loadings, but because GPFs are required to comply with the proposed PM standard in any state of soot loading, only results from low-soot-loading tests (which are worst case with respect to tailpipe PM) are included in the following demonstration of meeting the proposed PM standard. GPFs were regenerated before each set of tests by using a sawtooth regeneration cycle.

3.2.5.5 GPF cost

A GPF cost model was developed to estimate direct manufacturing cost (DMC) of a bare GPF and associated hardware in the exhaust system of a gasoline-powered light-duty vehicle or MDV where the GPF is installed downstream of the TWCs in its own aftertreatment enclosure (can). The cost model has been incorporated in the OMEGA model.

A bare GPF installed downstream of the TWCs may have higher DMC than a catalyzed GPF that replaces a TWC because the bare downstream GPF requires an additional substrate,

substrate matting, and can. However, some or all of the additional DMC of a bare downstream GPF may be offset by enabling a reduction in total precious metal content because the precious metal content can all be used on the thinner and lower heat capacity walls of the TWCs that warm up faster after an engine start. Overall, it is believed that the GPF cost model in OMEGA estimates a DMC that is either higher or similar to the DMC of a catalyzed GPF that replaces a TWC.

Indirect costs (IC), including research, development, OBD, and markup, of a bare downstream GPF are also calculated by OMEGA. OMEGA estimate the IC of a bare downstream GPF in the same way as it does for other emissions control components, so these IC are not included in the GPF DMC model discussed below.

The GPF DMC model is based on an ICCT GPF cost analysis for a bare "stand-alone" GPF (Minjares and Sanchez 2011). The DMC model considers costs for the GPF substrate, housing, accessories, pressure sensor, labor and 40 percent overhead, machinery, and warranty. Substrate and housing costs scale with GPF volume. The substrate cost in the ICCT analysis is reduced by 30 percent (from 30 $/literGPF to 21 $/literGPF) based on information from substrate suppliers. The reduced substrate cost reflects manufacturing learning. Accessories, pressure sensor, labor and 40 percent overhead, and machinery costs are a fixed dollar amount per vehicle ($39.58). Warranty costs are 3 percent of all of the above-mentioned costs. A production volume discount of 20 percent is then applied, and finally, total cost is converted from 2011 to 2021 dollars (multiplier of 1.2046).

To estimate the GPF size needed by a specific engine, and therefore the DMC, a GPF volume to engine displacement ratio is used. The ICCT analysis calculated GPF to engine volume ratios for three vehicles and suggested using the average result of 0.55. EPA compared the ICCT average to two more recent European GPF-equipped vehicles. The MY 2019 European Mustang had a volume ratio that is 8 percent lower than the ICCT average, while a MY 2018 European Wrangler had a volume ratio that is 13 percent higher than the ICCT average.

To provide an overview of the GPF DMC of a bare downstream GPF, the cost model was run for engines ranging in size from 1.0 to 7.0 liters using GPF to engine volume ratios from the 2018 Wrangler, the ICCT average, and the 2019 Mustang. Figure 3-22 shows the resulting DMC estimates. DMC for a bare downstream GPF ranges from $51 dollars for a 1.0 liter engine using the volume ratio of the 2019 Mustang, up to $166 dollars for a 7.0 liter engine using the volume ratio of the 2019 Wrangler.

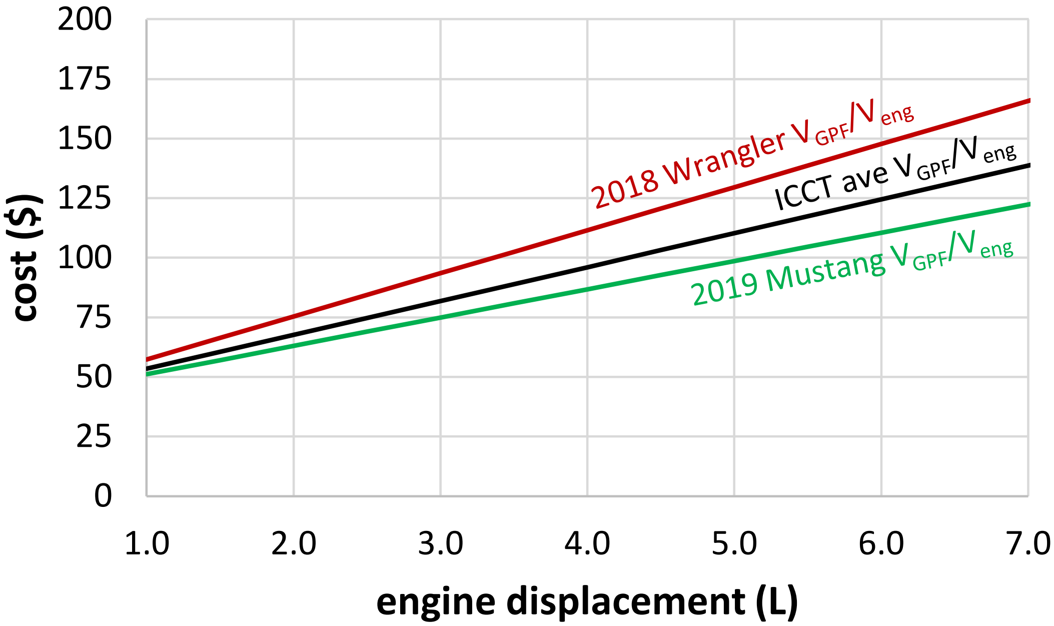

Figure 3-22: GPF cost estimate.

3.2.5.6 GPF impact on CO_2 emissions

Integrating GPF technology into vehicle aftertreatment systems has the potential to increase CO_2 emissions in two ways: during active GPF regeneration, and from increased backpressure. Active regeneration can increase CO_2 emissions while the engine adds more heat to the exhaust gas. However, based on discussions with vehicle manufacturers and GPF suppliers, and supported by testing conducted by EPA, most production vehicles will rarely or never need to use active GPF regeneration because systems with close-coupled GPFs or underfloor GPFs with insulated exhaust pipes (i.e., double wall) naturally cause sufficiently high GPF temperature for passive GPF regeneration. CO_2 increase due to active regeneration is therefore considered negligible in this analysis. The following paragraphs address the effect of GPF backpressure on CO_2 emissions.

GPF pressure drop (i.e., backpressure) and CO_2 increase were measured on four test vehicles across three test cycles (-7°C FTP, 25°C FTP, US06). Table 3-16 presents a summary of key vehicle and GPF specifications. Additional vehicle details are provided in Section 3.2.2.4.

Table 3-19: Vehicle and GPF specifications.

	MY2022 F250 7.3L	MY2021 F150 3.5L Powerboost HEV	MY2019 F150 5.0L	MY2011 3.5L Ecoboost
GPF model year	2022	2022	2019	2019
GPF type and location	bare underfloor	bare underfloor	catalyzed close-coupled	catalyzed underfloor
GPF size (L)	6.42 (total for two)	3.21	2.30 (total for two)	1.65
GPF volume / engine displacement (-)	0.88	0.92	0.46	0.47
GPF volume / ave US06 power (L/kW)	0.199	0.115	0.107	0.065
GPF ϕ x L (in)	6.443 x 6 (each)	6.443 x 6	5.2 x 3.3 (each)	5.66 x 4
GPF cell density (cpsi)	200	200	300	300
GPF wall thickness (mil)	8	8	12	12

Average GPF pressure drop for each test cycle and vehicle is shown in Figure 3-23. Average GPF pressure drop is highest in the US06 because this cycle demands the highest average power and has the highest average exhaust flow rate. Average GPF pressure drop is similar for the -7°C FTP and 25°C FTP because these cycles use the same drive trace. The 2011 F150 showed slightly higher GPF pressure drop in the -7°C FTP as compared to the 25°C FTP, presumably because powertrain friction increases at cold temperatures before the powertrain warms up. Figure 3-23 does not show GPF pressure drop for the 2019 F150 because the GPF differential pressure sensor was installed on this vehicle after -7°C FTP testing was conducted.

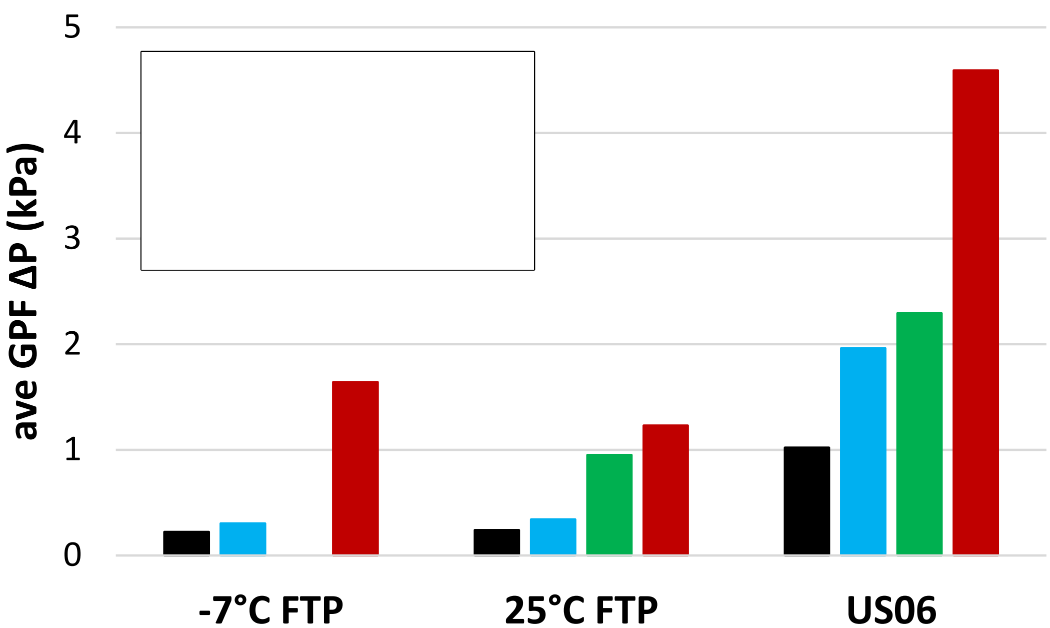

Figure 3-23: Cycle-average GPF pressure drop as a function of test cycle.

Figure 3-24 shows, as expected, GPF pressure drop in the US06 decreases asymptotically as the ratio of GPF volume to average US06 power increases. Larger GPF volume provides more GPF wall area for exhaust flow, and lower average US06 power results in reduced exhaust flow volume (due to reduced exhaust mass flow and lower exhaust temperature).

The results shown in Figure 3-23 show how for each test cycle (-7°C FTP, 25°C FTP, US06), average GPF pressure drop increases with decreasing ratio of GPF volume to average power in the US06. Based on a review of several European production vehicles and discussions with GPF suppliers, GPF volumes of the 2022 F250 and the 2021 F150 HEV are within typical production ranges for such vehicles, while GPF volumes of the 2019 F150 and 2011 F150 are relatively small for these vehicles, despite the GPF system on the 2019 F150 test vehicle coming from a European 2019 series production Mustang that uses the same engine displacement as the 2019 F150 test vehicle.

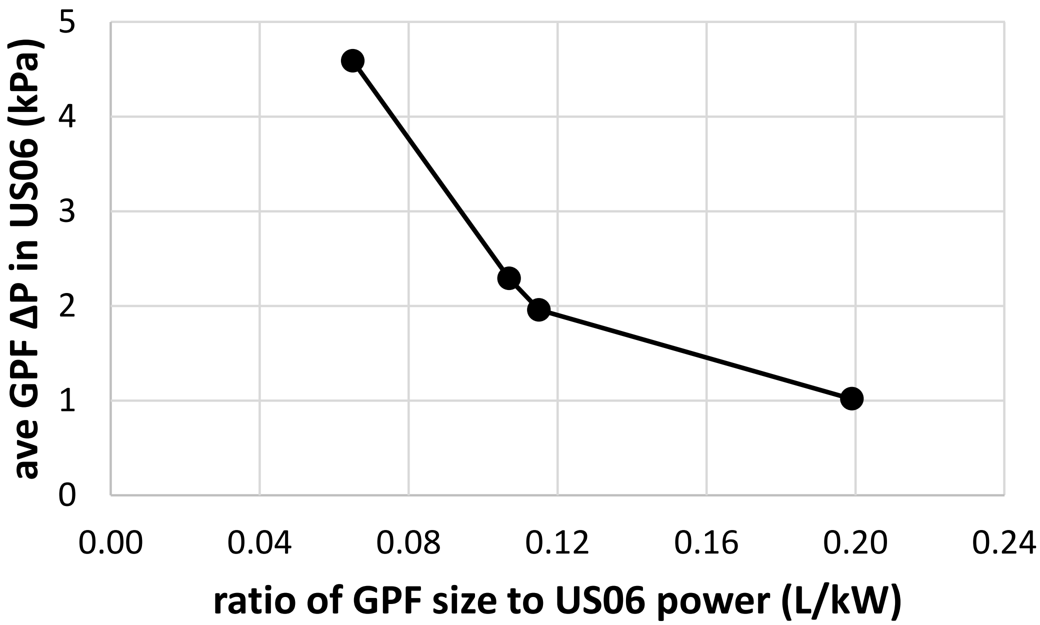

Figure 3-24: Cycle-average GPF pressure drop as a function of the ratio of GPF size to average power required to drive US06 cycle.

Higher GPF pressure drop increases the work that an engine must do to expel exhaust gas through the exhaust system. To maintain commanded power to follow a drive trace, the throttle is opened more, and this reduces intake pumping loss, partially offsetting the increased exhaust pumping work. The net effect is expected to be a slight reduction in brake thermal efficiency and a slight increase in CO_2 emissions. A more detailed discussion can be found in (Bohac and Ludlam, Characterization of a Lightly Loaded Underfloor Catalyzed Gasoline Particulate Filter in a Turbocharged Light Duty Truck 2023).

Table 3-17 shows the change in measured CO_2 emissions for each test cycle when GPFs were added, when results are averaged across the four test vehicles. Averaging across four test vehicles results in CO_2 increases between 0.0 percent for the 25°C FTP and 0.9 percent for the

US06. Since two of the test vehicles were equipped with somewhat undersized GPFs, these average CO_2 increases may be higher than for productions vehicles with more typical GPF volumes.

Table 3-20: Change in measured CO2 emissions for each test cycle when GPFs are added, averaged across four test vehicles (2022 F250, 2021 F150 HEV, 2019 F150, 2011 F150).

Test Cycle	CO_2 Increase (%)
-7°C FTP	0.6
25°C FTP	0.0
US06	0.9

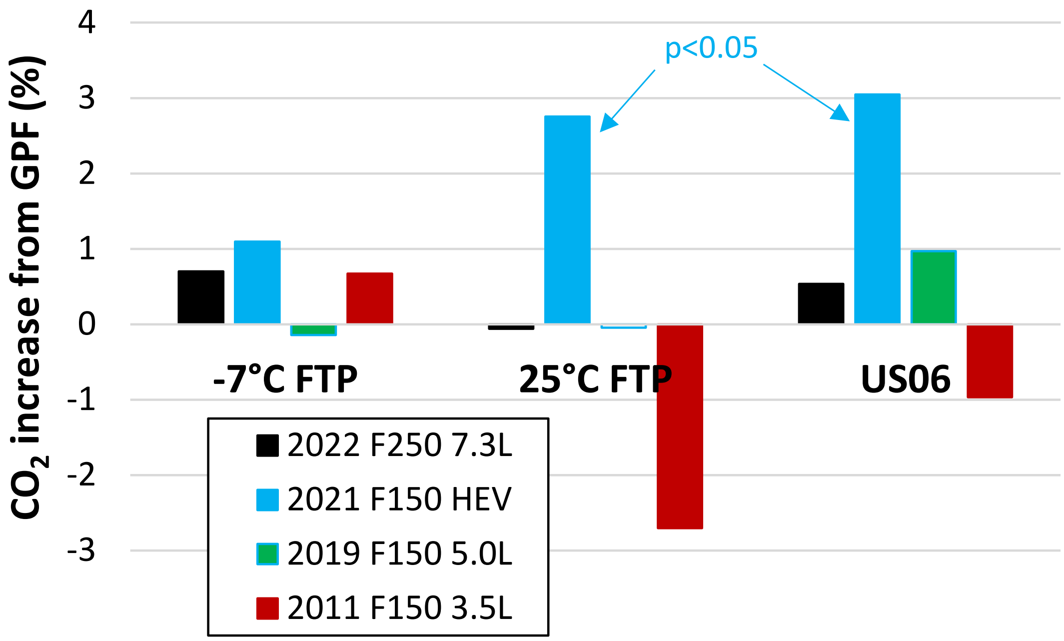

Figure 3-25: CO_2 increase caused by added GPF. Only the two light blue bars indicated are statistically significant to 95% confidence ($p<0.05$).

Considering the analyses summarized in Table 3-17 and Figure 3-25, it is estimated that integrating GPFs into vehicle aftertreatment systems likely causes less than 1 percent increase in CO_2 emissions in the -7°C FTP, 25°C FTP and US06 cycles.

3.2.6 Evaporative Emissions Control

The agency is proposing to require that incomplete medium duty vehicles meet the same on-board refueling vapor recovery (ORVR) standards as currently required for complete vehicles. Incomplete vehicles have not been required to comply with the ORVR requirements because on the potential complexity of their fuel systems, primarily the filler neck and fuel tank. Unlike complete vehicles which have permanent fuel system designs that are fully integrated into the vehicle structure at time of original construction by manufacturers, it was believed that incomplete vehicles which are typically finished at an upfitter who adds needed hardware and accessories, may need to change or modify some of fuel system components during their finishing assembly. For this reason, it was determined that ORVR might introduce a complexity for the upfitters that is unnecessarily burdensome.

In observations by the agency of current ORVR equipped vehicles and their incomplete versions, the agency believes that the fuel system designs are almost identical with only the ORVR components removed for the incomplete version. The complete and incomplete vehicles appear to share the same fuel tanks, lines, and filler tubes. The original thought that extensive differences between the original manufacturer's designs and the upfitter modifications to the fuel system would be required have not been observed. Therefore, the agency believes that almost all incomplete vehicles can comply with the same ORVR standards as complete vehicles with the addition of the same ORVR components on the incomplete vehicles as the complete version of the vehicle possesses

The current practice of manufacturers of the original incomplete vehicles is to specify to the upfitter that modifications of the fuel system are not allowed by the upfitter. This is because the incomplete vehicle manufacturers are responsible for all current evaporative requirements (2-day, 3-day, running loss, etc.) and almost any modification could compromise compliance with those program standards. There is also an aspect of compliance with crash and safety requirements that prevent upfitters from making changes to the fuel system components. For these reasons, with rare exception, the fuel system design and installation is completed by the original vehicle manufacturer. The exception that the agency observed is that some incomplete vehicles do not have the filler tube permanently mounted to a body structure until the upfitter adds the finishing body hardware (ie; flatbed, box). In these cases, the upfitter is limited to only attaching the filler tube to their added structure but must maintain the original manufacturer designs that are certified to meet existing EPA evaporative emission standards.

3.2.6.1 Technologies to Address Evaporative and Refueling Emissions

As exhaust emissions from gasoline engines continue to decrease, evaporative emissions become an increasingly significant contribution to overall HC emissions from gasoline-fueled vehicles. Opportunity exists to extend the usage of the refueling evaporative emission control technologies already implemented in complete medium-duty gasoline vehicles to the incomplete gasoline vehicle versions of the same basic vehicle. The primary technology we are considering is the addition of ORVR, which was first introduced to the chassis-certified light-duty and medium-duty applications beginning in MY 2000 (65 FR 6698, February 10, 2000). An ORVR system includes a carbon canister, which is an effective technology designed to capture HC emissions during refueling events when liquid gasoline displaces HC vapors present in the vehicle’s fuel tank as the tank is filled. Instead of releasing the HC vapors into the ambient air, ORVR systems recover these HC vapors and store them for later use as fuel to operate the engine.

The fuel systems on these 8,501 to 14,000 pound GVWR incomplete medium-duty gasoline vehicles are similar if not almost identical to complete medium-duty vehicles that are already required to incorporate ORVR. These incomplete vehicles almost always have identical fuel tanks to the complete medium-duty gasoline vehicles. There may be occasional optional larger fuel tanks requiring a greater ORVR system storage capacity and possibly some unique accommodations for dual tanks (e.g., separate fuel filler locations), but we expect they will maintain a similar design. Figure 3-26 presents a schematic of a standard ORVR system.

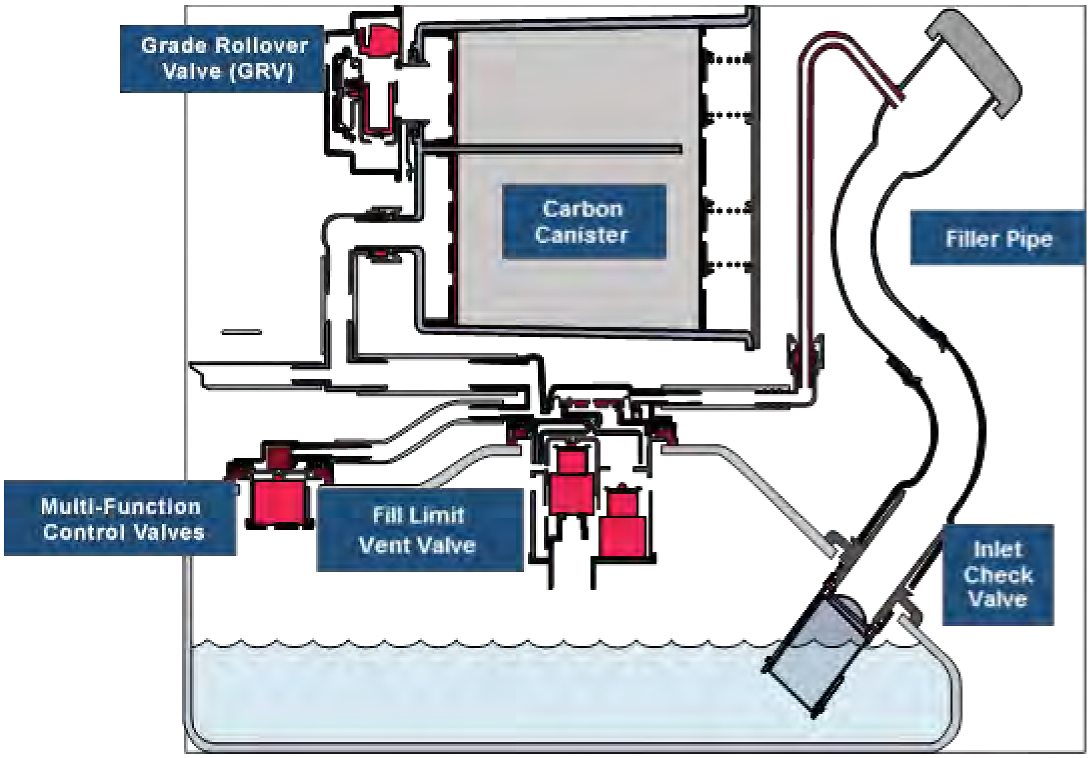

Figure 3-26: Schematic of an ORVR system34

3.2.6.2 Filler Pipe and Seal

In an ORVR system, the design of the filler pipe, the section of line connecting the point at which the fuel nozzle introduces fuel into the system to the gas tank, is integral to how fuel vapors displaced during a fuel fill will be handled. The filler pipe is typically sized to handle the maximum fill rate of liquid fuel allowed by law while also integrating one of two methods to prevent fuel vapors from exiting through the filler pipe to the atmosphere: a mechanical seal or a liquid seal approach. A dual fuel tank chassis configuration may require a separate filler pipe and seal for each fuel tank.

The mechanical seal is typically located at the top of the filler neck at the location where the fuel nozzle is inserted into fuel neck. The hardware piece forms a seal against the fuel nozzle by using some form of a flexible material (usually a plastic material) that makes direct contact with the fuel station fuel-filling nozzle to prevent fuel vapors from exiting the filler pipe as liquid fuel is pumped into the fuel tank. In the case of capless systems, this seal may be integrated into the spring-loaded seal door that opens when the nozzle is inserted into the filler pipe receptacle. There are concerns with a mechanical seal's durability due to wear over time, and its ability to maintain a proper seal with unknown service station fill nozzle integrity and variations beyond design tolerances.

[34] Stant ORVR System http://stant.com/orvr/orvr-systems/

The liquid seal approach uses the size and bends of the filler pipe to cause a condition where the entire cross-section of the filler pipe is located in the fuel tank or close to the entry into the fuel tank and is full of the incoming liquid fuel preventing fuel vapors from escaping up and out through the filler pipe. By creating a solid column of liquid fuel in the filler pipe, the liquid seal approach does not require a mechanical contact point with the fill nozzle to prevent escape of vapors. The liquid seal has been the predominant sealing method implemented in the regulated fleet in response to the ORVR requirements.

3.2.6.3 ORVR Flow Control Valve

As described above, the sealing of the filler pipe prevents the fuel vapors from escaping into the ambient air; however, the fuel vapors that are displaced by the incoming liquid fuel need to be routed to the canister. In order to properly manage the large volume of vapors during refueling that need to be controlled, most ORVR systems have implemented a flow control valve that senses that the fuel tank is getting filled with fuel and triggers a unique low-restriction flow path to the canister. This flow path is specifically used only during the refueling operation and is unique in that it provides the ability to quickly move larger volumes of fuel vapors into the tank than normally required under other operation outside of refueling events. The flow control valve will allow this larger flow volume path while refueling but then return to a more restrictive vapor flow path under all other conditions, including while driving and while parked for overnight diurnals.

The flow control valve is generally a fully-mechanical valve system that utilizes connections to the fuel tank and filler pipe to open and close vapor pathways with check valves and check balls and pressure switches via diaphragms. The valve may be integrated into the fuel tank and incorporate other aspects of the fuel handling system ("multi-function control valve" in Figure 3-26) including roll-over valve, fuel and vapor separators to prevent liquid fuel from reaching the canister, and other fuel tank vapor control hardware. Depending on the design, the filler pipe may also be integrated with the flow control valve to provide the necessary pressure signals. A dual fuel tank chassis configuration may require a separate flow control valve for each fuel tank.

3.2.6.4 Canister

The proven technology to capture and store fuel vapors has been activated charcoal. This technology has been used in vehicles for over 50 years to reduce evaporative emissions from sources such as fuel tanks and carburetors. When ORVR was originally discussed, existing activated charcoal technology was determined to be the appropriate technology for the capture and storage of refueling related fuel vapors. This continues to be the case today, as all known ORVR-equipped vehicles utilize some type of activated charcoal.

The activated charcoal is contained in a canister, which is made from a durable material that can withstand the fuel vapor pressures, vibration, and other durability concerns. For vehicles without ORVR systems, canisters are sized to handle evaporative emissions for the three-day diurnal test with the canister volume based on the fuel tank capacity. A dual fuel tank chassis configuration may require a separate canister for each fuel tank.

3.2.6.5 Purge Valve

The purge valve is the electro-mechanical device used to remove fuel vapors from the fuel tank and canister by routing the vapors to the running engine where they are burnt in the combustion chamber. This process displaces some amount of the liquid fuel required from the fuel tank to operate the engine and results in a small fuel savings. The purge valve is controlled by the engine or emission control electronics with the goal of removing the necessary amount of captured fuel vapors from the canister in order to prepare the canister for subsequent fuel vapor handling needs of either the next refueling event or vapors generated from a diurnal event. All on-road vehicles equipped with a canister for evaporative emissions control utilize a purge valve. Depending on the design, a dual fuel tank chassis configuration may require a separate purge valve for each fuel tank.

3.2.6.6 Design considerations for Unique Fuel Tanks

The commercial truck market gasoline applications may incorporate several fuel tank options that may require unique ORVR design considerations. While most commercial vehicle fuel tanks are similar to the already ORVR-compliant complete vehicles in the 8500 to 14,000 GVWR class, some of the commercial vehicles include larger tank sizes (up to 50 gallons) or may have a dual tank option. As described above, the canister sizing will be a function of the required amount of fuel vapor handling during refueling. Larger fuel tanks will require larger canisters with more activated charcoal than historically found in other gasoline vehicles. Some design challenges will likely exist in designing the canister system to handle the large vapor volumes while balancing the restriction to flow through the larger activated charcoal containing canisters.

Dual fuel tank systems, which have very limited availability, may also require some unique design considerations. Typically, the canister is located in very close proximity to the fuel tank to properly manage the refueling fuel vapors efficiently with minimal distance between the tank and canister. Dual fuel tanks may require duplicate ORVR systems to have the necessary flexibility to manage the refueling vapors, particularly since the fuel tanks are filled independently through separate filler pipe assemblies.

3.2.6.7 Onboard Refueling Vapor Recovery Anticipated Costs

MDVs certified as incomplete vehicles are not currently required to meet ORVR. There are four main equipment components and strategies incomplete medium-duty vehicles need to update to implement ORVR: increased working capacity of the carbon canister to handle additional vapors volumes during refueling, flow control valves to manage vapor flow pathway during refueling, filler pipe and seal to prevent vapors from escaping, and the purge system and management of the additional stored fuel vapors. The associated direct manufacturing costs for these updates are summarized below. No labor cost was identified so the direct manufacturing cost is equal to the piece cost plus tooling cost (per piece). ORVR requirements will be extended to medium-duty gasoline engines in incomplete vehicles starting in model year 2030. For our cost analysis, we assumed all medium-duty gasoline engines that are identified as incomplete light-heavy-duty trucks in MOVES will have an average fuel tank capacity of 35-gallons.

Capturing the increased vapor volume from the vapor displaced during a refueling event will require canisters to increase vapor or "working" capacity approximately 15 to 40 percent depending on the individual vehicle systems (i.e., fuel tank size). This can be achieved by increasing the canister volume using conventional carbon, the fundamental material used to store fuel vapors. A typical Tier 3 canister has approximately 2.6 liters of conventional carbon to capture overnight diurnal evaporative emissions for a 35-gallon fuel tank. An increase in required capacity to allow refueling vapors to be captured results in the need for an additional 1 liters of conventional carbon. A change in canister volume to accommodate additional carbon includes increased costs for retooling and additional canister plastic material, as well as design considerations to fit the larger canister on the vehicle. However, because these medium-duty vehicles almost always have a complete version already required to comply with refueling standards, the necessary larger canister sizes are already produced and available likely neglecting the need for any additional tooling investment.

An alternative to retooling for a larger single canister would be to add a second canister for the extra canister volume to avoid the re-tooling costs. Several smaller volume canisters are available on the market today. Another approach, based on discussions with canister and carbon manufacturers, can be achieved by using a higher adsorption carbon along with modifications to compartmentalization within the existing canister plastic shell that will increase the canister working capacity without requiring a larger canister size.

Additionally, there are two primary technologies used to prevent vapors from escaping into the atmosphere through the filler neck and around the fuel nozzle area when the vehicle is refueling that can affect the canister vapor capacity design requirements: a mechanical seal which makes direct physical contact with the refueling nozzle to create a nozzle to filler neck seal; or a liquid seal further down in the filler pipe which uses the liquid fuel mass flowing down the filler pipe and entering the tank to hydraulically prevent vapors from migrating back up the fill pipe. There is approximately a 20 percent reduction in carbon volume required if a mechanical seal is used at the filler neck versus a liquid seal approach. While mechanical seals are not currently the preferred technology, manufacturers facing the choices available for the larger volume fuel tanks and the need for a larger matching carbon containing canister to handle these large quantities of fuel vapors, may opt for more a mechanical seal design to avoid excess canister carbon requirements and possible retooling charges. We share our assumptions and cost estimates for both seal options in Table 3-18 and Table 3-19. A dual tank may require two seals if dual filler necks are used instead of a single filler neck and transfer pump to move fuel between the two tanks.

The second required equipment update would be to install flow control valves, which may be integrated into existing roll-over/vapor lines. The flow control valves are needed to manage the vapors during the refueling event by providing a low restriction pathway for vapors to enter the canister for adsorption and storage on the carbon materials. We anticipate vehicles would require on average one valve per vehicle which would be approximately $6.50 per valve. A dual tank system may require a flow control valve system per tank depending on the design approach.

Thirdly, as mentioned above, a filler pipe and seal system would be needed for each filler nozzle to keep the vapors contained during refueling. Manufacturers have the option of a mechanical seal that costs approximately $10.00 per seal, or a liquid seal which in itself costs nothing but may require hardware modifications to provide enough back pressure to stop the refueling nozzle fuel flow when tank reaches full capacity if the incomplete version doesn’t already share the same filler tube design with the refueling requirements compliant complete version.

Lastly, the engine control of the canister purge rates may need to be addressed. This update would include calibration improvements and potentially additional hardware to ensure adequate purge volumes are achieved as required to maintain an appropriate canister state to manage vapors generated during diurnal and subsequent refueling events. However, if the incomplete version shares engines and fuel systems with the complete vehicle versions, the development of calibrations for the required purge volumes has likely already been completed eliminating any need for further changes or development work. If required for a dual tank system, an extra purge valve may be needed if the two-tank system maintains independent canisters instead of a single common cannister as observed in dual-tank, single canister light-duty applications.

Table 3-18 shows our calculations estimating the amount of extra canister size for conventional carbon for a 35-gallon tank, using Tier 3 core evaporative requirements (i.e. 2-day and 3-day shed) as a baseline. Currently under Tier 3 requirements the canister and purge strategy are sized for the diurnal test and designed to meet the Bleed Emissions Test Procedure (BETP) requirements. During the diurnal test, the canister is loaded with hydrocarbons over two or three days, allowing the hydrocarbons to load a conventional carbon canister (1500 GWC, gasoline working capacity) at a 70 g/L effectiveness. During a refueling event, which takes place over a few minutes, the vapor from the gas tank is quickly loaded onto the carbon in the canister with an ORVR system, causing the efficiency of the canister loading to drop to 50 g/L effectiveness mainly because of the high volume of fuel vapors required to be adsorbed in the short period of a refueling event. Typically, a design safety margin adds an extra 10 percent carbon to ensure adequate performance over the life of the system. Therefore, even though there is typically less fuel vapor mass generated and managed during a refueling event than is generated over a three-day diurnal time period, the amount of carbon that is necessary to contain the vapor is higher for a refueling event.

Table 3-21: ORVR Specifications and Assumptions used in the Cost Analysis for Incomplete MDVs (8501 lbs to 14,000 lb GVWR).

	Tier 3 Baseline	ORVR Filler Neck Options	
		Mechanical Seal	Liquid Seal
	Diurnal	ORVR	
Diurnal Heat Build	72-96°F	80°F	
RVP	9 psi		
Nominal Tank Volume	35 gallons		
Fill Volume	40%	10% to 100%	
Air Ingestion Rate		0%	13.50%
Mass Vented per heat build, g/d	60		
Mass Vented per refueling event		128	158
Hot Soak Vapor Load	2.5		
Mass vented over 48-hour test	114		
Mass vented over 72-hour test	162		
1500 GWC, g/L [a]	70	50	50
Excess Capacity	10%	10%	10%
Estimated Canister Volume Requirement, liters[b]			
48-hour Evaporative only	1.8		
72-hour Evaporative only	2.5		
Total of 72-hour + ORVR[c]		2.8	3.5

a Efficiency of conventional carbon
b Canister Volume = 1.1(mass vented)/ 1500 GWC (Efficiency)
c ORVR adds .3 liters and 1 liter for Mechanical Seal and Liquid Seal respectively

Table 3-22: Estimated Direct Manufacturing Costs for ORVR Over Tier 3 as Baseline

	Liquid Seal	**Mechanical Seal**
	New Canister	**New Canister**
Additional Canister Costs	$10	$4
Additional Tooling (a)	$0.50	$0.50
Flow Control Valves	$6.50	$6.50
Seal	$0	$10
Total (b)	$17	$21

a Assumes the retooling costs will be spread over a five-year period
b Possible additional hardware for spitback requirements

3.3 On-board Diagnostics

EPA regulations state that onboard diagnostics (OBD) systems must generally detect malfunctions in the emission control system, store trouble codes corresponding to detected malfunctions, and alert operators appropriately. EPA adopted (as a requirement for an EPA certificate) the 2013 California Air Resources Board (CARB) OBD regulation, with certain additional provisions, clarifications and exceptions, in the Tier 3 Motor Vehicle Emission and Fuel Standards final rulemaking (40 CFR 86.1806-17; 79 FR 23414, April 28, 2014). Since that time, CARB has made several updates to their OBD regulations and continues to consider changes periodically. In this NPRM, EPA is proposing to update to the latest version of the CARB OBD regulation (California's 2022 OBD-II requirements are part of (Title 13 § 1968.2

California Code of Regulations 2022)). This is accomplished by adding a new section for vehicles built after 2027 model year and only putting in requirements in that section that are not in the new CARB regulation. EPA is also adding a new monitoring requirement for gasoline particulate filters (GPFs) since the CARB regulation does not yet have a requirement for a particulate filter diagnostic for gasoline vehicles and EPA is projecting that manufacturers will utilize GPFs as a control strategy in meeting our proposed PM standards in the time frame of this rulemaking.

As mentioned above, CARB has made changes to their regulation since we adopted the 2013 version. Most notably CARB added evaporative reporting and diagnostic language that both adds functions that we had in our Tier 3 regulation and clarifies which diagnostics are required and what to report. This makes the evaporative reporting language in our regulation obsolete and make it necessary to remove the language to prevent conflicts.

EPA has worked closely with CARB on the development of EPA's diagnostic requirements for GPFs. CARB has reviewed and helped determine the EPA requirements. EPA started with CARB's requirements for its diesel particulate filter diagnostic. EPA then removed the failure modes that both EPA and CARB felt weren't germane to the GPF system. This left three diagnostic requirements along with requirements for tracking and reporting. The required ratio for tracking and reporting is 0.150 as calculated using procedures in (Title 13 § 1968.2 California Code of Regulations 2022). The first is a monitor that is required if removing the GPF would cause PM to go above 10 mg/mi over the FTP. The second is a requirement to detect if frequent regeneration cycles cause HC, CO, or NO_X to exceed 1.5 times the standard for HC, CO, or NO_X. Or, if no number of cycles would cause the 1.5 times exceedance, then the diagnostic must trigger when the number of regeneration cycles exceed the manufacturers specified limit for regeneration cycles. The third requirement is for detecting when the GPF is missing from the system, significantly damaged, or destroyed (further details are available in the regulations). This third requirement along with checking regeneration cycles (too frequent and cycles not restoring the filter) is the default diagnostic set if the vehicle never exceeds 10 mg/mi with the GPF removed.

3.4 PHEV Accounting

3.4.1 <u>Proposed Approach for the Revised PHEV Utility Factor</u>

EPA is proposing to revise the light-duty vehicle PHEV Fleet Utility Factor curve used in CO_2 compliance calculation for PHEVs, beginning in MY 2027. The agency believes the current LD vehicle PHEV compliance methodology significantly underestimates PHEV CO_2 emissions. The mechanism that is used to apportion the benefit of a PHEV's electric operation for purposes of determining the PHEVs contribution towards the fleet average GHG requirements is the fleet utility factor (FUF), further explained below. We have analyzed available data and compiled literature (Krajinska, Poliscanova, Mathieu, & Ambel, Transport & Environment 2020), (Plötz, P., Moll, C., Bieker, G., Mock, P., Li, Y. 2020), (Plötz, P., Link, S., Ringelschwendner, H., Keller, M., Moll, C., Bieker, G., Dornoff, J., Mock, P. 2022), (Patrick Plötz et al 2021) showing that the current utility factors are overestimating the operation of PHEVs on electricity, and therefore would underestimate the CO_2 g/mi compliance result. The current and proposed FUF's are shown in Figure 3-27, shown below.

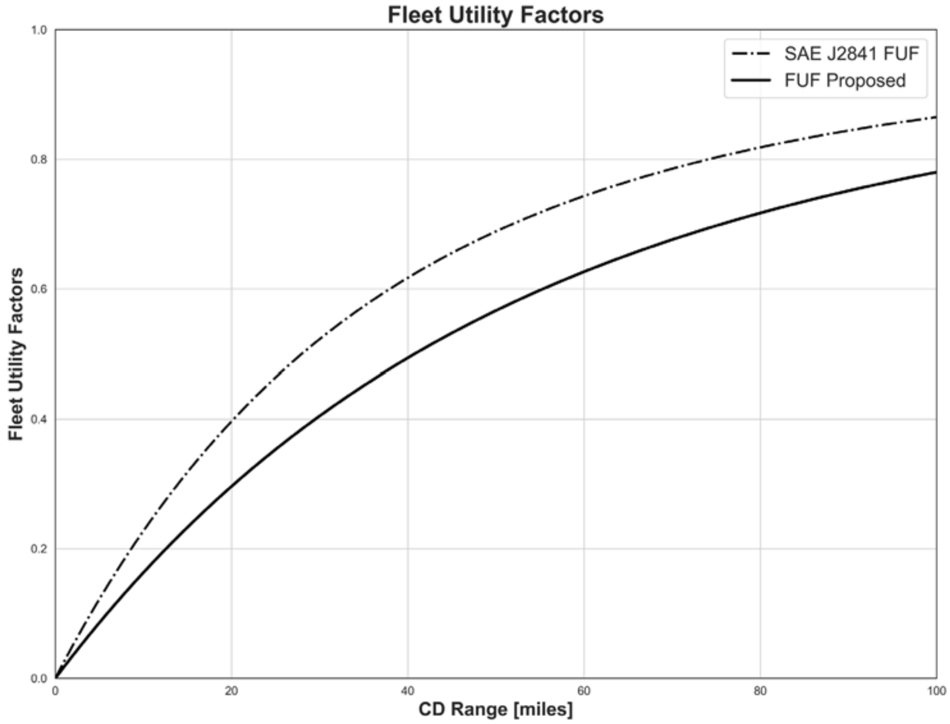

Figure 3-27: Current and Proposed Fleet Utility Factor for PHEV Compliance

The current FUFs were developed in SAE 2841 (SAE J2841 2010) and are used to estimate the percentage of operation that is expected to be in charge depleting mode (vehicle operation that occurs while the battery charge is being depleted, sometimes referred to as electric range.). The measurement of the charge depleting (CD) range is performed over the EPA city and highway test cycles, also called the 2-cycle tests. The tested cycle specific charge depleting range is used as an input to the FUF curves (or lookup tables, as shown in Tables 1 and 2 in 40 CFR §600.116-12) to determine the specific city and highway FUFs. The resulting FUFs are used to calculate a composite CO_2 value for the city and highway CO_2 results, by weighting the charge depleting CO_2 by the FUF and weighting the charge sustaining (CS) CO_2 by one minus the FUF.

The FUFs developed in SAE J2841 rely on a few important assumptions and underlying data: (1) trip data from the 2001 National Household Travel Survey,[35] used to establish daily driving distance assumptions, and (2) the assumption that the vehicle is fully charged before each day's operation. These assumptions are important because they affect the shape of the utility factor curves, and therefore affect the weighting of CD (primarily electric operation)[36] CO_2 and CS

[35] We used the latest NHTS data (2017) and executed the utility factor code that is in SAE J2841, Appendix C, and found that the latest NHTS data did not significantly change the utility factor curves. NHTS data can be found at U.S. Department of Transportation, Federal Highway Administration, 2017 National Household Travel Survey. URL: https://nhts.ornl.gov/

[36] The complexity of PHEV designs is such that not all PHEVs operate solely on the electric portion of the propulsion system even when the battery has energy available. Engine operation during these scenarios may be required because of such design aspects as blended operation when both the electric power and the engine are being utilized, or during conditions such as when heat or air conditioning is needed for the cabin and can only be obtained with engine operation

(primarily internal combustion engine operation)[37] CO_2 in the compliance value calculation. SAE J2841 was developed more than ten years ago during the early introduction of light-duty PHEVs and at the time was a reasonable approach for weighting the CD and CS vehicle performance for a vehicle manufacturer's compliance calculation given the available information. The PHEV market has since grown, and there is significantly more real-world data available to EPA on which to design an appropriate compliance program for PHEVs. The agency believes that the use of an FUF is still an appropriate and reasonable means of calculating the contribution of PHEVs to GHG emissions and compliance, but the real-world data available today no longer supports the FUF established in SAE J2841 more than a decade ago.

Because the tailpipe CO_2 produced from PHEVs varies significantly between CD and CS operation, both the charge depleting range and the utility factor curves play an important role in determining the magnitude of CO_2 that is calculated for compliance. In charge depleting mode EPA is proposing to maintain a zero gram per mile contribution when the internal combustion engine is not running. The significant difference noted above is the difference between, potentially, zero grams per mile in CD mode versus CO_2 grams per mile that are likely to be similar to a hybrid (non-plug-in) vehicle. The charge depleting range for a PHEV is determined by performing single cycle city and highway charge depleting tests according to SAE Standard J1711 (SAE J1711 2023), Recommended Practice for Measuring the Exhaust Emissions and Fuel Economy of Hybrid-Electric Vehicles, Including Plug-In Hybrid Vehicles. The charge depleting range is determined by arithmetically averaging the city and highway range values weighted 55 percent and 45 percent, respectively, as noted in §600.311-12(j)(4)(i) (Title 40 CFR § 600.311–12 2021).

3.4.1.1 FUF Comparisons with Real World Data

Recent literature and data have identified that the current utility factor curves may overestimate the fraction of driving that occurs in charge depleting operation (Plötz, P. and Jöhrens, J. 2021), (Transport & Environment 2022). This literature also concludes that vehicles with lower charge depleting ranges have even greater discrepancy in CO_2 emissions.

EPA and ICCT (Aaron Isenstadt, Zifei Yang, Stephanie Searle, John German 2022) have also evaluated recently available California Bureau of Automotive Repair (BAR) OBD data, (California Air Resource Board [OBD data records] 2022) that has been collected through the California Bureau of Automotive Repair and found that the data shows that, on average, there is more charge sustaining operation and more gasoline operation than is predicted by the current fleet utility factor curves. The BAR OBD data enable the evaluation of real-world PHEV distances travelled in various operational modes; these include charge-depleting engine-off distance, charge-sustaining engine-on distance, total distance traveled, odometer readings, total fuel consumed, and total grid energy inputs and outputs of the battery pack. These fields of data allow us to use the BAR OBD data to filter the data and calculate 5-cycle comparable real-world

[37] Because most CD operation occurs without engine operation, the CO_2 value for CD operation is often 0 or near 0 g/mi. This means that a high utility factor results in a CO_2 compliance value that is heavily weighted with 0 or near 0 g/mi.

driving ratios of charge depleting distance to total distance and to then compare to the existing FUFs, using the 5-cycle range from the fuel economy and environment label.[38]

There are some limitations to the PHEV data collected through the BAR OBD data. Data collection occurs through the California Bureau of Automotive Repair and is limited to vehicles with ownership changes, vehicles entering the state, or vehicles that are at least 8-years old (California Bureau of Automotive Repair [OBD data records] 2022). In addition, the PHEV BAR OBD data requirements are recent; they began in model year 2019 and were not fully phased in until model year 2021 (California Bureau of Automotive Repair [OBD data records] 2022). The dataset also contains some reporting errors and some very low mileage data.

To address some of the data collection issues, the BAR OBD data were filtered to exclude low mileage vehicles, vehicles with extreme or conflicting data, and vehicles that were missing critical data such as total distance travelled. Similar to the ICCT data filtering, EPA filtered the CARB OBD data by removing vehicles that met the following criteria: vehicles with less than 3000 km total distance travelled; vehicles and that have odometer readings that are greater than 20 percent different from the total distance travelled data; and vehicles where the total grid energy inputs and outputs of the battery pack differed by more than 20 percent.

[38] Because the data collected is real-world data, we used the combined city and highway 5-cycle label range as an input to the FUF curve described in SAE J2841, to create an apples-to-apples comparison. The existing regulatory FUFs are separate city and highway curves, and the charge depleting ranges that are used with the city and highway FUF curves are 2-cycle range.

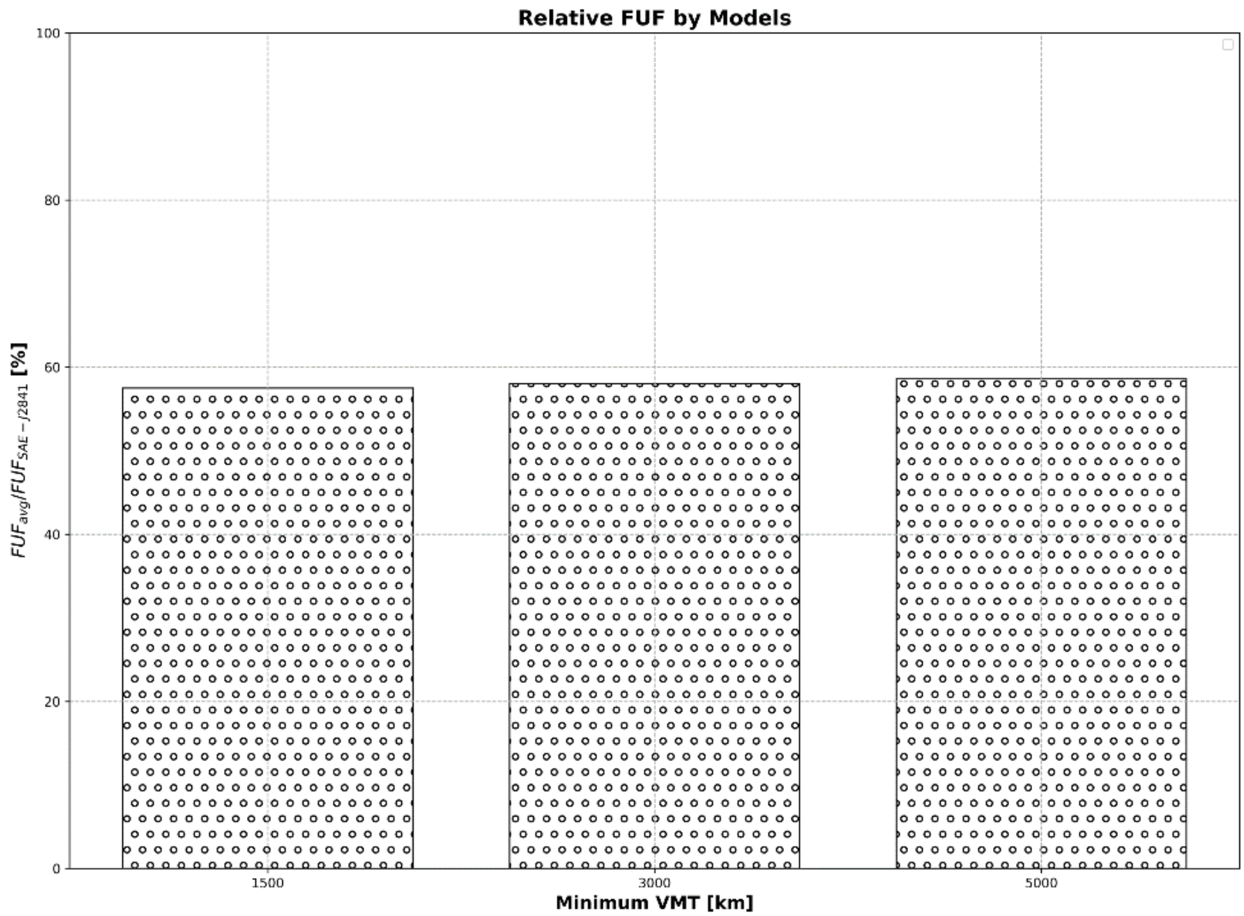

Figure 3-28: FUFs with various data filtering sensitivities

To investigate data sampling sensitivities, we used the minimum VMT values shown in Figure 3-28 (above) for filtering data using the October 2022 BAR OBD data (California Air Resource Board [OBD data records] 2022). As shown in Figure 3-28, the relative FUFs over the SAE J2841 FUFs are not significantly different at various minimum VMT filtering.

As of October 2022, the BAR OBD dataset has around 8,400 PHEV vehicles, and over 233.2 million vehicle miles traveled. The filtered dataset has 30 PHEV models, and 2060 individual vehicles that travelled 58.9 million miles.

A comparison of the results of EPA's data analysis of the BAR OBD data to the ICCT analyses is shown below in Figure 3-29. The combined city and highway FUF in SAE J2841 (corresponding to the 55 percent city/45 percent highway weighing of the city and highway FUFs) in the current regulations is labeled as "SAE J2841 FUF". EPA's data analysis of the CARB OBD data is labeled as "Linear Regression Fit" and the two ICCT curves are labeled as "ICCT-BAR" and "ICCT-FUELLY". The EPA "Linear Regression Fit" (where about 78 percent of the total data points are between 12- to 32-miles for the CD range when fitting samples >= 5) lies on top of the "ICCT-BAR" curve, showing good agreement between the two separate analyses of the BAR OBD data. In addition to the BAR OBD data, ICCT also evaluated a dataset from Fuelly.com.[39]; The curve that is fitted from the Fuelly.com data also yields lower utility factors than the SAE J2841 FUF curve, for the same charge depleting distance; however, the Fuelly curve is not as low as the BAR OBD curve.

The BAR OBD data is a recent and relatively large dataset that includes the charge depleting distance (or electric operating distance) and total distance, which makes it a reasonable source for evaluating the real-world utility factors for recent PHEV usage. However, we recognize that the curve developed from this data is a departure from the SAE J2841 FUF curves, that the BAR OBD data has some limitations (described above), and that the original SAE J2841 FUF methodology was also a reasonable approach at the time it was adopted. Therefore, we created the proposed curve by averaging the SAE J2841 FUF curve and the ICCT-BAR curve. The resulting proposed FUF curve lies almost on top of the ICCT-FUELLY curve. Some of the data suggest that a lower curve might more appropriately reflect current real-world usage, however, EPA recognizes that PHEV technology has the potential to provide significant GHG reductions and an overly low FUF curve could disincentive manufacturers to apply this technology. In addition, anticipated longer all-electric range and greater all-electric performance, partially driven by CARB's ACC II program, as well as increased consumer technology familiarity and available infrastructure should result in performance more closely matching our proposed curve. EPA will continue to monitor real-world data as it becomes available.

The proposed curve (see Figure 3-29, "FUF Proposed") is based on the Equation (3-1), (Title 40 CFR 600.116-12 2022) using the SAE J2841 FUF weighting coefficients, and a new normalized distance (ND) of five hundred eighty-three (583) miles. Other UF curves shown include: the current SAE J2841 FUF, which uses the combined city/highway FUF coefficients, and a ND of 399.9 miles; the label MDIUF[40] (SAE J2841 MDIUF), which uses the MDIUF weighting coefficients and a ND of 400 miles; the ICCT-developed curve for the Fuelly data (ICCT-FUELLY), which uses the MDIUF coefficients, and a ND of seven hundred (700) miles and the ICCT-developed curve for the BAR OBD data (ICCT-BAR), which uses the MDIUF coefficients, and a ND of nine hundred eighty-five (985) (Aaron Isenstadt, Zifei Yang, Stephanie Searle, John German 2022) miles.

The FUF and the MDIUF weighting coefficients (C_j) of the UF Proposed, ICCT-BAR, and ICCT-FUELLLY curves are listed in Table 2 of the SAE J2841 standard (SAE J2841 2010).

$$UF = 1 - \left[\exp\left(-\sum_{j=1}^{k}\left(\frac{CD}{ND}\right)^{j} C_j\right)\right]$$

where:
CD = charge depleting range in miles
ND = normalized distance
C_j = the weighting coefficient for term j
k = number of coefficients (10 for the MDIUF Fit and 6 for the FUF Fit)

[39] Fuelly [aggregated user-reported fuel economy data]. 2022. Retrieved from https://www.fuelly.com/car

[40] The SAE J2841, the FUF is recommended for fleet vehicle fuel consumption calculations, and the MDIUF is recommended to estimate of an individual vehicle's fuel economy. EPA has incorporated the FUF for compliance calculations, and the MDIUF for fuel economy labelling calculations. Among other differences, the MDIUF is a vehicle-weighted calculation, and the FUFs are VMT distance-weighted calculations..

Five hundred eighty-three (583) Normalized Distance (ND) was calculated by the minimization of the sum of the squared residual norm in Equation (3-2) when iterating the normalized distance constant *j*.

$$\sum_{i=0}^{n=400}\left[0.5\left(UF_{SAE\ J2841\ FUF}+UF_{ICCT-BAR}\right)-\ UF_{Proposed,\ ND_j}\right]_i^2$$

where:

ND_j = normalized distance for term *j* from 400 to 985

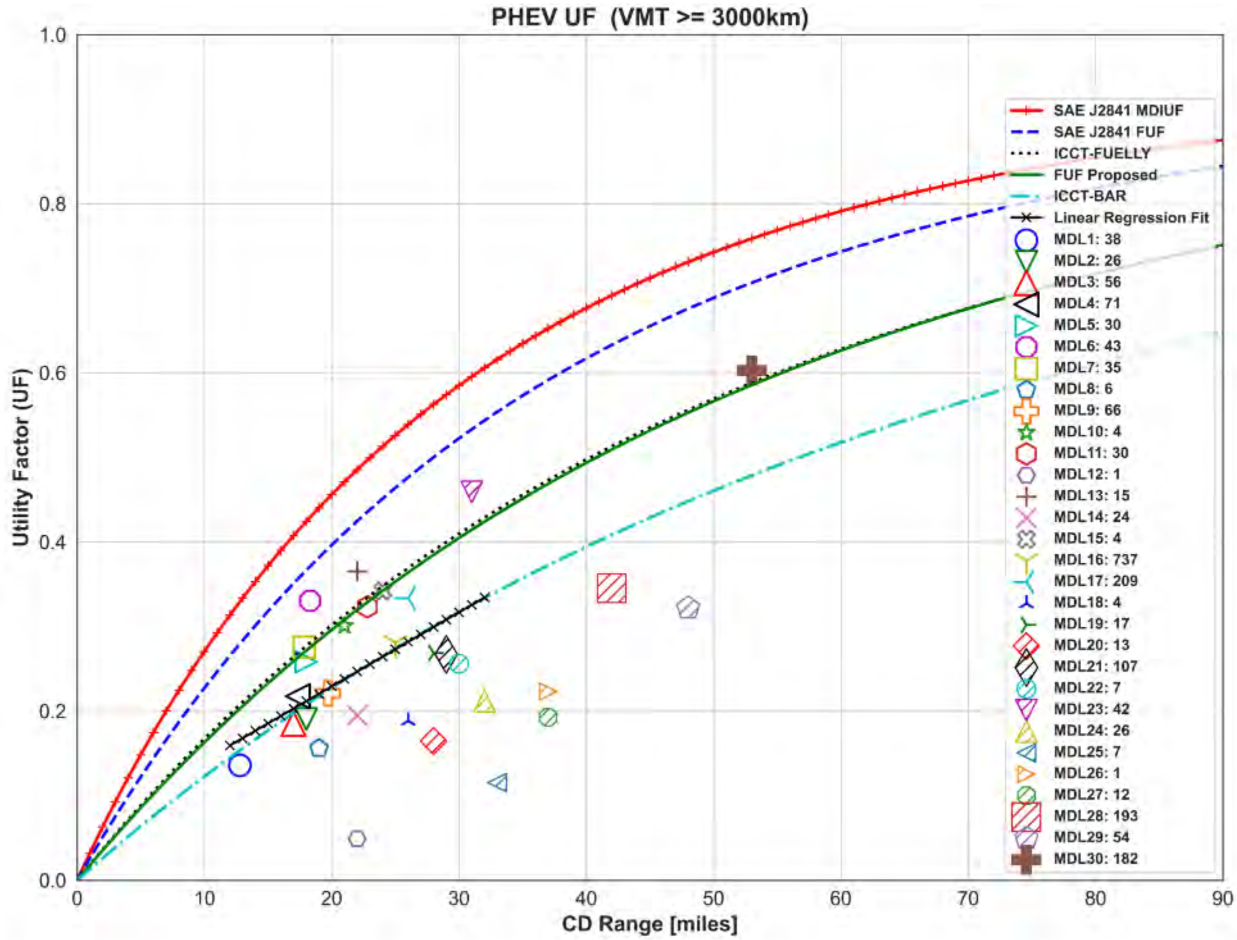

Figure 3-29: The Proposed FUF, SAE MDIUF/FUF, and ICCT-BAR/FUELLY Curves

As stated above, the proposed FUF curve in Figure 3-29 is constructed using the averages of the SAE J2841 FUF curve and the ICCT-BAR curve from the real-world charging data with the latest BAR OBD open-source data records. This method creates a proposed FUF curve that is adjusted to better reflect the real-world PHEV data (California Bureau of Automotive Repair [OBD data records] 2022).

Table 3-20 shows PHEV vehicles that had sample sizes greater than or equal to 10 in the CARB OBD dataset (California Air Resource Board [OBD data records] 2022) and also includes several additional high-volume PHEVs. The compliance CO_2 results range from a 19.5% to

47.8% (median = 31%) increase in CO_2 g/mi, for the example vehicles below, when using the proposed FUF compared to the existing FUF.

Table 3-23: CO_2 Emissions [g/mi] Calculated using Existing FUF and Proposed FUF

Mode l Year	Manufacturer	PHEV Model	Existing: Compliance CO_2 using Existing FUF	Proposed: Estimated Compliance CO_2 using Proposed FUF
2022	AUDI	Q5 E	116.3	165.7
2022	BMW	330E	100.2	132.5
2021	BMW	530E	114.4	147.1
2020	BMW	I8	126.7	156.8
2021	BMW	X3 xDrive	136.6	168.5
2022	BMW	X5	108.5	154.3
2019	CHEVROLET	VOLT	29.9	44.2
2021	CHRYSLER	PACIFICA	73.0	97.1
2022	FORD	ESCAPE	47.9	63.8
2021	HONDA	CLARITY	33.4	47.9
2022	HYUNDAI	IONIQ	47.3	62.0
2019	HYUNDAI	SONATA PHEV	63.7	86.0
2021	JEEP	WRANGLER 4XE	161.0	202.7
2022	KIA	NIRO	59.4	75.9
2020	KIA	OPTIMA PHEV	59.8	80.1
2022	KIA	SORENTO SX	68.7	90.5
2020	MERCEDES-BENZ	GLC 350E	122.5	160.4
2022	MINI	COOPER	116.7	142.3
2022	SUBARU	CROSSTREK	99.0	118.3
2022	TOYOTA	PRIUS PRIME	57.5	70.6
2022	TOYOTA	RAV4 PRIME	55.1	71.7
2022	VOLVO	S60	111.0	148.3
2022	VOLVO	XC60	155.2	196.8
2022	VOLVO	XC90	149.0	186.4

We believe that it is important for PHEV compliance utility factors to accurately reflect the apportionment of charge depleting operation, for weighting the 2-cycle CO_2 test results; therefore, we are proposing to update the city and highway fleet utility factor curves with a new, single curve that is shown in Figure 3-27 above. We are proposing a single curve to better reflect real world performance where the underlying real-world data is not parsed into city and highway data. Since the fleet average calculations are based on a combined city and highway CO_2 value, a single FUF curve can be used for these calculations.

3.5 GHG Emissions Control Technologies

3.5.1 Engine Technologies

The following is detailed information about the ALPHA inputs for internal combustion engines used to create ALPHA Outputs for Response Surface Equations (RSE's) used by OMEGA. These were first discussed and listed in Table 2-2. Specific details about each engine are contained in the engine's data package available on EPA's webpage (U.S. EPA 2023b). Each engine data package is contained in a .zip file identified using the engine name mentioned in the caption of the associated ALPHA efficiency map shown below.

3.5.1.1 2013 Chevrolet 2.5L Ecotec LCV Engine Reg E10 Fuel

This naturally aspirated engine features continuously variable valve timing, high-pressure direct injection, electronic throttle control, coil-on-plugs and has an 11.3:1 compression ratio. Testing was conducted in a test cell operated by FEV Engine Technologies and purchased to support the Mid Term Evaluation (MTE) Engine Benchmarking project. (Newman, K., Kargul, J., and Barba, D. 2015).

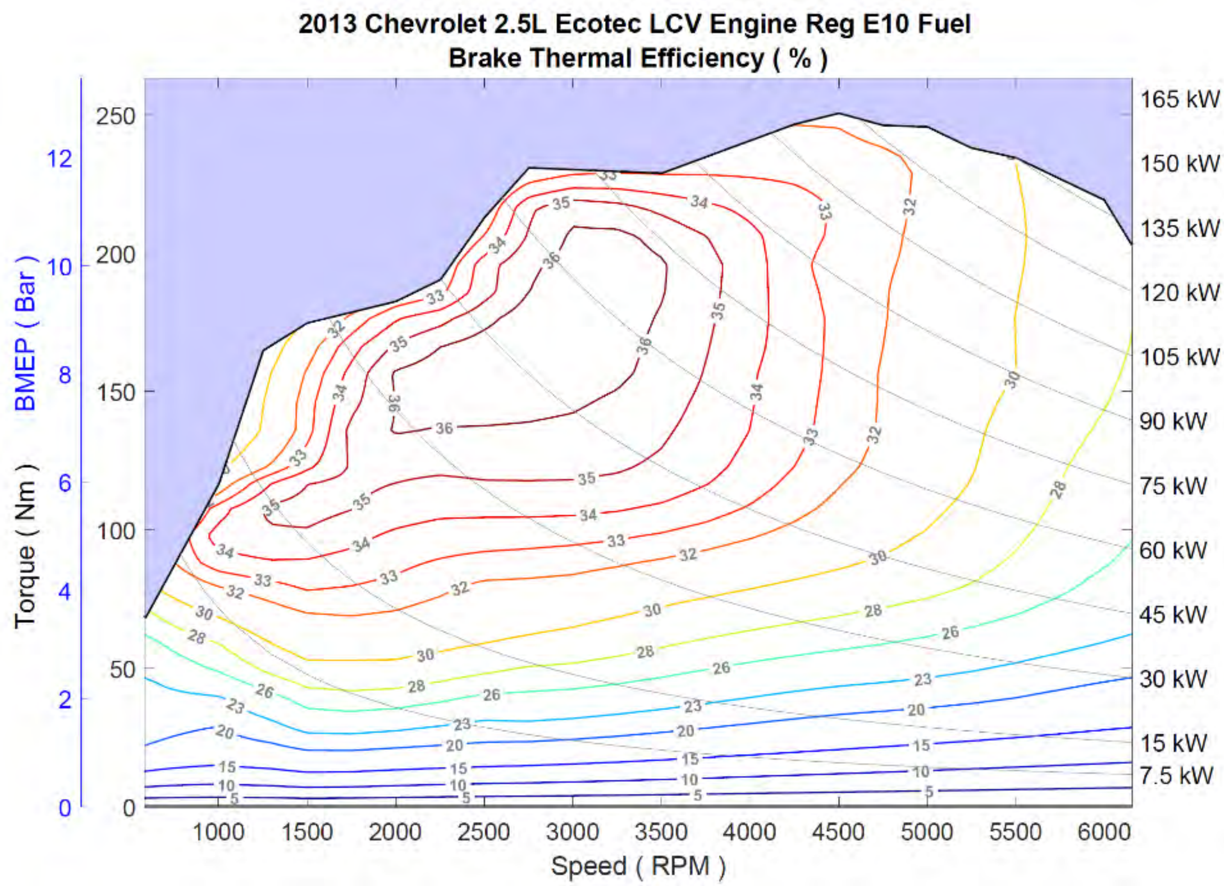

Figure 3-30 2013 Chevrolet 2.5L Ecotec LCV Engine Reg E10 Fuel (U.S. EPA 2023b)

3.5.1.2 GT Power Baseline 2020 Ford 7.3L Engine from Argonne Report Tier 3 Fuel[41]

This medium-duty naturally aspirated engine included port fuel injection, a 2-valve head, and a 10.5 compression ratio. The engine was modeled in GT-Power® and then calibrated and validated against test data available at Southwest Research Institute or provided by the Original Equipment Manufacturers (OEMs). (Thomas E. Reinhart 2021) The provided baseline model was only configured to simulate wide-open throttle operation with power enrichment and used a Wiebe function for describing combustion. Once the model achieved satisfactory results, the

[41] Not included in the draft but are likely to be added to the analysis.

engine performance was mapped over the speed and load range. The image and any supporting data available were digitized by loading the image into MATLAB and manually tracing the efficiency contours.

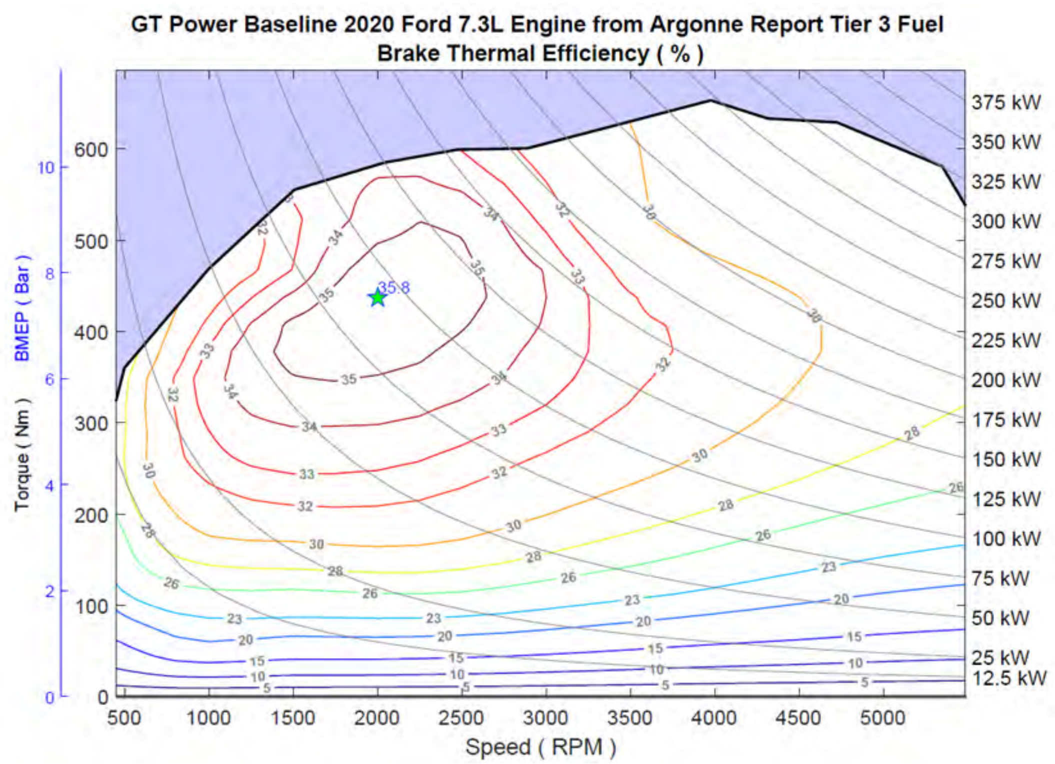

Figure 3-31 GT Power Baseline 2020 Ford 7.3L Engine from Argonne Report Tier 3 Fuel (U.S. EPA 2023b)

3.5.1.3 2014 Chevrolet 4.3L EcoTec3 LV3 Engine LEVIII Fuel

Features of this engine include side mount direct-injection, cylinder deactivation, continuously variable valve timing, pushrod, single cam, and active fuel management. The engine uses cylinder deactivation to improve thermal efficiency by reducing pumping losses during low-load operation. This testing was performed by the EPA at the National Center for Advanced Technology (NCAT) with the engine installed in a dynamometer test cell tethered as though the engine were operating in the vehicle. (Mark Stuhldreher 2016) Two methods of coupling the engine to the dynamometer were needed to gather data where the torque measurement was very sensitive to the engine's torsional accelerations. Direct drive shaft engine to dynamometer coupling worked best to gather most of the data but where needed, the engine was coupled to the dynamometer through its transmission and torque converter.

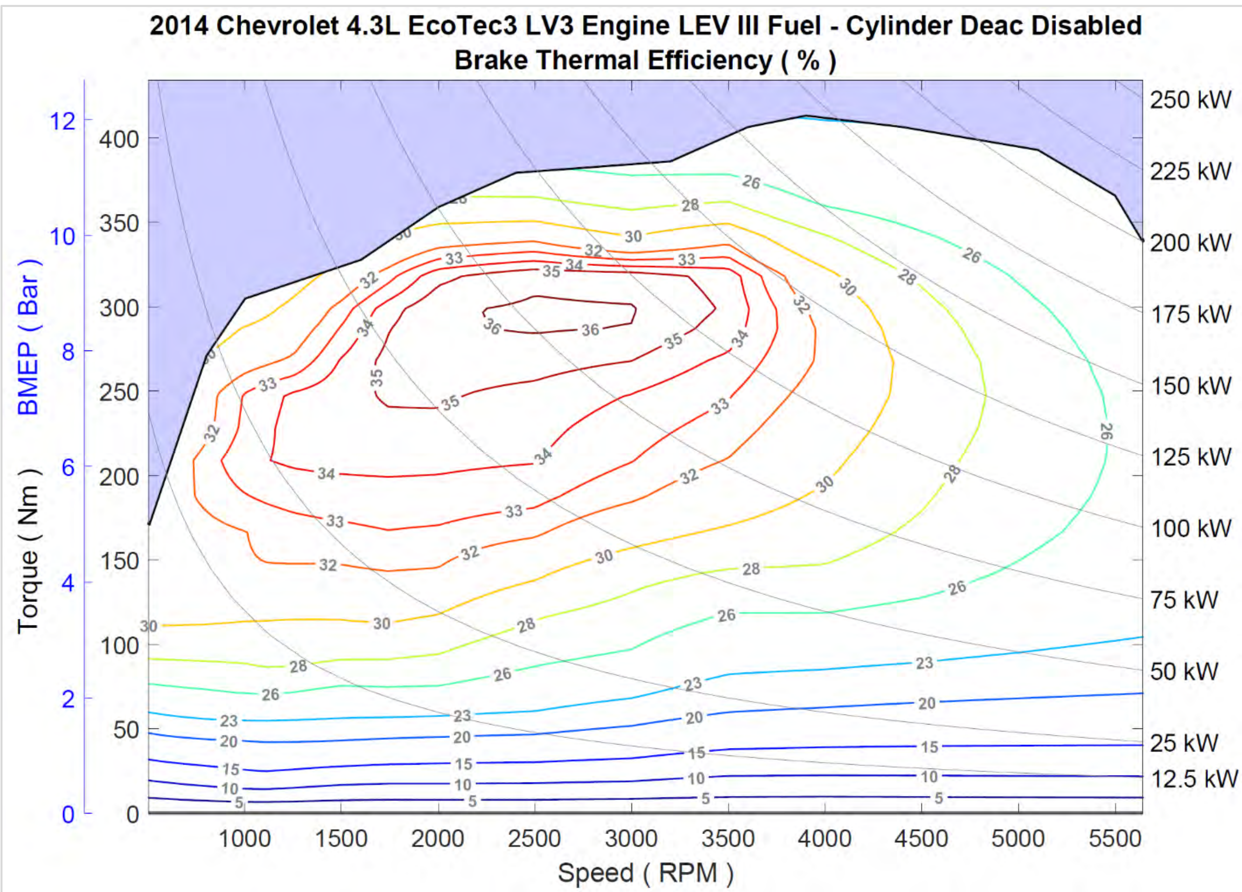

Figure 3-32 2014 Chevrolet 4.3L EcoTec3 LV3 Engine LEV III Fuel – Cyl Deac Disabled (U.S. EPA 2023b)

3.5.1.4 2013 Ford 1.6L EcoBoost Engine LEV III Fuel[42]

The selected feature of this turbocharged gasoline engine was the inclusion of spray-guided direct-injection. The testing was performed by the EPA at the National Center for Advanced Technology (NCAT) with the engine installed in a dynamometer test cell tethered as though the engine were operating in the vehicle. (Mark Stuhldreher, Charles Schenk, Jessica Brakora, David Hawkins, Andrew Moskalik, and Paul DeKraker 2015)

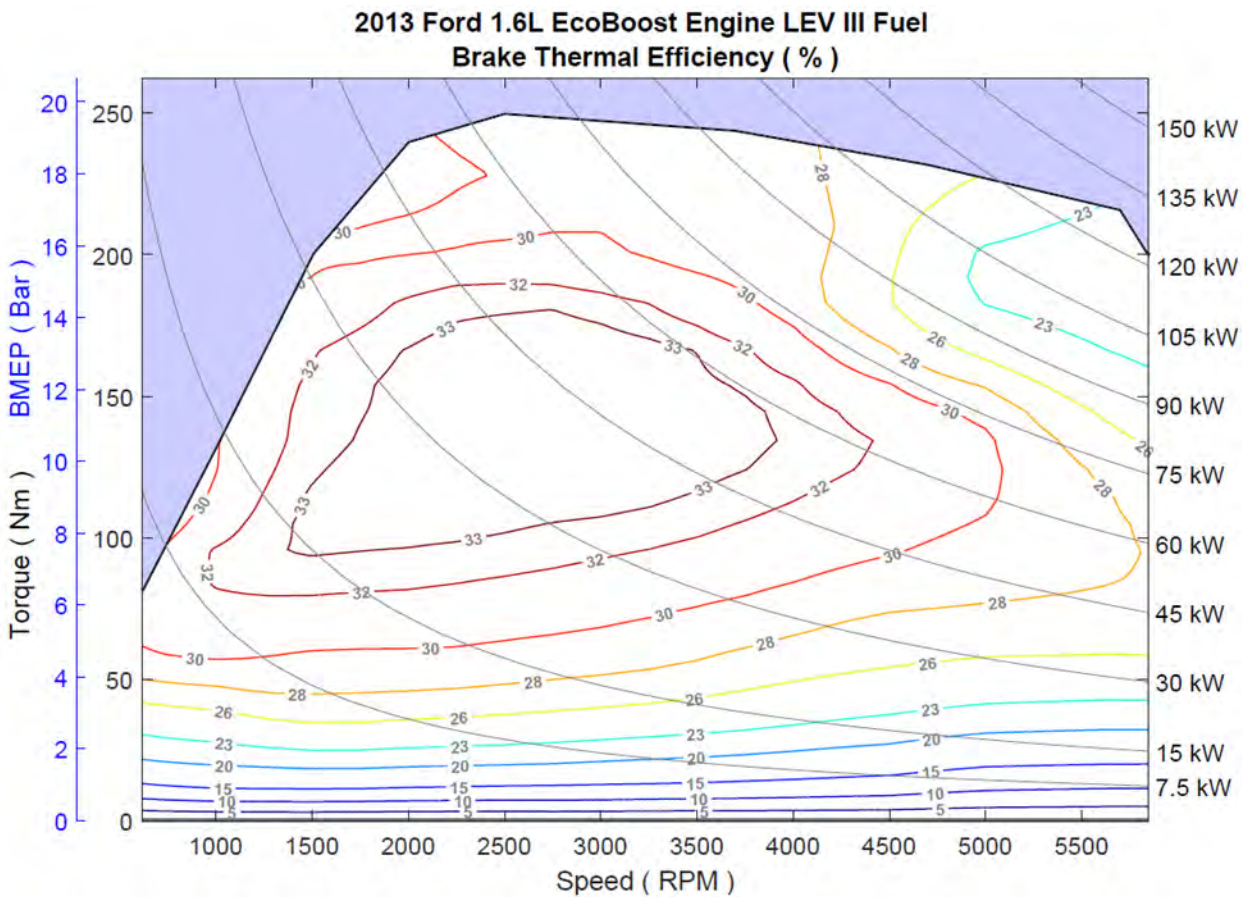

Figure 3-33 2013 Ford 1.6L EcoBoost Engine LEV III Fuel (U.S. EPA 2023b)

[42] Not included in the draft but are likely to be added to the analysis.

3.5.1.5 2015 Ford 2.7L EcoBoost Engine Tier 3 Fuel

This turbocharged engine features intake and exhaust cam phasing, direct injection, and integrated exhaust manifolds. The testing was performed by the EPA at the National Center for Advanced Technology (NCAT) with the engine installed in a dynamometer test cell tethered as though the engine were operating in the vehicle. This testing provided thorough test data for constructing the main operating portion of the engine map. There was also subsequent testing in a heavy-duty test cell to generate additional data for the high speed and high load mapping needed to construct a more complete engine map.

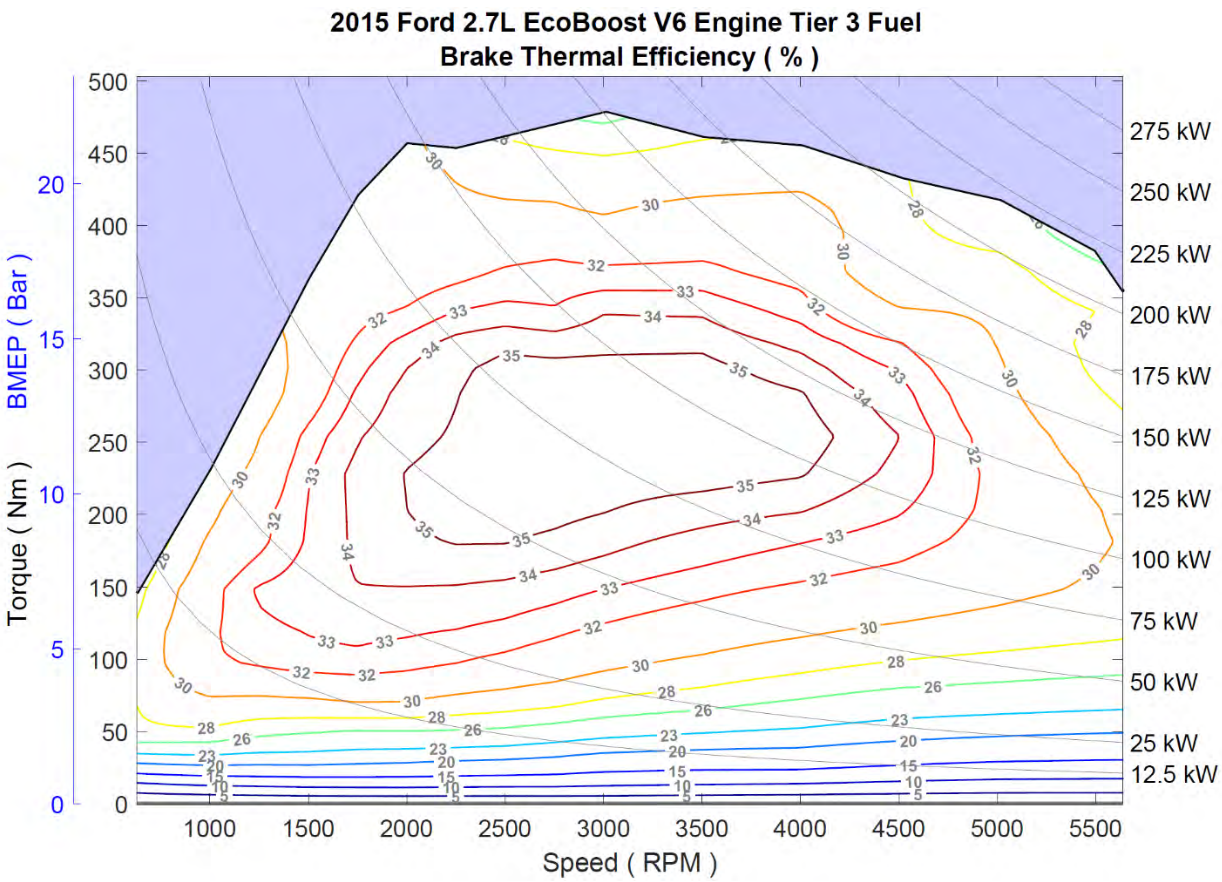

Figure 3-34 2015 Ford 2.7L EcoBoost V6 Engine Tier 3 Fuel (U.S. EPA 2023b)

3.5.1.6 2016 Honda 1.5L L15B7 Engine Tier 3 Fuel

Features of this engine include direct-injection, single-scroll turbocharger, and dual variable valve timing control (VTC). The testing was performed by the EPA at the National Center for Advanced Technology (NCAT) with the engine installed in a dynamometer test cell tethered as though the engine were operating in the vehicle. (Stuhldreher, Mark; Kargul, John; Barba, Daniel ; McDonald, Joseph; Bohac, Stanislav; Dekraker, Paul; Moskalik, Andrew; 2018) The engine was coupled to the dynamometer using a modified manual transmission and clutch with a torsional spring assembly and rubber isolated driveshaft to allow for stable torque measurements. Both steady-state and transient engine test data were collected during the benchmark testing. Two different test procedures were needed to appropriately replicate steady-state engine operation at low/mid loads and transient engine operation at high loads when the engine is protecting itself.

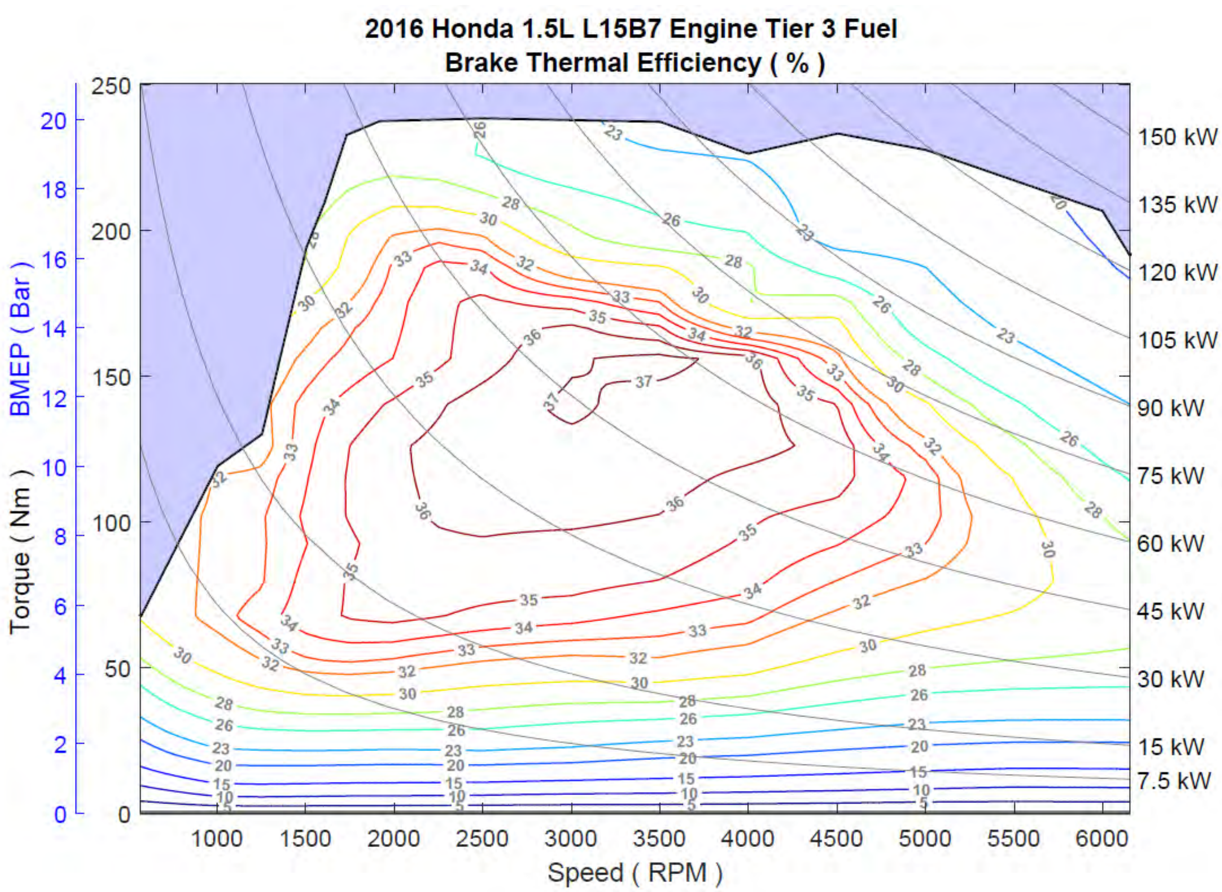

Figure 3-35 2016 Honda 1.5L L15B7 Engine Tier 3 Fuel (U.S. EPA 2023b)

3.5.1.7 Volvo VEP 2.0L LP Gen3 Miller Engine from 2020 Aachen Paper Octane Modified for Tier3 Fuel

This Miller cycle engine includes an increased compression ratio, a short intake valve opening duration, an integrated exhaust manifold, a new intake port and piston design together with a VGT turbo as described in Dahl et al (2020), *"The New Volvo Mild Hybrid Miller Engine"* presented in Aachen Colloquium Automobile and Engine Technology. (Daniel Dahl, Ayolt Helmantel, Fredrik Wemmert, Mats Morén, Staffan Rengmyr, and Ali Sahraeian 2020) The image provided in this paper was digitized by loading the image into MATLAB and manually tracing the efficiency contours. NCAT used the peak BSFC and BTE values referenced in the paper to calculate the lower heating value for the test fuel having a reported RON of 98 and because the authors did not provide any test data for this engine using Tier 3 fuel, the decision was made to use ALPHA's Octane Modifier to also develop an estimated Tier 3 fuel map.

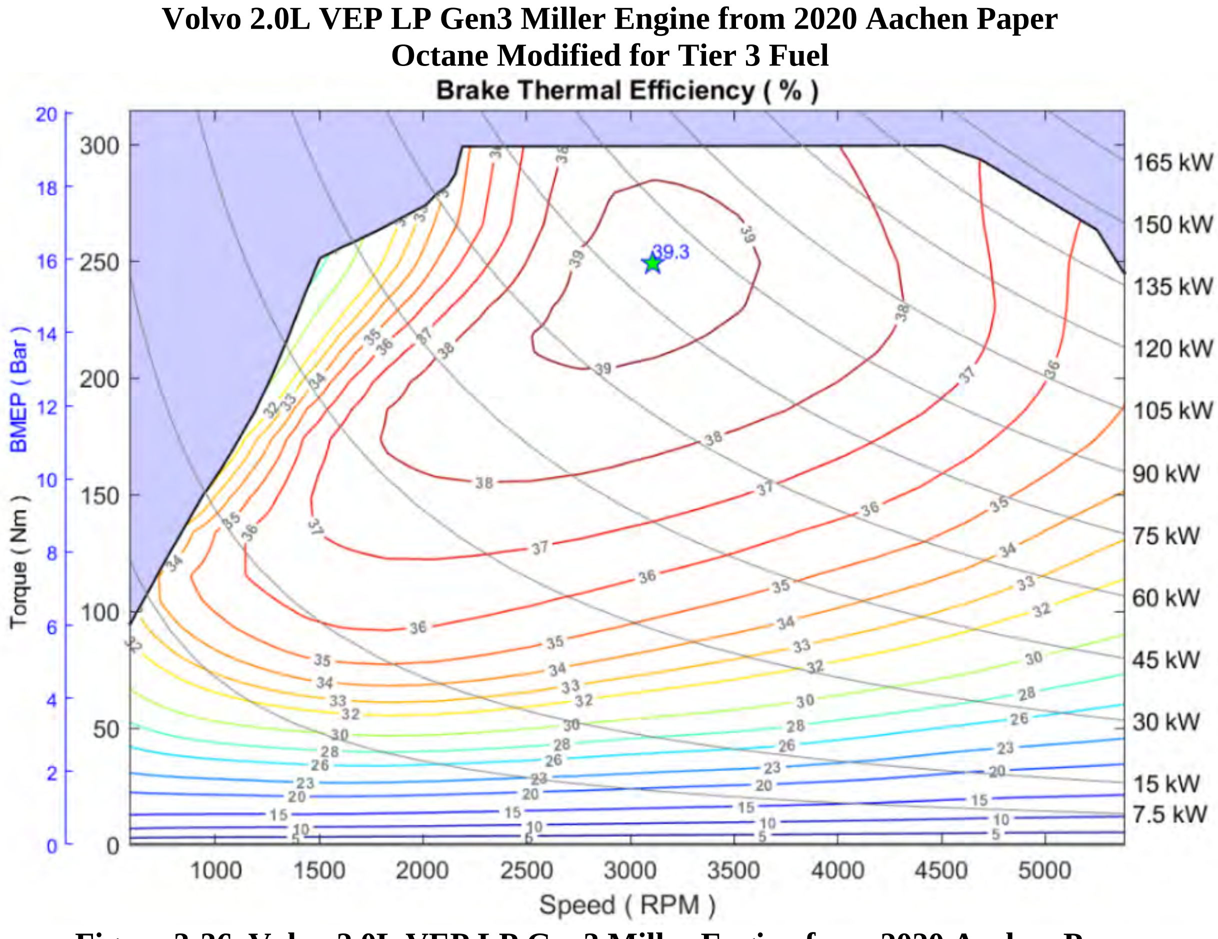

Figure 3-36 Volvo 2.0L VEP LP Gen3 Miller Engine from 2020 Aachen Paper Octane Modified for Tier 3 Fuel (U.S. EPA 2023b)

3.5.1.8 Geely 1.5L Miller GHE from 2020 Aachen Paper Octane Modified for Tier 3 Fuel

Zhang et al (2020), *"Geely Hybrid Engine: World Class Efficiency for Hybrid Vehicles"* presented in the 29th Aachen Colloquium (GuiQiang Zhang, Qian Wang, Guang Chen, et al. 2020) reported this engine has a high efficiency Miller-cycle combustion system with high tumble and turbulence kinetic energy, low friction, optimized mixture formation using a new 350 bar fuel injection system and a 13:1 compression ratio. These features are then combined with a fully matched turbocharger with highly cooled low pressure EGR and a water-charge air cooler. The image provided in this paper was digitized by loading the image into MATLAB and manually tracing the efficiency contours. Since the fuel used to map this engine had a relatively high lower heating value there was an assumption of a likely corresponding high RON value of 98 and because the authors did not provide any test data for this engine using Tier 3 fuel, the decision was made to use ALPHA's Octane Modifier to also develop an estimated Tier 3 fuel map.

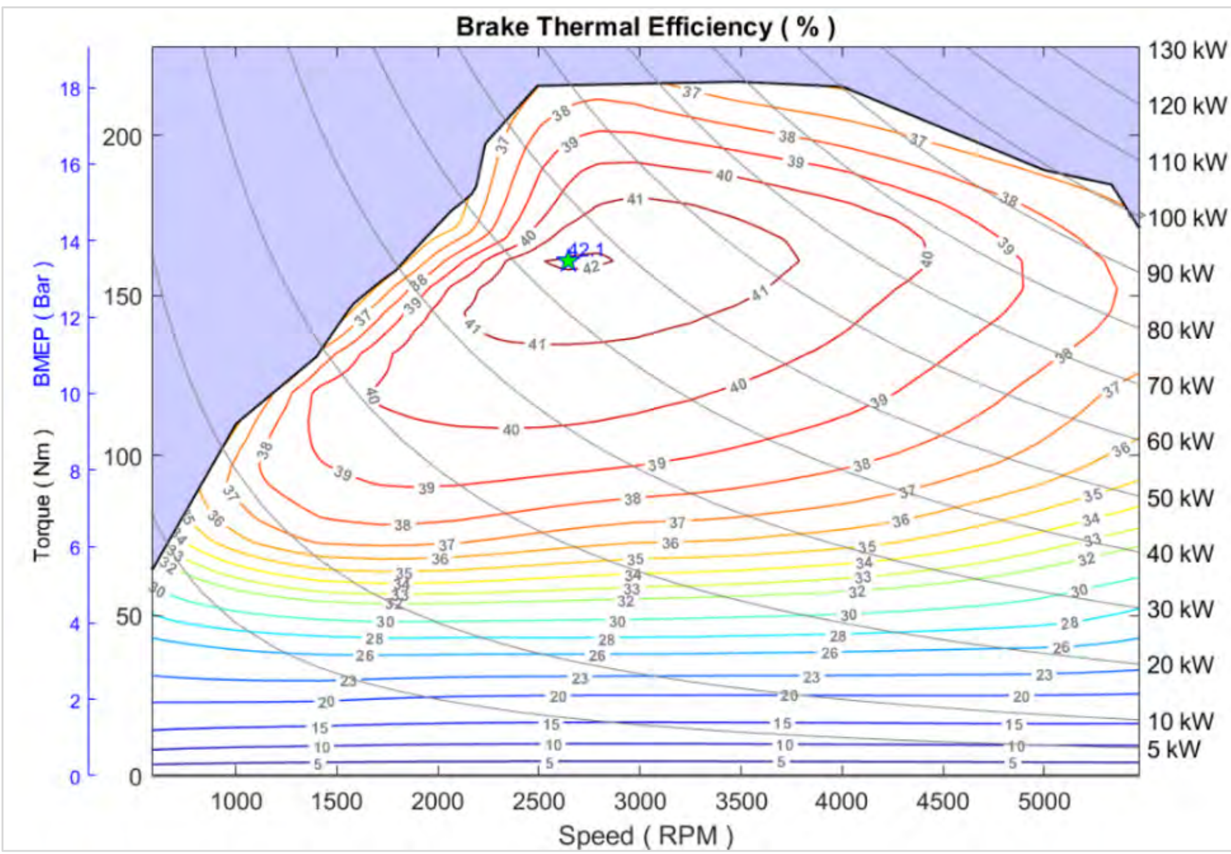

Figure 3-37 Geely 3-cyl 1.5L Miller GHE from 2020 Aachen Paper Octane Modified for Tier 3 Fuel (U.S. EPA 2023b)

3.5.1.9 2018 Toyota 2.5L A25A-FKS Engine Tier 3 Fuel

This 4-cylinder, naturally aspirated, Atkinson Cycle gasoline engine with cooled-EGR also includes direct & port injection, VVT electric intake & hydraulic exhaust, high induction turbulence/high speed combustion, high energy ignition, friction reduction, a variable capacity oil pump, and an electric water pump. The testing was performed by the EPA at the National Center for Advanced Technology (NCAT) with the engine installed in a dynamometer test cell tethered as though the engine were operating in the vehicle. The engine was coupled to the dynamometer using an automatic transmission and torque converter to allow for an accurate gathering of test data where the torque measurement is very sensitive to the engine's torsional accelerations. (John Kargul, Mark Stuhldreher, Dan Barba, Charles Schenk, Stani Bohac, Joseph McDonald, and Paul Dekraker 2019)

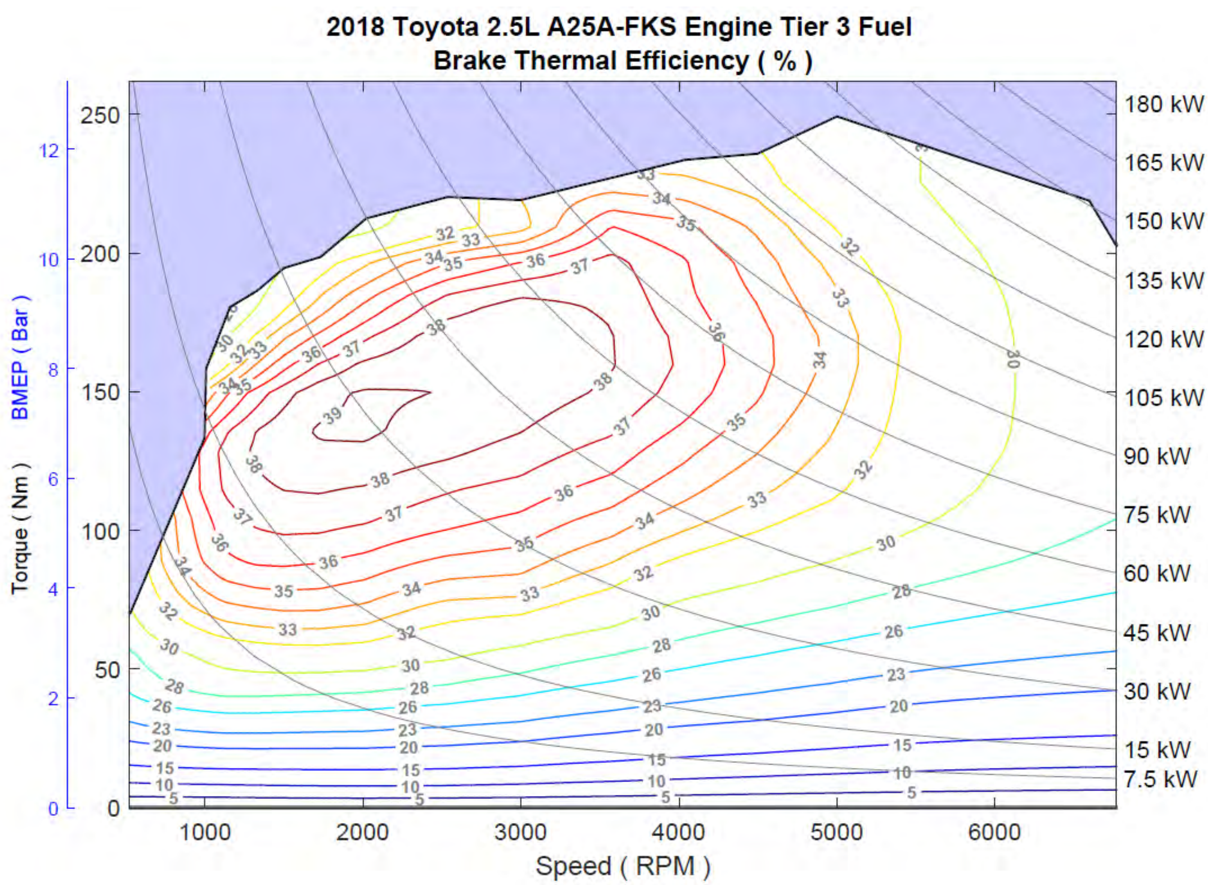

Figure 3-38 2018 Toyota 2.5L A25A-FKS Engine Tier3 Fuel (U.S. EPA 2023b)

3.5.1.10 Toyota 2.5L TNGA Prototype Hybrid Engine from 2017 Vienna Paper Octane Modified for Tier 3 Fuel

This inline 4 cylinder 2.5L gasoline naturally aspirated (NA) engine is thoroughly described in Tadashi Toda et al (2017), *"The New Inline 4 Cylinder 2.5L Gasoline Engine with Toyota New Global Architecture Concept"* presented at Internationales Wiener Motorensymposium. (T. Toda, M. Sakai, M. Hakariya, and T. Kato 2017) Features include high energy ignition coil motor-driven VVT for Atkinson cycle, a D-4S system (direct and port injection) with new multi hole injectors, cooled EGR, and a variable oil-pressure pump system. The image provided in this paper was digitized by loading the image into MATLAB and manually tracing the efficiency contours. There was no information presented regarding the fuel used for the map, so the decision was made assuming that data in the paper was based on a Tier 2 fuel and to use ALPHA's Octane Modifier to develop an estimated Tier 3 fuel map.

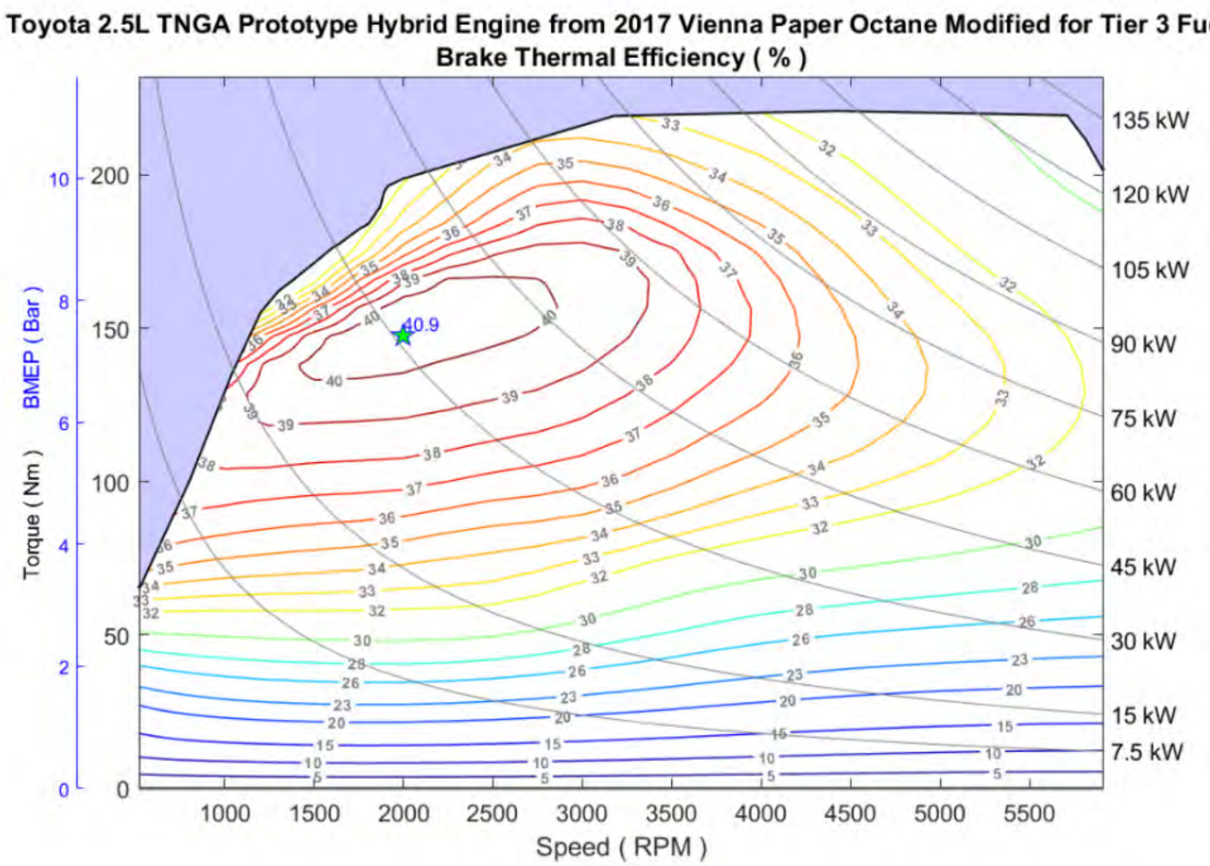

Figure 3-39 Toyota 2.5L TNGA Prototype Hybrid Engine from 2017 Vienna Paper Octane Modified for Tier 3 Fuel (U.S. EPA 2023b)

3.5.2 Electrification Technologies

The following is detailed information about the ALPHA inputs for electric inverters, motors, and generators used to create ALPHA Outputs for Response Surface Equations (RSE's) used by OMEGA. These were first discussed and listed in Table 2-3. Specific details about each electric motor are contained in the engine's data package available on EPA's webpage (U.S. EPA 2023a). Each engine data package is contained in a .zip file identified using the electric motor name mentioned in the caption of the associated ALPHA efficiency map shown below.

3.5.2.1 2010 Toyota Prius 60kW 650V MG2 EMOT

The 60kW 650V MG2 electric motor paired with an inverter and a 36hp (27kW) nickel-metal hydride battery pack was combined with a 1.8L 4-cylinder Atkinson cycle engine. The component benchmarking testing for this program was conducted by Oak Ridge National Laboratory's (ORNL) Power Electronics and Electric Machinery Research Center (PEEMRC), a broad-based research center for power electronics and electric machinery (e-motor) development. (Olszewski, Mitch 2011) The resulting measurements were used to create a combined efficiency map of the main drive e-motor and inverter without including any gearing, categorized together as an EMOT.

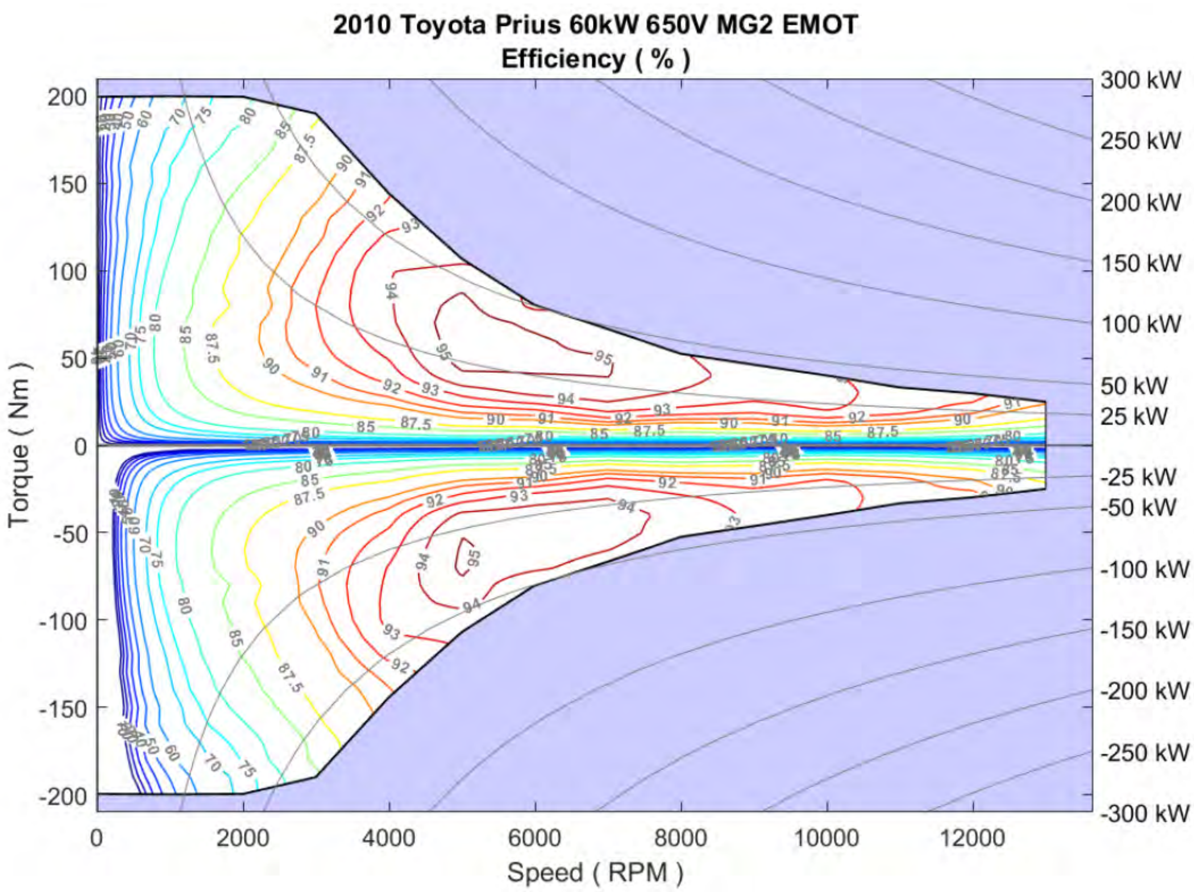

Figure 3-40 2010 Toyota Prius 60kW 650V MG2 EMOT (U.S. EPA 2023a)

3.5.2.2 Est 2010 Toyota Prius 60kW 650V MG1 EMOT

The Toyota Prius uses a secondary electric motor called an MG1, which functions as a generator to transfer power from the ICE to recharge the battery. Oak Ridge National Laboratory (ORNL) did not specifically benchmark this electric generator motor, presumably because of its similarity to the MG2 electric drive motor discussed in the previous section. (Olszewski, Mitch 2011) However, chassis test data provided by Southwest Research Institute (SwRI) indicated the maximum operating power for the MG1 generator motor is different than the MG2 drive motor. The maximum power curve for the MG1 is a constant value rather than variable as MG2's power curve. Consequently, the MG2 ORNL benchmark data was used along with the max power data provided from the SwRI chassis test data to create a constant power version for the MG1. The MG1 efficiency map estimates the combined efficiency of the main generator e-motor and its inverter, categorized together as an EMOT. The "Est" in the front of the e-motor's name indicates that it is an estimated map.

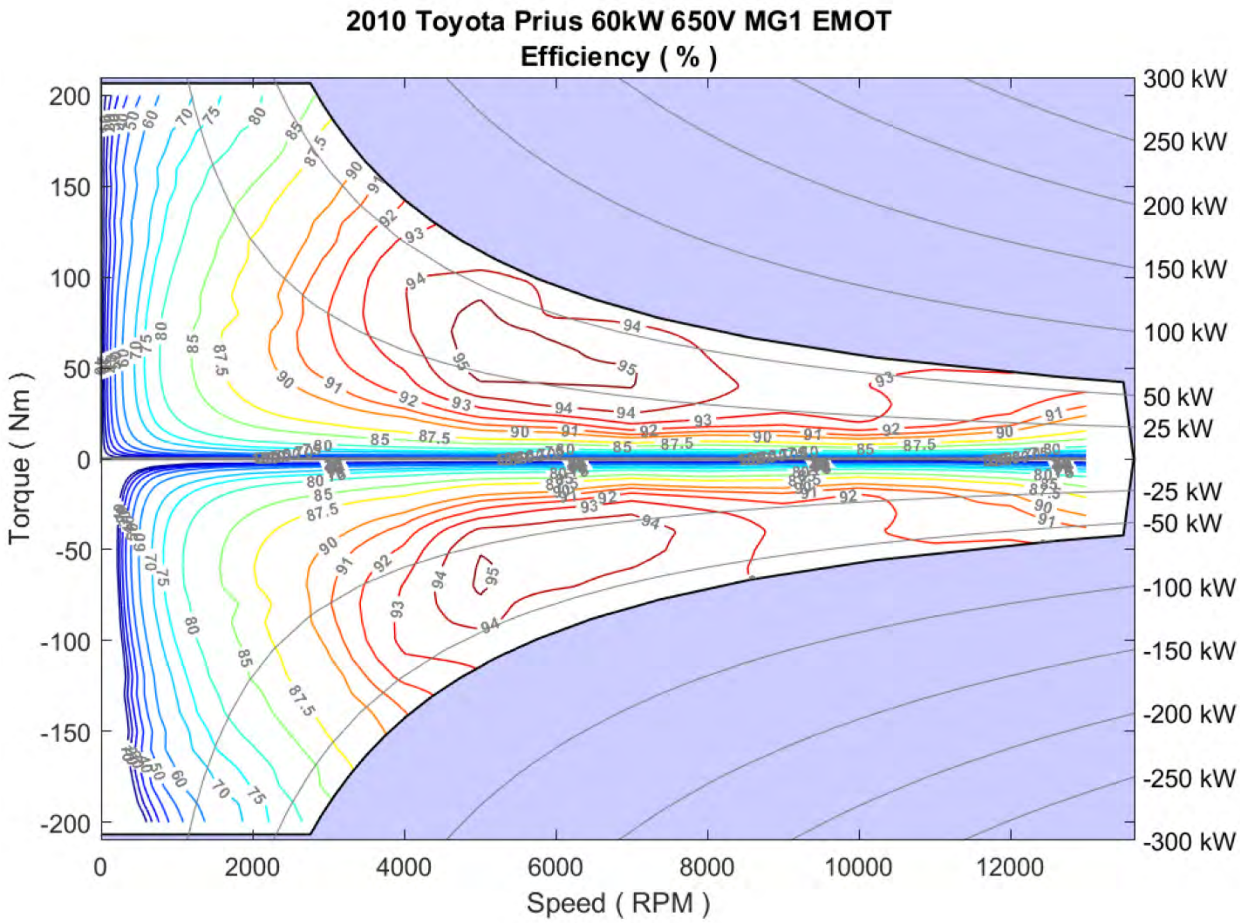

Figure 3-41 Est 2010 Toyota Prius 60kW 650V MG1 EMOT (U.S. EPA 2023a)

3.5.2.3 2011 Hyundai Sonata 30kW 270V EMOT

This 30 kW 270V electric motor was paired with an inverter, categorized together as an EMOT, and powered by a 270-volt lithium polymer battery. The map was created using benchmarked data that measured the efficiency of the combination of the main drive e-motor and its inverter without including any gearing. The component testing for this program was conducted by Oak Ridge National Laboratory's (ORNL) Power Electronics and Electric Machinery Research Center (PEEMRC), a broad-based research center for power electronics and electric machinery (e-motor) development (Rogers, Susan 2012)

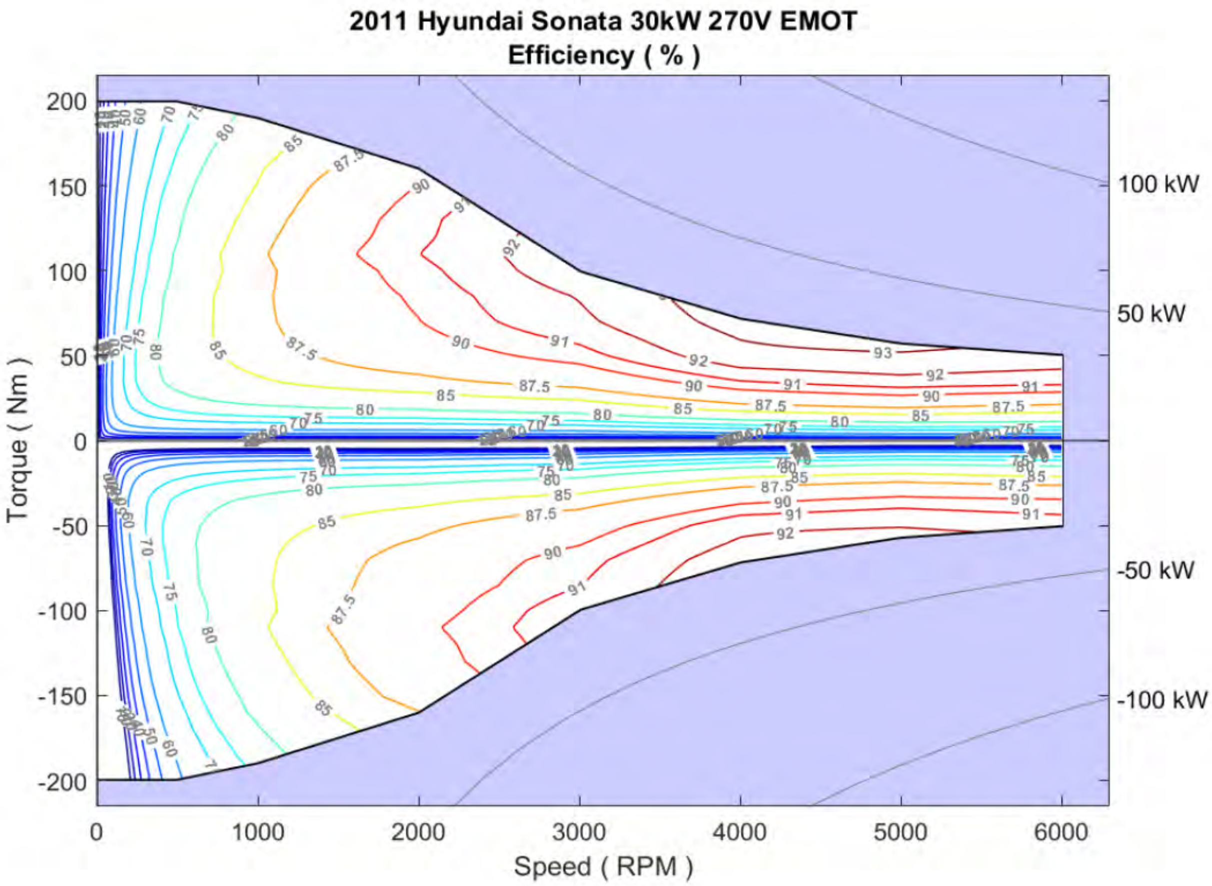

Figure 3-42 2011 Hyundai Sonata 30kW 270V EMOT (U.S. EPA 2023a)

3.5.2.4 2012 Hyundai Sonata 8.5kW 270V BISG

Hyundai's Hybrid Starter Generator (HSG) electric motor with published specifications listed as 43 Nm, 8.5kW, and 15,750 rpm was paired with an inverter and powered by a 270-volt lithium polymer battery. The application of this type of electric motor is normally found in mild hybrid electric vehicles (MHEV), often called P0 mild hybrids. The goal was to create a map representing the combined efficiency of the starter/generator motor, its inverter, and the drive belt, categorized together as a BISG (belt-inverter-starter/generator). The component testing for this program was conducted by Oak Ridge National Laboratory's (ORNL) Power Electronics and Electric Machinery Research Center (PEEMRC), a broad-based research center for power electronics and electric machinery (e-motor) development. (Rogers, Susan 2013)

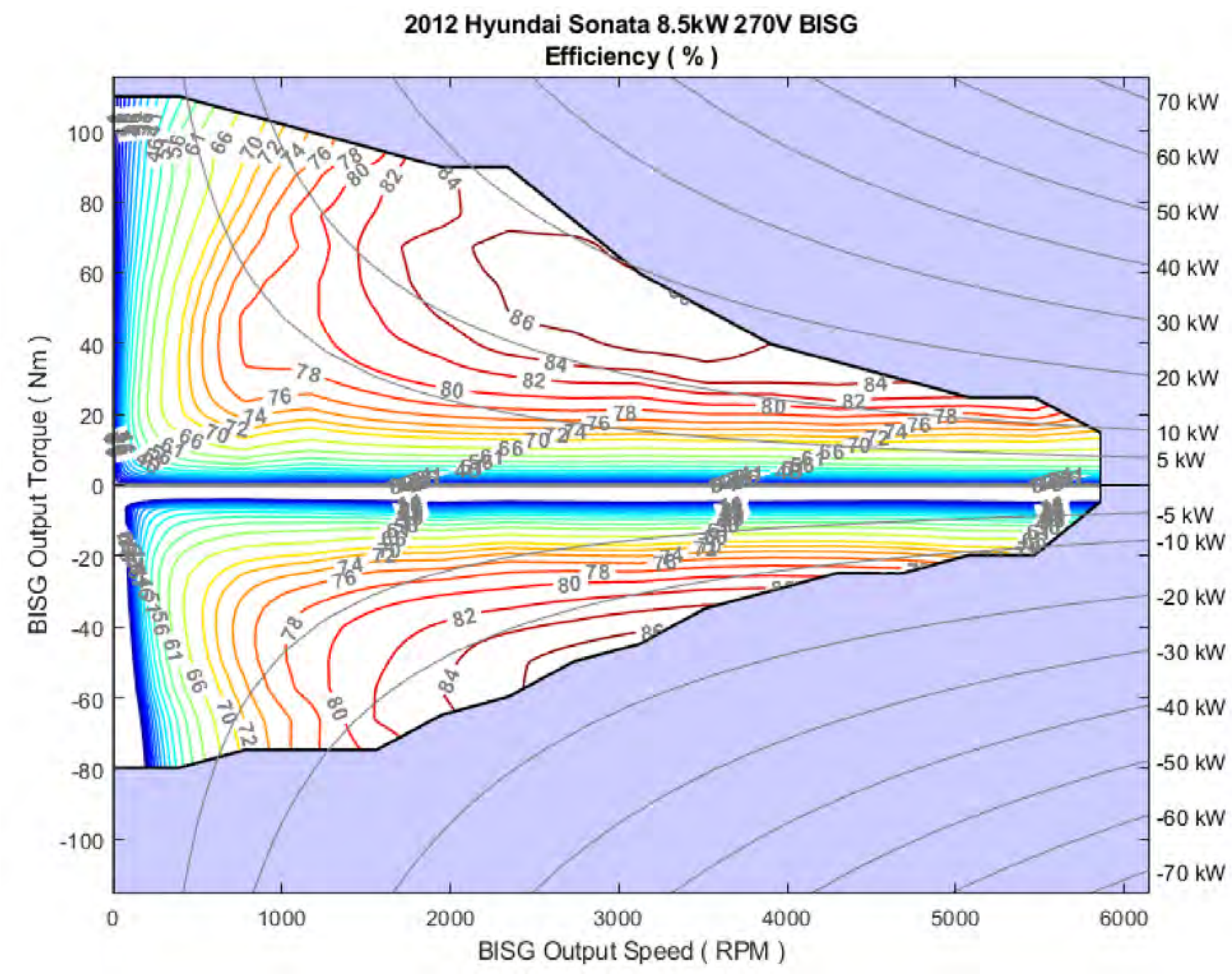

Figure 3-43 2012 Hyundai Sonata 8.5kW 270V BISG (U.S. EPA 2023a)

3.5.2.5 Generic IPM 150kW EDU

The Generic IPM 150kW 350V Electric Drive Unit (EDU) efficiency map was generated using confidential benchmarking test data from several state-of-the-art internal permanent magnet synchronous reluctance (IPMSRM) e-motors used in current production battery electric vehicles. Transformation functions whose coefficients- represent the averaged power consumption data were utilized to blend and transform the confidential test data. The final map was then scaled to 150kW to represent a generic EDU suitable for use in a BEV. The generated efficiency map represents the combined operating boundaries and electrical power consumption of the electric motor, inverter, and gearing, categorized together as an EDU. The gear ratio for this EDU is 9.5:1.

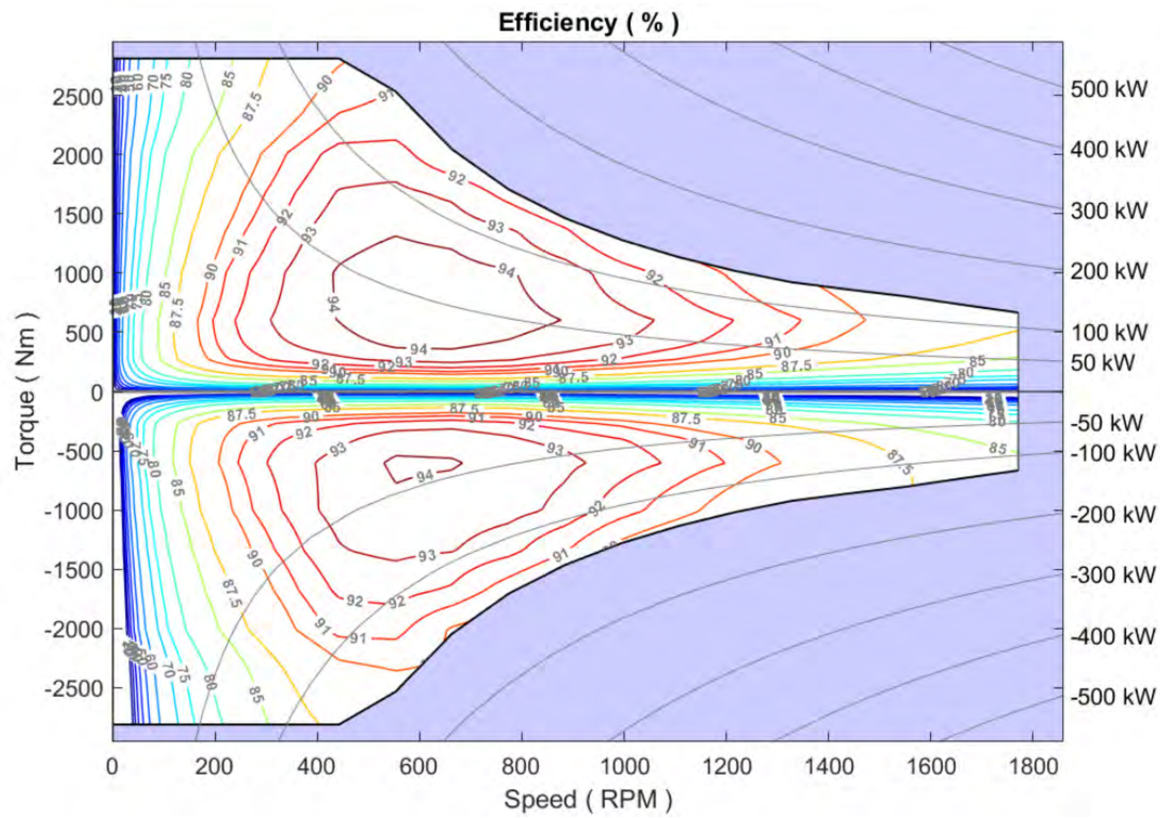

Figure 3-44 Generic IPM 150kW EDU (U.S. EPA 2023a)

3.5.3 <u>Vehicle Architectures</u>

A summary of the five vehicle architectures used in ALPHA 3.0 is provided in Section 2.4.4. Figure 2-3 summarizes the five vehicle models used to simulate vehicle efficiency for this proposal, including the conventional model used in previous versions of ALPHA, the three new hybrid electric models, and the one new battery electric vehicle model added for ALPHA 3.0.

3.5.4 Other Vehicle Technologies

Depending on vehicle design, other vehicle technologies such as transmissions, non-hybrid stop-start, electrified power steering, accessories, secondary axle disconnect, low drag brakes, and air conditioning may have been used in the creation of ALPHA outputs for the Response Surface Equations (RSE's) used by OMEGA. These other technologies were first discussed in the previous version of ALPHA used for the *2017 Final Determination* (U.S. EPA 2017) and the modeling has not changed. While the EPA believes that the proposed standards will be largely met through electrification, because the proposed standards are performance based, improvements in all vehicle and powertrain technologies will contribute to a vehicle manufacturer's compliance.

Chapter 3 References

40 CFR 1066.801(c)(1)(i). 2023.

40 CFR 1066.815. 2023.

40 CFR 1066.831. 2023.

40 CFR 1066.835. 2023.

40 CFR 1066.840. 2023.

61 FR 54852. 1996. (October 22). https://www.govinfo.gov/content/pkg/FR-1996-10-22/pdf/96-24485.pdf.

77 FR 62624. 2012. (October 15). https://www.govinfo.gov/content/pkg/FR-2012-10-15/pdf/2012-21972.pdf.

86 FR 74434. 2021. (December 30). https://www.federalregister.gov/documents/2021/12/30/2021-27854/revised-2023-and-later-model-year-light-duty-vehicle-greenhouse-gas-emissions-standards.

88 FR 4296. 2023. (January 24). https://www.govinfo.gov/content/pkg/FR-2023-01-24/pdf/2022-27957.pdf.

Aaron Isenstadt, Zifei Yang, Stephanie Searle, John German. 2022. Real world usage of plug-in hybrid vehicles in the United States,. https://theicct.org/publication/real-world-phev-us-dec22/, ICCT.

Argonne National Laboratory. 2022. Assessment of Light-Duty Plug-in Electric Vehicles in the United States, 2010-2021 (ANL-22/71). Argonne National Laboratory.

Battery Design. 2022. GM Ultium. June 8. https://www.batterydesign.net/gm-ultium/.

Benjamini, Yoav. 1988. "Opening the box of a boxplot." The American Statistician 42 (4): 257-262.

Boger, T., and W. Cutler. 2019. Reducing Particulate Emissions in Gasoline Engines. Warrendale, PA: SAE International.

Bohac, S. V., and S. Ludlam. 2023. "Characterization of a Lightly Loaded Underfloor Catalyzed Gasoline Particulate Filter in a Turbocharged Light Duty Truck." Journal of Engineering for Gas Turbines and Power 145(2): 021024. doi:10.1115/1.4056047.

Bohac, S. V., S. Ludlam, J. Martin, W. T. Preston, and M. D. Hays. 2022. "PAH Emissions from a GPF-Equipped Light Duty Truck during Soot Accumulation and Regeneration." 31st CRC Real World Emissions Workshop, San Diego, CA, March 14-16, 2022.

Bond, T.C., S. J. Doherty, and D. W., et al. Fahey. 2013. "Bounding the Role of Black Carbon in the Climate System, A Scientific Assessment." J. Geophys. Res. Atmos. 118, pp. 5380-5552.

Borger, T., D. Rose, P. Nicolin, B. Coulet, and A. Bachurina. 2018. "Severe Soot Oxidations in Gasoline Particulate Filter Applications." SAE Papaer 2018-01-1699.

Boston, W. 2023. "EVs Made Up 10% of All New Cars Sold Last Year." Wall Street Journal. January 16. https://www.wsj.com/articles/evs-made-up-10-of-all-new-cars-sold-last-year-11673818385.

BrightDrop. 2022. "2024 BrightDrop Zevo 400 and Zevo 600 Order Guide." November 4. https://www.gobrightdrop.com/ca/_assets/files/2024-brightdrop-en-ca-zevo-400-and-zevo-600-order-guide-12-23-22.pdf.

California Air Resource Board [OBD data records] . 2022. October. https://www.bar.ca.gov/records-requests.

California Bureau of Automotive Repair [OBD data records]. 2022. https://www.bar.ca.gov/records-requests.

Chan, T. W., Meloche, E., Brezny, R. 2014. "Black Carbon Emissions in Gasoline Exhaust and a Reduction Alternative with a Gasoline Particulate Filter." Environ. Sci. and Technol. 48 (10): 6027-6034. doi:10.1021/es501791b.

Chan, T. W., Meloche, E., Kubsch, J., Brezny, R., Rosenblatt, D., Rideout, G. 2013. "Impact of Ambient Temperature on Gaseous and Particle Emissions from a Direct Injection Gasoline Vehicle and its Implications on Particle Filtration." SAE Paper 2013-01-0527. doi:10.4271/2013-01-0527.

Chan, T. W., Saffaripour, M., Liu, F., Hendren, J., Thomson, K. A., Kubsh, J., Brezny, R., Rideout, G. 2016. "Characterization of Real-Time Particle Emissions from a Gasoline Direct Injection Vehicle Equipped with a Catalyzed Gasoline Particulate Filter During Filter Regeneration." Emiss. Control Sci. Technol. 2 (2): 75-88. doi:10.1007/s40825-016-0033-3.

Christianson, M. G., E. Bardasz, and W. Nahumck. 2010. "Impact of Lubricating Oil Condition on Exhaust Particulate Matter Emissions from Light Duty Vehicles." SAE International Journal of Fuels and Lubricants Vol. 3, No. 2, pp. 476-488.

Daniel Dahl, Ayolt Helmantel, Fredrik Wemmert, Mats Morén, Staffan Rengmyr, and Ali Sahraeian. 2020. "The New Volvo Mild Hybrid Miller Engine." 29th Aachen Colloquium Sustainable Mobility. Aachen.

Fortune Business Insights. 2022. Automotive E-commerce Market Size, Share & COVID-19 Impact Analysis. July. Accessed December 13, 2022. https://www.fortunebusinessinsights.com/automotive-e-commerce-market-105728.

Frigge, Michael, David C. Hoaglin, and Boris Iglewicz. 1989. "Some implementations of the boxplot." The American Statistician 43 (1): 50-54.

GuiQiang Zhang, Qian Wang, Guang Chen, et al. 2020. "Geely Hybrid Engine: World Class Efficiency for Hybrid Vehicles." 29th Aachen Colloquium Sustainable Mobility. Aachen: 29th Aachen Colloquium Sustainable Mobility.

John Kargul, Mark Stuhldreher, Dan Barba, Charles Schenk, Stani Bohac, Joseph McDonald, and Paul Dekraker. 2019. "Benchmarking a 2018 Toyota Camry 2.5-liter Atkinson cycle engine with cooled-EGR." SAE International Journal of Advances and Current Practices in Mobility 1 (2): 601-638. doi:10.4271/2019-01-0249.

Joshi, A., and T. V. Johnson. 2018. "Gasoline Particulate Filters - a Review." Emission Control Science and Technology (4)219-239. doi:10.1007/s40825-018-0101-y.

Konstandopoulos, A. G., and Papaiononnou, E. 2008. "Update on teh Science and Technology of Diesel Particulate Filters." KONA Power Part J, 26(0), pp. 36-65.

Krajinska, Poliscanova, Mathieu, & Ambel, Transport & Environment. 2020. "A new Dieselgate in the making." November: https://www.transportenvironment.org/discover/plug-hybrids-europe-heading-new-dieselgate/.

Lambert, C., T. Chanko, D. Dobson, X. Liu, and J. Pakko. 2017. "Gasoline Particle Filter Development." Emiss. Control Sci. Technol. 3:105-111. doi:10.1007/s40825-016-0055-x.

Mark Stuhldreher. 2016. "Fuel efficiency mapping of a 2014 6-cylinder GM EcoTec 4.3 L engine with cylinder deactivation." SAE Technical Paper. No. 2016-01-0662. doi:10.4271/2016-01-0662.

Mark Stuhldreher, Charles Schenk, Jessica Brakora, David Hawkins, Andrew Moskalik, and Paul DeKraker. 2015. "Downsized Boosted Engine Benchmarking and Results." SAE Technical paper no. 2015-01-1266. doi:10.4271/2015-01-1266.

Minjares, R. J., and F. P. Sanchez. 2011. "Estimated Cost of Gasoline Particulate Filters." ICCT Working Paper 2011-8.

Newman, K., Kargul, J., and Barba, D. 2015. "Benchmarking and Modeling of a Conventional Mid-Size Car Using ALPHA." SAE Technical Paper 2015-01-1140. doi:10.4271/2015-01-1140.

North American Council for Freight Efficiency. 2021. "Vans & Step Vans: Market Segment & Fleet Profile Fact Sheet." Accessed December 13, 2022. https://nacfe.org/wp-content/uploads/2022/01/Vans-Step-Vans-RoL-E-Fact-Sheet.pdf.

OAQPS, EPA. 2014. "2014 National Air Toxics Assessment (NATA) Technical Support Document (TSD)."

Olszewski, Mitch. 2011. EVALUATION OF THE 2010 TOYOTA PRIUS HYBRID SYNERGY DRIVE SYSTEM. Oak Ridge National Laboratory (ORNL).

Patrick Plötz et al. 2021. "From lab-to-road: real-world fuel consumption and CO2 emissions of plug-in hybrid electric vehicles." Environ. Res. Lett. 16 054078, https://iopscience.iop.org/article/10.1088/1748-9326/abef8c. doi:1748-9326/abef8c.

Plötz, P. and Jöhrens, J. 2021. "BMU_Kurzpapier_UF_final.pdf." https://www.isi.fraunhofer.de/content/dam/isi/dokumente/cce/2021/.

Plötz, P., Link, S., Ringelschwendner, H., Keller, M., Moll, C., Bieker, G., Dornoff, J., Mock, P. . 2022. "Real-world usage of plug-in hybrid electric vehicles in Europe: A 2022 update on fuel consumption, electric driving, and CO2 emissions." ICCT, June .

Plötz, P., Moll, C., Bieker, G., Mock, P., Li, Y. 2020. "real-world-usage-of-plug-in-hybrid-electric-vehicles-fuel-consumption-electric-driving-and-co2-emissions." ICCT. September. https://theicct.org/publication/.

Public Law 117-169. 2022. "The Inflation Reduction Act of 2022." August 16. https://www.govinfo.gov/content/pkg/PLAW-117publ169/pdf/PLAW-117publ169.pdf.

Riley, D. 2023. "Ram 1500 BEV Expected To Hit Market With 500 Miles of Range." Wards Auto. January 5. https://www.wardsauto.com/print/389039.

Rogers, Susan. 2012. "FY2012 Annual Progress Report - Advanced Power Electronics and Electric Motors Program."

Rogers, Susan. 2013. FY2013 Annual Progress Report for the Advanced Power Electronics and Electric Motors Program. Oak Ridge National Laboratory (ORNL).

S&P Global. 2022b. "Growth of Li-ion battery manufacturing capacity in key EV markets." May 20. Accessed November 22, 2022. https://www.spglobal.com/mobility/en/research-analysis/growth-of-liion-battery-manufacturing-capacity.html.

—. 2022a. "US ready for a battery factory boom, but now it needs to hold the charge." October 3. Accessed November 22, 2022. https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/us-ready-for-a-battery-factory-boom-but-now-it-needs-to-hold-the-charge-72262329.

SAE J1711. 2023. "Recommended Practice for Measuring the Exhaust Emissions and Fuel Economy of Hybrid-Electric Vehicles, Including Plug-in Hybrid Vehicles." Issued 1999-03, Revised 2010-06, Revised 2023-02, February.

SAE J2841. 2010. "Utility Factor Definitions for Plug-In Hybrid Electric Vehicles Using Travel Survey Data." Issued 2009-03, Revised 2010-09, September.

Saito, C., T. Nakatani, Y. Miyairi, and et al. 2011. "New Particulate Filter Concept to Reduce Particle Number Emissions." SAE Paper 2011-01-0814. doi:10.4271/2011-01-0814.

Seabaugh, Christian. 2022. "Take a Look Inside Amazon's New Rivian Delivery Van." Motor Trend, November 24. Accessed March 9, 2023. https://www.motortrend.com/news/checking-in-on-the-rivian-amazon-edv-electric-van/.

Southwest Research Institute. 2022. "Heavy-duty Gasoline Engine Low NOx Demonstration Final Report, EPA Contract 68HERC20D0014."

Streeter, M. 2021. "The C8 Corvette's Software Watchdog Will Force You To Obey The Engine Break-In Limits." Jalopnik. January 27. https://jalopnik.com/the-c8-corvettes-software-watchdog-will-force-you-to-ob-1846142481.

Stuhldreher, Mark; Kargul, John; Barba, Daniel ; McDonald, Joseph; Bohac, Stanislav; Dekraker, Paul; Moskalik, Andrew;. 2018. "Benchmarking a 2016 Honda Civic 1.5-liter L15B7 Turbocharged Engine and Evaluating the Future Efficiency Potential of Turbocharged Engines." SAE International Journal of Engines 116: 1273-1305. doi:10.4271/2018-01-0319.

Sun, Zin, Minggao Ouyang, and Han Hao. 2022. "Surging lithium price will not impede the electric vehicle boom." Joule 6 (8): 1738-1742. https://doi.org/10.1016/j.joule.2022.06.028.

T. Toda, M. Sakai, M. Hakariya, and T. Kato. 2017. "The New Inline 4 Cylinder 2.5L Gasoline Engine with Toyota New Global Architecture Concept." Internationales Wiener Motorensymposium. Vienna.

Thomas E. Reinhart. 2021. Engine Efficiency Technology Study: Final Report, SwRI Project No. 03.26457. San Antonio: Southwest Research Institute.

Title 13 § 1968.2 California Code of Regulations. 2022. (November 22).

Title 40 CFR § 600.311–12. 2021. https://www.ecfr.gov/current/title-40/chapter-I/subchapter-C/part-86/subpart-N/section-86.1360.

Title 40 CFR § 86.1803-01. 2023.

Title 40 CFR 600.116-12. 2022. https://www.ecfr.gov/current/title-40/chapter-I/subchapter-Q/part-600/subpart-B/section-600.116-12.

Transport & Environment. 2022. TE-Anlaysis_-Update-of-PHEV-utility-factors-1.pdf. https://www.transportenvironment.org/wp-content/uploads/2022/06/.

Tukey, J. W. 1977. Exploratory data analysis. Vol. 2. Addison-Wesley.

U.S. Census Bureau. 2022. February 18. Accessed December 13, 2022. https://www.census.gov/retail/index.html.

U.S. EPA. 2023b. Combining Data into Complete Engine ALPHA Maps. Accessed February 2, 2023. https://www.epa.gov/vehicle-and-fuel-emissions-testing/combining-data-complete-engine-alpha-maps.

—. 2023a. Complete Electric Motor ALPHA Maps. https://www.epa.gov/vehicle-and-fuel-emissions-testing/combining-data-complete-emotor-alpha-maps.

U.S. EPA. 2022. "Control of Air Pollution from New Motor Vehicles: Heavy-Duty Engine and Vehicle Standards Regulatory Impact Analysis, EPA-420-R-22-035." https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P1016A9N.pdf.

—. 2022b. Data on Cars used for Testing Fuel Economy. https://www.epa.gov/compliance-and-fuel-economy-data/data-cars-used-testing-fuel-economy.

—. 2017. "EPA-420-R-17-001: Final Determination on the Appropriateness of the Model Year 2022-2025 Light-Duty Vehicle Greenhouse Gas Emissions Standards under the Midterm Evaluation." https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100QQ91.pdf.

—. 2023. "Preamble to the Light- and Medium-Duty Multipollutant Emissions Standards." Preamble to the Light- and Medium-Duty Multipollutant Emissions Standards.

U.S. EPA. 2016. "Proposed Determination on the Appropriateness of the Model Year 2022-2025 Light-duty Vehicle Greenhouse Gas Emissions Standards under the Midterm Evaluation, EPA-420-R-16-020." https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100Q3DO.pdf.

U.S. EPA. 2022. "The 2022 EPA Automotive Trends Report: Greenhouse Gas Emissions, Fuel Economy, and Technology since 1975, EPA-420-R-22-029." Accessed December 13, 2022. https://www.epa.gov/system/files/documents/2022-12/420r22029.pdf.

U.S. EPA, CARB, U.S. DOT NHTSA. 2016. "Draft Technical Assessment Report: Midterm Evaluation of Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards for Model Years 2022-2025, Report No. EPA-420-D-16-900." https://nepis.epa.gov/Exe/ZyPDF.cgi/P100OXEO.PDF?Dockey=P100OXEO.PDF.

van Nieuwstadt, M., A. Shah, E. Serban, and D. Martin. 2019. "Regeneration Strategies for Gasoline Particulate Filters." SAE Paper 2019-01-0969. doi:10.4271/2019-01-0969.

Wood Mackenzie. 2022. Battery & raw materials - investment horizon outlook to 2032. Wood Mackenzie.

Chapter 4: Consumer Impacts and Related Economic Considerations

This chapter discusses the impacts of the proposed rule on consumers and related economic considerations, where "consumer" refers to buyers and lessees of new light-duty vehicles for personal use. Regarding consumer impacts, we examine the implications of the proposed standards on consumers from three frames of reference, namely the purchase decision, the ownership experience, and social benefits and costs. These three perspectives overlap but also differ in important ways, which we discuss in this chapter. In addition, these three frames of reference relate to EPA OMEGA modeling (see DRIA Chapter 2) and inform EPA's analysis of costs and benefits (see DRIA Chapter 10). Furthermore, the impacts of this proposed rule on consumers affect projections of vehicle sales and consequently inform EPA's employment analysis, which we also discuss in this chapter.

In our representation of the purchase decision, we include costs that consumers incorporate into their purchase decision; how consumers respond to costs; and how consumer perceptions of technologies change or do not change over time. In the discussion of the ownership experience, we focus on vehicle use and on consumer savings and expenses for BEVs and ICE vehicles across three body styles. Specifically, we present projected savings and expenses for average MY 2032 vehicles at the time of purchase and averaged over the first eight years of vehicle life. In the discussion of consumer-related costs and benefits, we include components of social costs and benefits that are included in the benefit-cost analysis and that have direct consumer impacts. In the discussion of vehicle sales, we explain how sales impacts are modeled, as well as show how total vehicle sales are expected to increase. We conclude with a discussion of employment impacts in which we discuss potential impacts of the growing prevalence of electric vehicles, present a quantitative discussion of partial employment impacts on sectors directly impacted by this proposed rule, and discuss potential employment impacts on other related sectors.

4.1 Modeling the Purchase Decision

In this section, we focus our discussion on our modeling of the consumer purchase decision. The vehicle purchase decision is a complex process (Jackman, et al. 2023, 12-14) (Taylor and Fujita 2018). Consumers consider and value a wide array of vehicle attributes and features as they develop and seek to satisfy their purchase criteria (Fujita, et al. 2022). Body style is a particularly important consumer criterion. Individuals tend to consider vehicle within a body style (Fujita, et al. 2022). Thus, we model vehicle choice within body style, namely sedan and wagons, CUVs and SUVs, and pickups and across other vehicle attributes. Value, as in "value for the money," is also among the most compelling vehicle attributes that consumers consider (Fujita, et al. 2022, 748 & 754) (Jackman, et al. 2023). "Value" is a multi-factor consideration; it includes factors such as purchase, fueling, maintenance, and repair costs, wholly or in part. Thus, these costs play an important role in consumers' decision processes as does consumer sensitivity to those costs, which we capture and quantify in our analyses. Also important to the vehicle purchase decision, but harder to capture and quantify, are consumers' diverse perceptions of other vehicle attributes. These more subjective assessments pertain to vehicle attributes such as comfort, design, image, and performance (Fujita, et al. 2022, 748), as well as to technology (e.g., ICE vehicle, PEV) where decision rules (e.g., compensatory, non-compensatory), attitudes (e.g., technological affinity), and psychological biases (e.g., risk and uncertainty aversion, loss aversion) may be at play (Taylor and Fujita 2018, 37).

In the following discussion of consumers' decision processes, we narrow our focus and modeling to the following key elements: costs that consumers incorporate into their purchase decisions (i.e., purchase, fueling, maintenance, repair, and depreciation); how consumers respond to costs (i.e., logit parameters); and how consumer perceptions of technologies change or do not change over time (i.e., share weight parameters). In addition, as enablers of consumer acceptance of PEVs grow and expand rapidly, we expect that electrification of the light-duty vehicle market will also accelerate dramatically.[43] Thus, we specifically attend to the choice consumers will increasingly make between BEVs and ICE vehicles by estimating the proportions of new vehicle sales expected to be BEVs and ICE vehicles. In our modeling, methods are the same for all body styles and powertrains, though the inputs may differ. We address those differences in the following chapters.

4.1.1 Costs Incorporated in the Purchase Decision

During the vehicle purchase decision process, consumers reference a wide variety of information during the stages of vehicle purchase. This includes what consumers believe they already know and what they learn from other parties (e.g., friends, family) and external sources (e.g., vehicle labels, websites). From one consumer to the next and from one purchase to another, this information varies in type, quality, and precision. In our representation of the vehicle purchase decision, consumers incorporate into their purchase decisions reasonably good estimates of the number of miles they expect to drive per year, fueling expenses and efficiency, and other ownership expenses in addition to purchase price. In our modeling, consumers assume that approximate annual VMT is 12,000 miles, annual non-fuel ownership costs for BEVs are $1,600, and annual non-fuel ownership costs for ICE vehicles are $2,000. In addition, via the fuel economy and environment label, consumers have implicit information regarding the "refueling efficiency" of BEVs and ICE vehicles, estimated to be 0.9 and 1 respectively, which are captured in the consumer purchase decision.[44] These purchase price and ownership costs are translated into total cost per mile, also called consumer generalized cost. This translation allows the consumer as represented in the model to compare vehicles. It also requires costs to be spread over time (i.e., annualize) and miles traveled. In our modeling, we annualize purchase price over 5 years using a 10% discount rate. We summarize the above information in Table 4-1.

[43] There are numerous indicators of increasing and rapid electrification in the LD vehicle market. In recent years, BEV sales have grown exponentially with more than 16.5 million PEVs on the road globally in 2021. BEV options for consumers across body styles and price points have grown by many orders of magnitude. Large public and private investment in BEV and EVSE technologies and deployment have been made and announced. Currently, consumer demand for BEVs appears to be unsatiated as evidenced by BEV supply shortages and waiting lists, suggesting that current market conditions are ripe for enabling rapid growth in PEV adoption. See Preamble I.A.2.ii for more information. Also see Jackman et al. (2023) for a summary of PEV acceptance enablers and obstacles.

[44] The fuel economy and environment label is affixed to every new vehicle sold in the United States. The test procedures used to determine MPGe and kWh per 100 miles for BEVs take into account charging inefficiencies.

Table 4-1: Consumer generalized cost inputs

Powertrain	Annual VMT (miles)	Annual Non-Fuel Ownership Costs	Fueling Efficiency
BEV	12,000	$1,600	0.9
ICE	12,000	$2,000	1

With the above inputs and the objective of developing total cost per mile (aka consumer generalized cost), we represent the consumer purchase decision with a series of related equations, all of which represent consumer costs as consumers estimate them. We begin the series of related equations with total cost per mile, which can logically be separated into fuel costs per mile and non-fueling costs per mile, as in the equation below.

$$Total\ cost\ per\ mile = \ fuel\ costs\ per\ mile + nonfueling\ costs\ per\ mile$$

Fueling cost per mile depends on fuel cost, fuel economy, and refueling efficiency. However, these measures clearly differ between BEVs and ICE vehicles due to the energy source (i.e., electricity and liquid fuel), units (i.e., kilowatt hours and gallons), and fueling efficiency.[45]

$$fuel\ costs\ per\ mile_{BEV} = (cost\ per\ kWh * kWh\ per\ mile) \div fueling\ efficiency$$

$$fuel\ costs\ per\ mile_{ICEV} = (cost\ per\ gallon * gallons\ per\ mile) \div fueling\ efficiency$$

Note that because fueling efficiency for BEVs is 0.9, which is less than 1, dividing by fueling efficiency increases BEV fuel cost per mile. For ICE vehicles, fueling efficiency is 1 and has no effect on ICE vehicle fuel cost per mile.[46]

Non-fueling ownership costs include purchase price, often referred to as up-front or capital costs, and annual non-fueling costs like maintenance and repair. To populate the second term of the total cost per mile equation, we annualize non-fueling ownership costs, then convert them to per mile values. To annualize capital costs over a 5-year time period, we first calculate the annualization factor using a 10% discount rate.

$$annualization\ factor = rate * \left(1 + \frac{1}{(1 + rate)^{time\ period - 1}}\right)$$

Then, we multiply the annualization factor and capital costs to determine annualized capital costs.

$$annualized\ capital\ costs = annualization\ factor * captial\ costs$$

The remaining non-fueling ownership costs are given as annual values in Table 4-1. Thus, total annualized non-fueling costs are the sum of annualized capital costs and annual non-fueling ownership costs. We then calculate non-fueling costs per mile by dividing that sum by estimated

[45] Note that throughout the equations in the chapter, we will be abbreviating ICE vehicle to ICEV.

[46] To estimate gallons per mile in OMEGA, we divide estimated onroad grams of CO_2 per mile by the estimate fuel carbon intensity.

annual vehicle miles.[47] The following equation shows this calculation and provides the last term of the total cost per mile calculation.

$$nonfueling\ costs\ per\ mile = \frac{annualized\ capital\ costs + annual\ nonfueling\ ownership\ costs}{annual\ VMT}$$

With the above equation, we have all of the components needed to determine total cost per mile given by the first equation in this section. Total cost per mile is the cost component of the consumer decision process as represented in our modeling, which we also refer to as consumer generalized cost. It is important to note that consumer generalized costs are not meant to be perfectly consistent with costs calculated within the effects module of OMEGA. The values here represent the perceptions and expectations of consumers during the decision process, and are not reflective of the values used in our benefit cost analysis.

4.1.2 Consumer Response to Costs and Perceptions of Technology

Total sales are determined as described in Chapter 4.4 below. Here we focus on how we model consumer choice and arrive at the proportions of total sales that are BEVs and ICE vehicles, which we call market shares.[48] We calculate the proportions of BEVs and ICE vehicles as one calculates weighted averages. Thus, proportions of BEVs and ICE vehicles are given by the market share equations given below.

$$market\ share_{BEV} = \frac{weight_{BEV}}{weight_{BEV} + weight_{ICEV}}$$

$$market\ share_{ICEV} = \frac{weight_{ICEV}}{weight_{BEV} + weight_{ICEV}}$$

The weight components of these equations come from a logit formulation that we use to represent consumer choice and describe below. This representation of consumer choice includes consumer generalized costs (i.e., total costs per mile) as well as consumer response to costs (i.e., logit parameter) and consumer perceptions of technology (i.e., shareweight parameters).

Setting aside the mathematics of the logit formulation for now, we first describe consumer choice conceptually. Consumers match vehicle attributes to purchase criteria in their purchase decision (Fujita, et al. 2022). In addition to body style and powertrain, the vehicle attributes we

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[47] OMEGA also includes a dollar adjustment factor where needed to ensure that costs estimated in OMEGA are in a consistent dollar year. Specifically, in the calculation of nonfueling costs per mile, the sum of annualized capital costs and annual nonfueling ownership costs is also divided by a dollar adjustment factor. This ensures that costs are estimated in 2020 dollars. The dollar adjustment factor is estimated using the GDP Implicit Price Deflator published by the U.S. Bureau of Economic Analysis (see Chapter 2.6.7 of this DRIA).

[48] EPA's OMEGA model estimates total vehicle production and sales separately from BEV and ICE vehicle market shares. In short, sales are based on EIA sales projections, market conditions/modeling context not included in EIA sales projections, market-based estimates of demand elasticity for vehicles, and producer decision processes. See Chapter 2 and Chapter 4.4.

incorporate into our modeling of consumer choice are represented by an estimate of generalized consumer cost, as derived in Chapter 4.1.1. Generalized consumer cost creates a comparable metric across the variety of vehicle attributes for all vehicles, and the monetization of purchase price and ownership costs implicitly includes consumer preferences over vehicle attributes, including powertrain. Thus, generalized consumer cost effectively provides an ordering of vehicle alternatives within body styles. Typically, when presented with two identical items, a hypothetical consumer will select the lower priced item. In reality, vehicle attributes and features differ, as do consumers and their purchase criteria. Consumers purchase comparable vehicles over a range of prices. Mathematically, we apply a logit exponent of 0.8 to total cost per mile (aka consumer generalized cost), per Chapter 4.1.1, to achieve this effect.[49]

$$weight_{BEV} = shareweight_{BEV} * (total\ cost\ per\ mile_{BEV})^{logit}$$

$$weight_{ICEV} = shareweight_{ICEV} * (total\ cost\ per\ mile_{ICEV})^{logit}$$

Our modeling separately attends to powertrain (i.e., BEVs and ICE vehicles) for several reasons. BEV technology is "consumer facing," meaning that the technology is clearly apparent to consumers, in addition to the vehicle attributes that consumers associate with the technology (e.g., acceleration, noise, efficiency, repair and maintenance costs). Also, historically, new BEVs sales made up single digit percentages of the new vehicle market. However, BEV sales have grown rapidly, PEV approval is strong, and PEV acceptance (i.e., awareness, access, approval, and adoption) is expected to continue to grow in response to ongoing and emerging market enablers of PEV purchase, such as increasing exposure to and familiarity with PEVs resulting from more models, greater PEV prevalence, expanding infrastructure, and advertising (Jackman, et al. 2023). We capture this evolution of consumer acceptance of BEVs using parameters called shareweights. Conceptually, shareweights represent non-cost elements of the consumer purchase decision. These elements primarily include internal and external characteristics of individuals and households (e.g., attitudes, demographics) and also of their physical, social, economic and governmental systems in which they reside (Jackman, et al. 2023). Shareweights can remain constant over time if consumer acceptance of the technology is not changing; they can increase if consumer acceptance of the technology is increasing; or they can decrease if consumer acceptance waning.

Mathematically, the shareweight is multiplied by the exponential term in the weight equations above. Effectively, the shareweight mediates the effect of total cost per mile term on the consumer purchase decision. For ICE vehicles, the shareweight in every year and in every scenario is equal to 1. This means that consumer acceptance of ICE vehicles does not change over time, and the ICE vehicle purchase decision, as modeled, depends on the vehicle attributes that consumer generalized cost implicitly encapsulates. A constant shareweight of 1 reflects the long-established nature of ICE technology in the light-duty vehicle market and the expectation that consumer attitudes toward ICE vehicles is stable. For BEVs, shareweights increase over time, beginning below one and increasing to or toward 1 in the No Action Case and Proposal scenario. As such, BEV shareweights reflect growth in BEV acceptance over time, from lower levels in the early years of BEVs, to the higher levels of BEV acceptance that we are currently

[49] The Global Change Analysis Model (GCAM) also uses the logit formulation to represent economic choice (GCAM n.d.) (Taylor 2023 (forthcoming)).

observing, and into the future, when BEV attributes will increasingly drive the purchase decision (Jackman, et al. 2023) as with ICE vehicles. Table 4-2 shows shareweight values for the No Action case and Proposal by body style for BEVs and for all body styles for ICE vehicles. Figure illustrates shareweight values for just BEVs by body style; shareweights for ICE vehicles are always 1 for all body styles.

Table 4-2: Central case shareweight values by body style for light-duty

	BEV			ICE
Calendar Year	**Sedans/Wagons**	**CUV/SUV**	**Pickups**	**All body styles**
2022	0.69	0.17	0.03	1.00
2023	0.77	0.22	0.04	1.00
2024	0.83	0.29	0.06	1.00
2025	0.88	0.37	0.08	1.00
2026	0.92	0.47	0.12	1.00
2027	0.94	0.61	0.17	1.00
2028	0.96	0.77	0.23	1.00
2029	0.97	0.92	0.31	1.00
2030	0.98	0.98	0.40	1.00
2031	0.99	1.00	0.50	1.00
2032	0.99	1.00	0.60	1.00
2033	0.99	1.00	0.69	1.00
2034	1.00	1.00	0.77	1.00
2035	1.00	1.00	0.83	1.00
2036	1.00	1.00	0.88	1.00
2037	1.00	1.00	0.92	1.00
2038	1.00	1.00	0.94	1.00
2039	1.00	1.00	0.96	1.00
2040	1.00	1.00	0.97	1.00
2041	1.00	1.00	0.98	1.00
2042	1.00	1.00	0.99	1.00
2043	1.00	1.00	0.99	1.00
2044	1.00	1.00	0.99	1.00
2045	1.00	1.00	1.00	1.00
2046	1.00	1.00	1.00	1.00
2047	1.00	1.00	1.00	1.00
2048	1.00	1.00	1.00	1.00
2049	1.00	1.00	1.00	1.00
2050	1.00	1.00	1.00	1.00

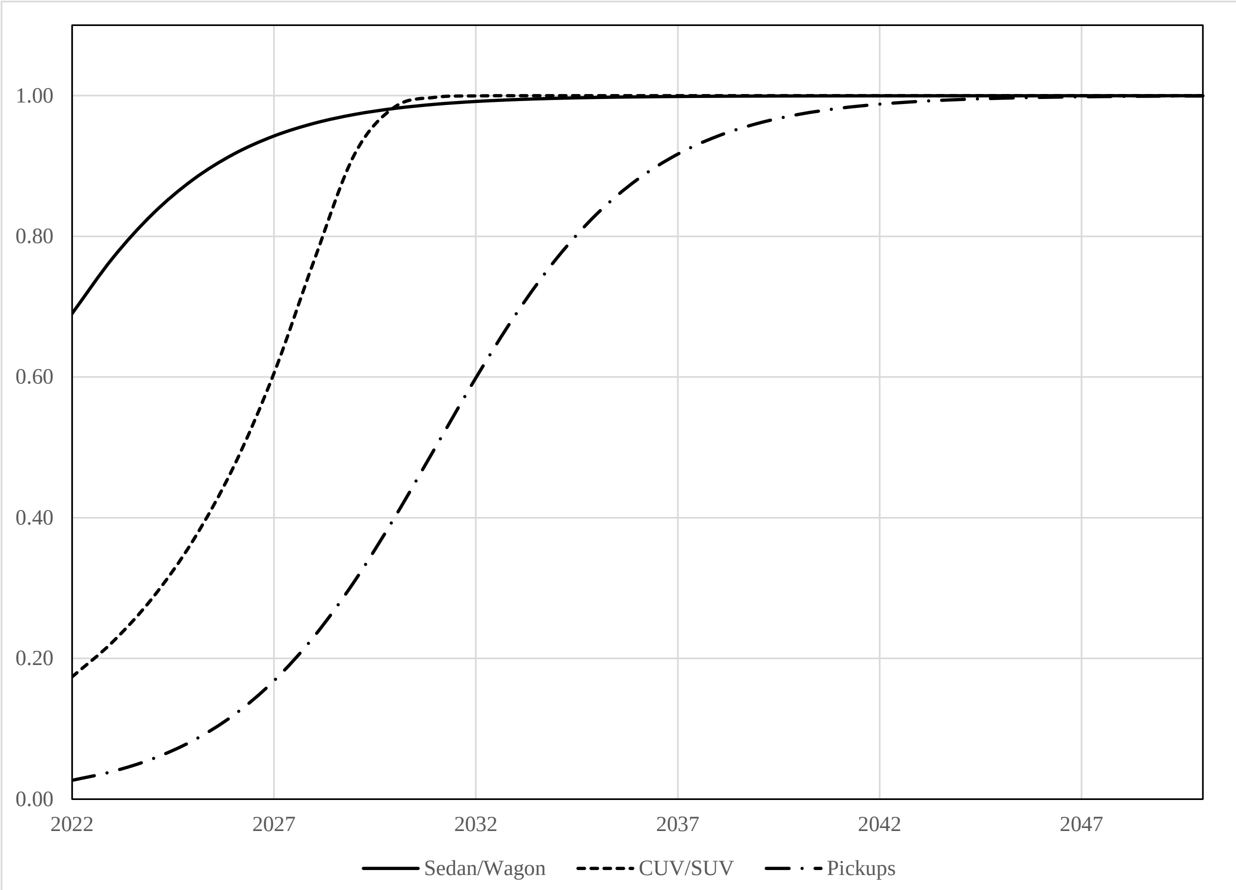

Figure 4-1: Central case shareweight values by body style for LD BEVs.

The BEV shareweights shown in Figure 4-1were developed by EPA as calibrated values using the generalized logistic form.[50] By calibrating shareweight values specifically for this analysis rather than, for example, using values directly from GCAM or other choice models, we are ensuring consistency with EPA's other modeling assumptions such as the projected state of ICE and BEV technologies, production constraints, consumer awareness, charging infrastructure, etc. Our approach to calibration involved determining the appropriate relative position of shareweights by body style, determining appropriate value bounds, and finally, appropriate absolute shareweight values.

We expect that the historical progression of market uptake of BEVs by body style that is already apparent in the market, will continue in the future. Beginning with sedans, then CUVs and SUVs, and followed by pickup trucks, we have accounted for this staggered timing of BEV acceptance by bodystyle by including a time difference between body styles at any given shareweight value. The resulting progression is seen as the gap between the shareweight curves moving from left to right along the horizontal axis in Figure 4-1.

[50] We use the generalized logistic form in the calibration of shareweights. Specifically, $Y(t) = \frac{K-A}{(C+Qe^{-Bt})^{1/\nu}}$, where t is time and $Y(t)$ is shareweight at time t.

We calibrated absolute shareweight values so that the overall BEV shares produced by the OMEGA model would align with an external projection of BEV sales published by IHS Markit (IHS Markit 2021). For calibration purposes, but unlike our Central case analysis, we included ZEV mandates in ACC2-adopting states consistent with consideration of state-level policies in the IHS Markit projection. Similarly, the calibration of shareweight values did not include the IRA BEV incentive provisions because the IHS Markit projections were made prior to the passage of the IRA. The calibration points (for MYs 2026 and 2030) and OMEGA results for the calibration case are shown in Figure 4-2.

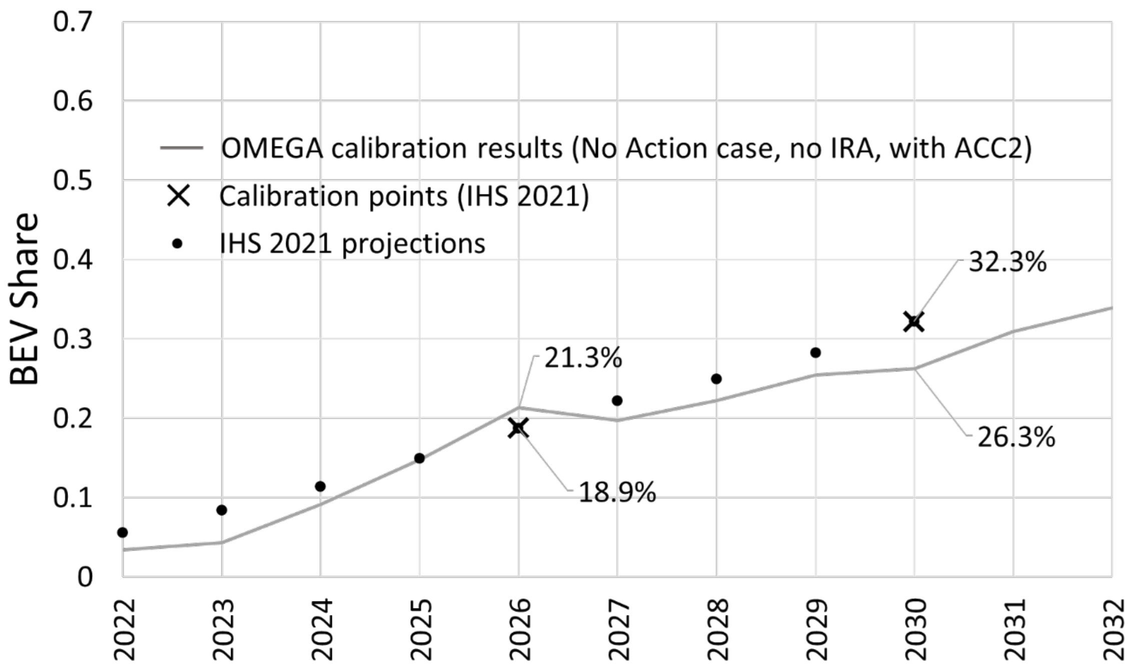

Figure 4-2: Calibration of No Action-No IRA case with ACC2 to third party projections.

As noted, the calibration of shareweights was based on projections made prior to the IRA being signed into law. We have assumed for this analysis that the while the IRA will incentivize BEVs for both vehicle manufacturers and consumers, the primary mechanisms of the incentive will be through lower BEV production costs and lower net price for consumers. We have not attempted to account for ways in which the IRA's influence on BEV penetration could, in turn, further increase consumer acceptance of BEVs at a given price, for example by increasing awareness of BEVs. In other words, for this analysis, we are treating shareweight values as exogenous to our policy assumptions. Therefore, we apply the same shareweight values for the Proposed Standards and all three Alternative cases. Similarly, with the exception of the two BEV Acceptance sensitivity cases, we use the same shareweight values for all Central case and remaining Sensitivity case analyses.

For clarity, Figure 4-3 shows BEV shares projected using the OMEGA model for the Central case, which does not include ACC2. Shares for the "No Action case, no IRA" are somewhat lower than shown in Figure 4-2 for the calibration case, which does include ACC2.

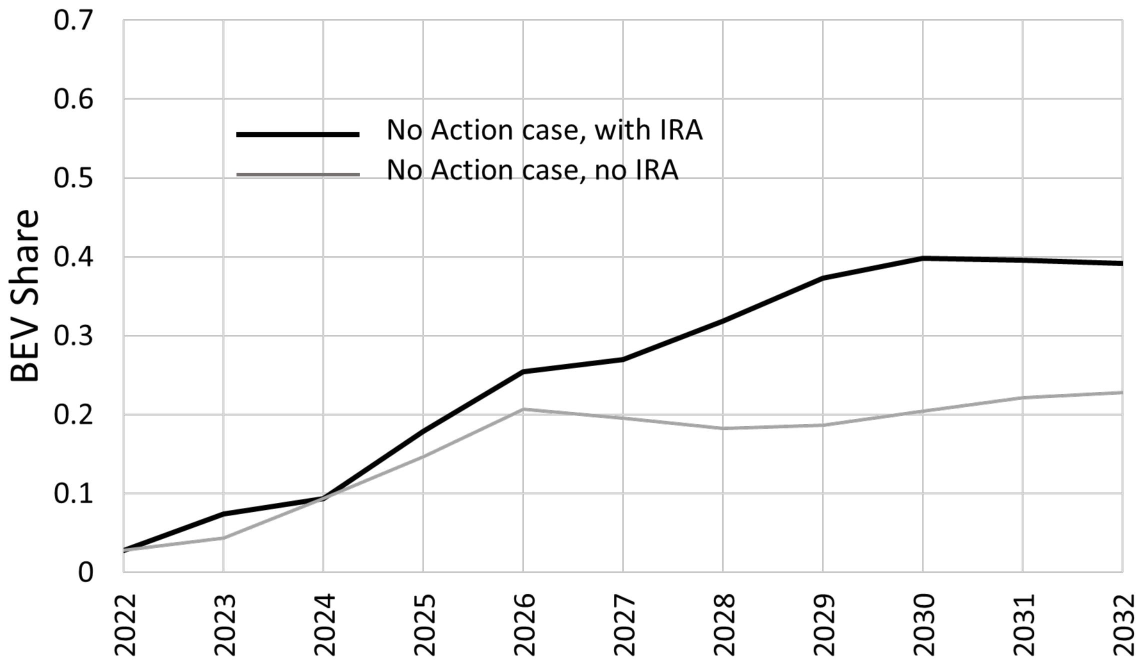

Figure 4-3: Comparison of BEV penetrations for No Action - No IRA and No Action - IRA cases, both without ACC2

Shareweights complete the weight calculations for BEVs and ICE vehicles (i.e., the second pair of equations in this section), and therefore, the calculation of BEV and ICE vehicle market shares (i.e., the first pair of equations in this section). Market shares are multiplied by total vehicle sales, per Chapter 4.4, to arrive at the OMEGA's estimate of BEV and ICE vehicle sales

4.1.3 Sensitivities

The shareweights used in the No Action case, Proposal, and Alternatives reflect the current state of the art in terms of the scientific literature on consumer acceptance of PEVs (Jackman, et al. 2023), existing policy-relevant models and modeling paradigms (Taylor 2023 (forthcoming)), and calibration to third party estimates as well as Congressional investments (e.g., BIL, IRA). We refer to those above shareweights as the Central case.

We acknowledge, however, that a very rapid transition to electric vehicles may be under way as appears to be reflected in the popular media. In a Faster BEV Acceptance case, BEV acceptance could rise very quickly and exceed acceptance of ICE vehicles by orders of magnitude. For sedans and wagons this could mean that, within just a few years BEV acceptance will match that of ICE vehicles. In other words, all else equal, a consumer is just as likely to choose a BEV as an ICE vehicle. In fact, recent evidence from suggests that BEVs may already be preferred, all else equal (Gillingham, et al. 2023). Specifically, Gillingham et al. (2023) examined all new LD vehicles sold in the U.S. between 2014 and 2020 and compared existing electric vehicles to their most similar ICE vehicle counterpart. They found that BEVs are preferred to the ICE counterpart in some segments. In addition, a survey from Consumer Reports in 2022 indicates that more than 70 percent of survey respondents felt that BEVs are as good or better than ICE vehicles, up from about 46 percent in 2017. (Bartlett 2022) Assuming more rapid BEV acceptance, BEV acceptance continues to rise notably through to 2032, at which time it tapers off at roughly three times that of ICE vehicles. CUVs, SUVS, and Pickups follow suit, lagging somewhat in timing and not reaching the same level of preference over ICE vehicles that sedans and wagons reach. Table 4-3 and Figure 4-4 show shareweights for faster BEV acceptance shareweight values by body style.

Table 4-3: Faster BEV acceptance shareweight values by body style for light-duty

Calendar Year	BEV Sedans/Wagons	BEV CUVs/SUVs	BEV Pickups	ICE Vehicle All body Styles
2022	0.72	0.24	0.05	1.00
2023	0.94	0.35	0.08	1.00
2024	1.19	0.50	0.11	1.00
2025	1.45	0.67	0.17	1.00
2026	1.70	0.88	0.24	1.00
2027	1.93	1.11	0.34	1.00
2028	2.14	1.35	0.46	1.00
2029	2.32	1.59	0.62	1.00
2030	2.47	1.81	0.80	1.00
2031	2.60	2.00	1.00	1.00
2032	2.69	2.17	1.20	1.00
2033	2.77	2.31	1.38	1.00
2034	2.82	2.42	1.54	1.00
2035	2.87	2.51	1.66	1.00
2036	2.90	2.58	1.76	1.00
2037	2.93	2.64	1.83	1.00
2038	2.95	2.68	1.89	1.00
2039	2.96	2.71	1.92	1.00
2040	2.97	2.73	1.95	1.00
2041	2.98	2.75	1.96	1.00
2042	2.98	2.76	1.98	1.00
2043	2.99	2.77	1.98	1.00
2044	2.99	2.78	1.99	1.00
2045	2.99	2.78	1.99	1.00
2046	2.99	2.79	2.00	1.00
2047	3.00	2.79	2.00	1.00
2048	3.00	2.79	2.00	1.00
2049	3.00	2.80	2.00	1.00
2050	3.00	2.80	2.00	1.00

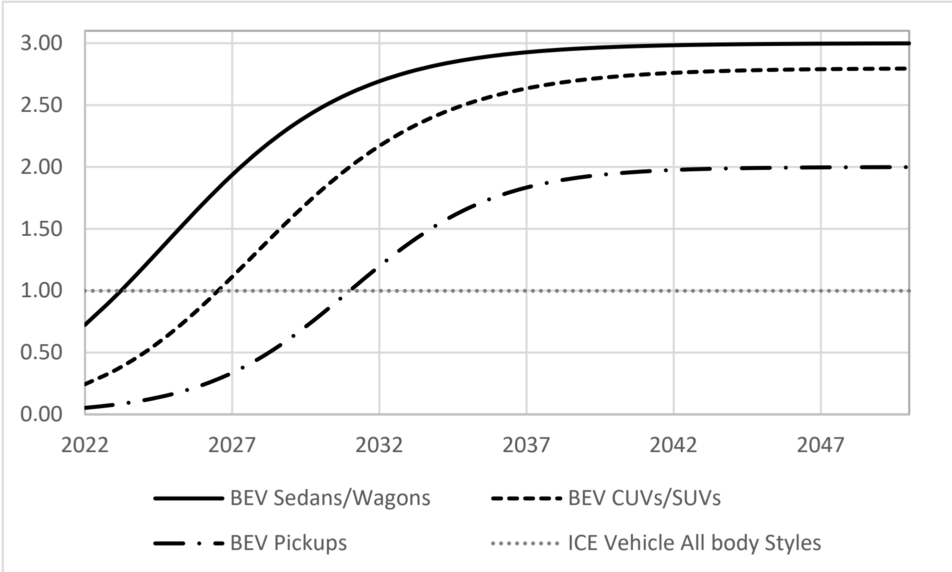

Figure 4-4: Faster BEV acceptance shareweight values by body style for light-duty

Though we believe it to be very unlikely given the thoroughness of the Central case and evidence of BEV acceptance discussed throughout this chapter, we acknowledge that BEV acceptance may be slower than characterized in the Central case. Jackman et al. (2023) discusses some of the issues new vehicle buyers might have with purchasing a PEV, such as lack of familiarity with PEVs and uncertainty about charging infrastructure. As we discuss in Chapter 5.3.1, we believe the large investments in charging infrastructure from the private sector and the U.S. government via the BIL and IRA will counter and resolve these uncertainties over time. Nevertheless, in characterizing slower acceptance, we assume that CUVs, SUVs, and Pickup trucks will be less preferred than ICE vehicles for a sizeable subset of the population, perhaps based on use cases like towing and/or remote locations. We also parametrize shareweights for sedan and wagons, CUVs and SUVs, and pickups so that acceptance begins to grow less rapidly in the early to mid-2030's, roughly coincident with the expiration of IRA producer and consumer incentives. Table 4-4 and Figure 4-5 show slower BEV acceptance shareweight values by body style for light-duty

Table 4-4: Slower BEV acceptance shareweight values by body style for light-duty

Calendar Year	BEV Sedans/Wagons	BEV CUVs/SUVs	BEV Pickups	ICE Vehicle All body Styles
2022	0.13	0.07	0.01	1.00
2023	0.16	0.09	0.02	1.00
2024	0.20	0.12	0.03	1.00
2025	0.24	0.15	0.04	1.00
2026	0.29	0.20	0.05	1.00
2027	0.35	0.25	0.07	1.00
2028	0.41	0.31	0.10	1.00
2029	0.48	0.38	0.13	1.00
2030	0.56	0.47	0.17	1.00
2031	0.63	0.55	0.21	1.00
2032	0.71	0.64	0.25	1.00
2033	0.77	0.71	0.29	1.00
2034	0.83	0.77	0.33	1.00
2035	0.88	0.81	0.37	1.00
2036	0.91	0.84	0.40	1.00
2037	0.94	0.87	0.43	1.00
2038	0.96	0.88	0.45	1.00
2039	0.97	0.89	0.46	1.00
2040	0.98	0.89	0.47	1.00
2041	0.99	0.90	0.48	1.00
2042	0.99	0.90	0.49	1.00
2043	0.99	0.90	0.49	1.00
2044	1.00	0.90	0.49	1.00
2045	1.00	0.90	0.49	1.00
2046	1.00	0.90	0.50	1.00
2047	1.00	0.90	0.50	1.00
2048	1.00	0.90	0.50	1.00
2049	1.00	0.90	0.50	1.00
2050	1.00	0.90	0.50	1.00

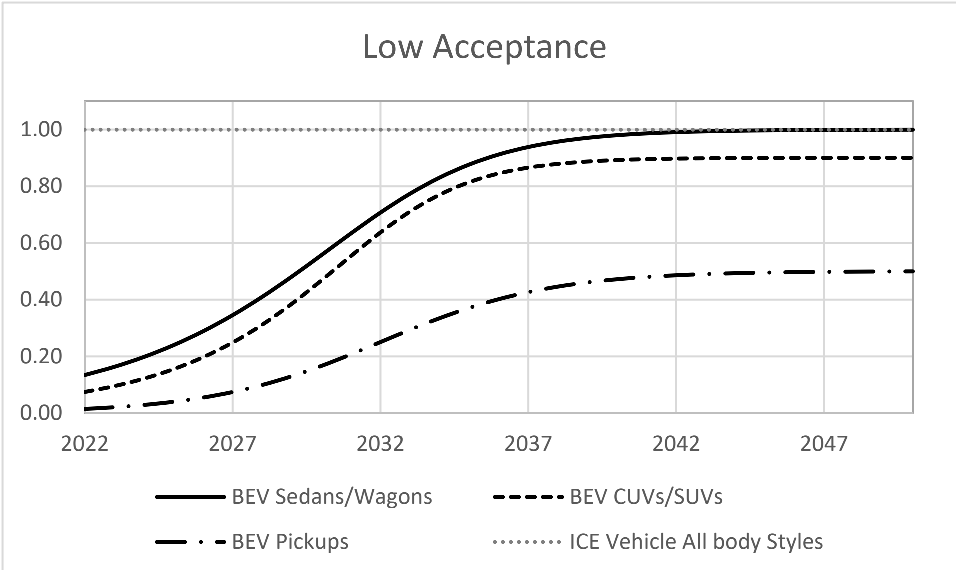

Figure 4-5: Slower BEV acceptance shareweight values by body style for light-duty

4.2 Ownership Experience

Having described how we model the consumer purchase decision in Chapter 4.1, we turn to the estimated effects of the proposed standards on individual consumers. In this section, we focus specifically on the ownership experience of vehicle consumers, including vehicle miles traveled and rebound effect, consumer savings and expenses, and other ownership considerations. A discussion of consumer-related social benefits and costs appears in Chapter 4.3.

4.2.1 Vehicle Miles Traveled and Rebound Effect

Critical to estimating the impacts of emissions standards is the number of vehicle miles traveled (VMT). In the 2021 rulemaking, as well as in this proposed rule, we acknowledge that individual vehicle miles vary. (U.S. EPA 2021) However, in our analyses, aggregate vehicle miles are determined exogenously (see DRIA Chapter 9 for details). While measures and estimates of VMT for ICE vehicles is well-established in previous EPA LD rules, and described in DRIA Chapter 9, how much consumers drive their BEVs has been changing as the technology evolves and BEV become more common. Thus, in the following discussion, we give particular attention to electric vehicle miles traveled (eVMT).

The rebound effect is the means by which aggregate VMT is influenced by the policy alternatives. The rebound effect generally refers to the additional energy consumption that may arise from the introduction of a more efficient, lower cost energy service. Previous rules incorporated the rebound effect based on changes in fuel cost per mile, without distinguishing between vehicles with different fuel sources. With the growing number of battery electric vehicles, we acknowledge that rebound may differ for BEVs and ICE vehicles. To clarify the following discussion, we define rebound separately for ICE vehicles and for PEVs. We name them combustion rebound and electric rebound, respectively. Whether a mile is a combustion mile or electric mile is determined by the energy source that generates the mile, not necessarily by the vehicle type. PHEVs, for example, produce both combustion and electric miles, BEVs produce only electric miles, and ICE vehicles produce only combustion miles.[51] Combustion rebound is defined as above, namely as the additional miles traveled as a result of increased vehicle fuel efficiency and the consequent lower cost per mile of driving. For combustion rebound, "fuel efficiency" refers specifically to liquid fuels. Electric rebound is also defined as the additional miles traveled as a result the lower cost per mile of driving due to reduced energy intensity (kWh/mi).

Importantly, the rebound effect offsets, to some degree, the energy savings benefits of efficiency improvements. Because rebound driving consumes fuel and generates emissions, the magnitude of the rebound effect influences actual fuel savings and emission reductions that will result from the standards. Furthermore, rebound driving provides value to the consumer if they choose to drive more. We discuss these costs and benefits in Chapter 4.3, and in Section VIII of the Preamble. In this chapter, we address miles driven and rebound.

4.2.1.1 Basis for Vehicle Miles Traveled for Battery Electric Vehicles

The eVMT literature consists of a handful of studies, including the very recent studies listed in Table 4-5. Two of the listed studies are based on California data collected by UC Davis researchers, and both find that annual VMT for PEVs (eVMT) is similar to annual VMT for ICE vehicles (Chakraborty et al. 2022; Raghavan and Tal 2021). The three other studies, using New York, California, and national data, find that annual VMT for PEVs is less than annual VMT for ICE vehicles (Nehiba 2022) (Burlig, et al. 2021) (Davis 2019).[52] These studies offer a similar summary of the scarce pre-existing data and research related to eVMT in the U.S. Namely, though lower cost per mile has historically been associated with more driving, this has not been observed for PEVs, for which the cost of driving per miles is lower than for ICE vehicles.[53] Instead, average annual VMT for PEVs has historically been estimated to be lower than for ICE vehicles. This observation has been attributed to the shorter range of first generation PEVs, typically less than 100 miles just five or six years ago, as well as to substitution across vehicles for multiple vehicle households, and to the typical type of households who bought an electric vehicle in the time frame of the data (Chakraborty, Hardman and Tal 2022) (Davis 2022) (Raghavan and Tal 2021) (Davis 2019), that is, households with characteristics correlated with lower VMT regardless of vehicle technology (Chakraborty, Hardman and Tal 2022). This area of research continues to face several challenges including the relatively low market penetration and uneven distribution of PEVs; the rapid evolution of PEV technology and the PEV market; and the relative difficulty in obtaining comprehensive data on how PEVs are driven (Burlig, et al. 2021) (Chakraborty, Hardman and Tal 2022) (Nehiba 2022) (Jackman, et al. 2023). As a result, the data that are available for empirical analyses are not likely representative of the current and future general population of car buyers and their driving behavior.

Table 4-5: Recent scientific studies of eVMT

Study	Average Annual Electric VMT Results	Data Description

[51] Similarly, Raghavan and Tal (2021) define eVMT "as the miles driven by off-board grid electricity." Relatedly, the fraction of VMT electrified using off-board electricity is the utility factor (UT).

[52] (Nehiba 2022) notes that forthcoming work from K. Gillingham, B. Spiller, and M. Talevi finds "similar levels of BEV mileage and a common trend of increasing mileage across model years" for vehicles in Massachusetts.

[53] See Chapter 11.2.3 of this DRIA, which compares fueling costs for PEVs and ICE vehicles within its discussion of energy security.

(Chakraborty, Hardman and Tal 2022)	“Overall, we observe that factors influencing PEV VMT are like those observed for conventional gasoline vehicles. We find that PEVs drive a similar amount as conventional vehicles, not less ... as some have suggested.”	Location: California Years: 2015-2019 Sources: Two surveys with reported odometer readings and on-board recorders Number of PEVs: 16,736 (survey) and 369 (on board recorders)
(Raghavan and Tal 2021)	Average annual eVMT by vehicle model ranged from 10,841 for the Nissan Leaf to 17,236 for the Tesla Model S with 80kWh battery capacity.	Location: California Years: 2015 (survey and logger), 2017 (survey only), 2019 (logger only) Sources: GPS loggers on vehicles in two-car households and online survey Number of households: 73
(Nehiba 2022)	“The average BEV in New York is driven 9,060 miles/year, substantially less than the 10,910 miles/year average for all passenger cars and light truck s in New York in 2019 … However BEV vehicle miles increased rapidly across vehicle model years, suggesting that BEV and … ICEV mileage may be converging.”	Location: New York Years: January 2017 – January 2021 Sources: Annual vehicle safety inspection odometer readings; residential and residential electricity prices matched by zip code
(Burlig, et al. 2021)	“ … our estimates [of overall household electricity load around EV registration events] indicate that EV load in California is surprisingly low. … Given the fleet of EVs in our sample, and correcting for the share of out-of-home charging, our estimates translate to approximately 1,700 electric vehicle miles traveled (eVMT) per year for plug-in hybrid EVs (PHEVs) and 6,700 eVMT per year for battery EVs (BEVs). These eVMT values are substantially less than internal combustion engine (ICE) VMT.”	Location: California Year: 2014-2017 Sources: 10 percent of residential electricity meters in the Pacific Gas and Electric (PG&E) utility territory (362,945 households) merged with EV registration records (63,765 vehicles) Number of PEVs: 57,290
(Davis 2019)	“These data show that electric vehicles are driven considerably less on average than gasoline- and diesel-powered vehicles. In the complete sample, electric vehicles are driven an average of 7,000 miles per year, compared to 10,200 for gasoline and diesel-powered vehicles. The difference is highly statistically significant and holds for both all-electric and plug-in hybrid vehicles, for both single- and multiple-vehicle households, and both inside and outside California.”	Name: 2017 National Household Travel Survey Location: United States Year: 2017 Source: Survey with reported annual vehicle miles Number of PEVs: 862

Based on these study results and the transparency with which they communicate data limitations, there is no evidence that PEVs are driven more than ICE vehicles, and study results conflict regarding whether annual eVMT is less for PEVs. EPA concludes that the existing empirical evidence does not support the conclusion that average annual eVMT differs from annual VMT for ICE vehicles. Therefore, EPA analyses use the same annual VMT for PEVs and ICE vehicles in the No Action case.

4.2.1.2 Basis for the Rebound Effect for Internal Combustion Engines

In the 2021 rule, EPA provided a summary of the historical and recent literature on the light-duty (LD) vehicle rebound effect, the ways it is defined (e.g., direct, indirect, economy-wide, short- to medium-run, long-run), how it is estimated, and the basis for the rebound effect used for internal combustion engine vehicles (ICE vehicles). Based on that review and assessment of studies of the LD rebound effect, EPA used a single point estimate of 10 percent for the direct, short- to medium-run rebound effect for ICE vehicles in the 2021 rule. In this current rule, EPA is again using a value of 10 percent as an input to the agency's analyses for the direct, short- to medium-run rebound effect for ICE vehicles. We refer the reader to RIA Chapter 3, and Preamble Section 1 of the 2021 rule for the full discussion of the rebound effect and the point estimate used. (U.S. EPA 2021)

4.2.1.3 Basis for Rebound Effect for Battery Electric Vehicles

As described briefly above, the rebound effect for BEVs is the additional miles traveled as a result of increased vehicle fuel efficiency and the consequent lower cost per mile of driving. As with ICE vehicles, it is estimated via the relationship between VMT and fuel price (i.e., an elasticity), specifically the response of eVMT to changes in electricity price. If we extrapolate the ICE VMT rebound literature to PEVs, we expect eVMT to rise (decline) in response to reductions (increases) in electricity price. EPA identified two current studies that estimate an eVMT rebound effect in the U.S., which we list in Table 4-6. Using data gathered from California PEV drivers, Chakraborty, Hardman, and Tal (2022) find no evidence of an eVMT rebound effect. Nehiba (2022) finds a rebound effect of 10 percent in an analysis of the "entire BEV population in New York."[54] Nehiba (2022) also finds that the responsiveness of eVMT to electricity prices "falls as public charging stations – where prices are often decoupled from electricity costs – become available," which may signal that conventional approaches to estimating rebound for ICE vehicles may not be sufficient for eVMT rebound.[55]

[54] Note that while we include Nehiba (2022) in our revies of the scientific literature regarding eVMT rebound, Nehiba (2022) is a working paper; by definition, it is a work in progress that to our knowledge has not been subject to formal peer review.

[55] For estimating PEV VMT and eVMT rebound, Davis (2022) and Raghavan and Tal (2021) both note the potential importance of understanding the substitution across vehicles in households with both an ICE vehicle and a PEV. They also note that BEV utilization in multi-vehicle household has scarcely been studied even though 89% of households with an EV also had a non-electric vehicle according to the 2017 National Household Travel Survey.

Table 4-6: Recent scientific studies of eVMT rebound

Study	Electric Rebound Results	Data
(Chakraborty, Hardman and Tal 2022)	"Moreover, while lower electricity price at home may lead to a higher share of PEV VMT in total household VMT, we do not identify the presence of 'rebound effect'."	Location: California Years: 2015-2019 Sources: Two surveys with reported odometer readings and on-board recorders Number of PEVs: 16,736 (survey) and 369 (on board recorders)
(Nehiba 2022)	"A 10% increase in per mile [residential] electricity costs reduces mileage by 1%," but "BEV drivers become less responsive to residential prices when public charging stations … become available."	Location: New York Years: January 2017 – January 2021 Sources: Annual vehicle safety inspection odometer readings; residential and residential electricity prices matched by zip code

Given the estimates of eVMT rebound provided by Chakraborty et al. (2022) and Nehiba (2022), we are left with only two research-based hypotheses: eVMT rebound is 0 percent or eVMT rebound is 10 percent, the same VMT rebound as for ICE vehicles. Given the historical evidence that BEVs are not driven more than ICE vehicles, EPA assumes no eVMT rebound in our analyses.

4.2.2 Consumer Savings and Expenses

Over time, the price of the average new vehicle has risen as producers shift business models toward larger and more expensive vehicles and as vehicles become safer, more durable, and less polluting. Based on the proposed standards, we project that on average, vehicle technology costs will increase by $1,200 (See Preamble Section VI.B and Chapter 10 of the DRIA). This increase in production costs reflects modest advancements in ICE vehicle technology as well as substantial increases in BEV market share (See Preamble Section IV.D.).

Specifically, consumer uptake of zero-emission vehicle technology is expected to continue to grow with increasing market presence, more model choices, expanding infrastructure, and decreasing costs to consumers. First, annual sales of LD PEVs in the U.S. have grown robustly and are expected to continue to grow. This history of robust growth, combined with vehicle manufacturers' plans to expand of PEV production, strongly suggests that PEV market share will continue to grow rapidly. Second, the number of PEV models available to consumers is increasingly meeting consumer demand for a variety of body styles and price points. Specifically, the number of BEV and PHEV models available for sale in the U.S. has more than doubled from about 24 in MY 2015 to about 60 in MY 2021, with offerings in a growing range of vehicle segments (U.S. DOE and U.S. EPA 2015) (U.S. DOE and U.S. EPA 2021). Recent model announcements indicate that this number will increase to more than 80 models by MY 2023 (M.J. Bradley and Assoc. 2021), and more than 180 models by 2025 (ERM 2022). Third, the expansion of charging infrastructure appears to have kept up with PEV adoption (See DRIA Chapter 5.3). This trend is expected to continue, particularly in light of very large public and private investments (See Chapter 5.3). Lastly, as the cost of batteries falls, PEV production rises (ERM 2022), and purchase incentives, such as the Inflation Reduction Act Clean Vehicle Credit, become available, PEV purchase prices are dropping. Among the many studies that address cost parity, an emerging consensus suggests that purchase price parity is likely to be achievable by the mid-2020s for some vehicle segments and models, and total cost of ownership (TCO) parity even sooner for a broader segment of the market (Slowik, et al. (ERM 2022) (Burnham, Gohlke, et al. 2021).

Given the trends described above, the following provides a summary of estimated consumer savings and expenses experienced by individual new vehicle owners of BEVs and ICEVs for three body styles – sedans and wagons, CUVs and SUVs, and pickups. Specifically, we provide OMEGA estimated national average individual vehicle ownership savings and expenses associated with new model year 2032 BEVs and ICEVs. We also provide information from other sources, as indicated in Table 4-7. Consistent with OMEGA and EPA's benefit cost analysis, the EPA estimated dollar amounts are given in 2020 dollars (2020$) with no discounting. Other dollar amounts are consistent with original sources and noted. Further, we calculate averages over the first 8 years of vehicle life. This coincides with the timeframe of EPA OMEGA modeling and is the current average amount of time the first owner has possession of the vehicle (Blackley n.d.) (Autolist 2022).[56,57]

Table 4-7 groups savings and expenses based on whether they occur with vehicle purchase (i.e., upfront), reoccur (i.e., average annual), or represent an optional, one-time household investment (i.e., one-time optional). For upfront purchase-related items and one-time household investments, we present the full amounts. For recurring savings and expenses, we present average annual, undiscounted amounts over the first 8 years of vehicle life. Many line items are drawn from EPA OMEGA modeling. Others are drawn from the scientific literature. All sources are noted.

Importantly, Table 4-7 represents a subset of ownership savings, expenses, incentives, and investments that meet the following criteria: evidence demonstrates that dollar amounts differ for BEVs and ICEVs, the dollar amounts can reasonably be expected to be experienced by buyers of MY 2032 vehicles; data and generally accepted conventions exist to estimate reasonably precise quantities; and bounds on uncertainty can be established. These criteria imply the exclusion of savings and expenses that vary substantially across individuals and/or locations and can be calculated for a specific person or place based on information in the table and other readily available information. Furthermore, this discussion should not be

[56] The average vehicle ages at which original owners sell their cars, SUVs, and pickup trucks were 8.4, 8.3 and 8.7 years, respectively, according to a study conducted by iSeeCars.com. “iSeeCars.com analyzed more than 5 million 5-year-old or older used cars sold by their original owners between Jan. 1, 2014 and Dec. 31, 2018. Models which were owned for less than 5 years were excluded from the analysis, to eliminate the effect of short lease terms on the data. Models that were in production for less than 9 of the 10 most recent model years (2010 to 2019), heavy-duty trucks and vans, and models no longer in production as of the 2019 or 2020 model years were also removed from further analysis. The average age of each vehicle, defined as nameplate + bodystyle, was mathematically modeled using the ages of cars when they were first listed for sale” (Blackley n.d.). In contrast, Argonne National Laboratories (Burnham, Gohlke, et al. 2021, 116) state that the typical period of initial ownership is “approximately 5 years” without citation.

[57] According to S&P Global, the average age of vehicles on U.S. roadways is approximately 12 years (S&P Global Mobility 2021). Argonne National Laboratory “analyzed survivability rates from data published by the National Highway Traffic Safety Administration (NHTSA) of the U.S. Department of Transportation (Lu 2006) and by the EPA (EPA 2016), finding the average lifetime of a vehicle in the United States was approximately 14 years in 2006 and just under 16 years in 2016” (Burnham, Gohlke, et al. 2021, 24).

interpreted as a "total cost of ownership" analysis but as a summary of MY2032 vehicle expenses and savings across body styles and powertrains under the proposed standards that fit the above criteria.[58] Lastly, these consumer ownership savings and expenses should not be confused with the societal costs and benefits that appear in Chapter 4.3 and DRIA Chapter 10.

The sources of the expenses and savings that are included in Table 4-7 are listed below:

- Purchase Price – EPA OMEGA modeled average retail price. OMEGA first estimates the cost to the manufacturer to produce a given vehicle. Then, the model performs an iterative search where the Producer offers different combinations of ICEV and BEV shares and levels of cross-subsidization between BEV and ICE vehicles until the Consumer and Producer are in agreement for vehicle shares and price. The resulting prices are defined by the sum of the marked-up vehicle production costs and any internal cross-subsidies applied by the model. This resulting price, representing a retail price, is the value shown in the table.

- Federal Purchase Incentive – Maximum potential consumer purchase incentive provided via the Inflation Reduction Act ($7,500). The actual purchase incentive any given consumer might receive is based on several eligibility requirements for the consumer and the actual vehicle. This is a savings for consumers and appears as a negative value in Table 4-7.

- Vehicle Miles – EPA OMEGA estimated national average annual per vehicle miles traveled.

- Retail Fuel – EPA OMEGA estimated national average annual per vehicle fuel expense.

- Refueling Time – EPA OMEGA estimated and monetized national average annual per vehicle refueling time. See Chapter 4.3.5 below for procedure for estimating and monetizing refueling time.

- Maintenance – EPA OMEGA estimated national average annual maintenance expenses.

- Repair – EPA OMEGA estimated national average annual repair expenses.

- Registration – National average annual vehicle registration fee according to Burnham, Gohkle, et al. (2021) is $68 for ICE vehicles. The additional national average fee is $73 for BEVs, totaling to $141 for BEVs.

[58] Argonne National Laboratory provides a comprehensive and recent summary of total cost of ownership (TCO) of vehicles, which includes a review of other TCO studies (Burnham, Gohlke, et al. 2021). Total costs of ownership analyses typically aim to provide a full accounting of ownership costs rather than fitting the criteria specified here.

- Residential Charging Equipment & Installation – National estimated range of expenses associated with home charging equipment and installation. In Chapter 5.3 of the DRIA, we provide a description and summary of charging infrastructure investments, including home charging.

Table 4-7: National per vehicle ownership savings and expenses for new model year 2032 vehicles under the proposed standards (2020 dollars)

	Sedan/Wagon	**CUV/SUV**	**Pickup**			
	BEV (Electric)	**ICEV (Gasoline)**	**BEV (Electric)**	**ICEV (Gasoline)**	**BEV (Electric)**	**ICEV (Gasoline)**
Upfront Purchase Related Expenses and (Savings)						
Purchase Price[a] (2020$)	34,100	28,900	42,100	35,000	46,700	43,200
Maximum Federal Purchase Incentive (2020$)	(7,500)	-	(7,500)	-	(7,500)	-
Net Purchase Price (2020$)	26,600	28,900	34,600	35,000	39,200	43,200
Annual Eight-Year Average Expenses and (Savings)						
Vehicle Miles[a] (miles/year)	15,700	15,700	16,300	16,300	17,700	17,800
Retail Fuel[a] (2020$/year)	520	1,350	690	1,720	980	2,250
Refueling Time[a] (2020$/year)	110	50	160	70	140	80
Maintenance[a] (2020$/year)	550	870	590	940	700	1,100
Repair[a] (2020$/year)	400	510	290	390	240	310
Registration[b] (2019$/year)	140	70	140	70	140	70
Total Average Annual Expenses ($/year)	1,720	2,850	1,870	3,190	2,200	3,810
Optional One-Time Investment						
Residential Charging Equipment & Installation[c] (2019$)	0-3,700	-	0-3,700	-	0-3,700	-
a Per OMEGA. b Per Burnham, Gohlke, et al. (2021). c Per DRIA Chapter 5.3.						

In the above table, when comparing new BEVs and ICE vehicles within body style, we make several important observations. First, on average, net purchase expenses are lowest across all body styles for BEVs, assuming the maximum Federal purchase incentive of $7,500 available on vehicles at this price point.[59] Second, on average, BEV owners save on fuel, maintenance, and repair when compared to ICE vehicles buyers, roughly $1,100 per year for sedans and wagons, $1,300 per year for CUVs and SUVs, and $1,600 per year for pickups. In contrast, the average annual registration fees for BEVs are larger on average than for ICE vehicles, and time spent fueling a BEV requires a few more hours per year on average than fueling ICE vehicles (monetized in Table 4-7). However, registration fees and refueling time are small compared to other ownership expense.

In the above table we also show a range of investments into residential charging equipment and installation. Importantly, home charging is not required for BEV ownership, and charging at home is feasible via a standard 120 volt outlet (aka Level 1 which delivers 2 to 5 miles of range per hour) or 240 volt outlet (Level 2 which delivers 10 to 20 or more miles of range per hour) ((Borlaug, et al. 2020) citing (U.S. Department of Energy (DOE) 2020)). In some cases, additional equipment or upgrades for vehicle charging may not be needed.[60] Charging at home does deliver convenience. It very likely reduces time spent actively charging, as well as the time-associated expense, since charging occurs when the vehicle is parked. In fact, Level 2 charging at home has been shown to be associated with PEV continuance, that is, purchasing a PEV after relinquishing a previous PEV (Hardman and Tal 2021). When electrical upgrades are desired, home charging equipment and installation costs differ from one household to the next based, primarily on housing type (e.g., detached, attached, apartment) and type of upgrade required (e.g., none, outlet upgrade, charger upgrade). Thus, the table provides a range described in Chapter 5 of this DRIA, though national average estimates are available. For example, Nichols (2019) estimates that Level 1 investments typically range from $400 to $900, and Level 2 investments typically range from $680 to $4,100 (Nicholas 2019, 6). Borlaug et al. (2020) estimate median capital costs for residential Level 2 charging equipment and installation to be $1,836 (Borlaug, et al. 2020).[61] Bauer et al. (2021) show per electric vehicle estimate for home charging to be $850.

Consumers who chose to purchase a new MY 2032 BEV instead of an ICE vehicle save between $1,100 and $1,600 at the time of purchase and between $9,000 and $13,000 on operating expenses over the first 8 years of vehicle life. Those savings, summarized in Table 4-8, are substantial and would be experienced by a BEV owner whether or not they considered that savings at the time of purchase.

Table 4-8: Estimated average savings over the first 8 years of vehicle life when MY 2032 BEV purchased instead of ICE vehicle (2020 dollars)

[59] For new vehicles, the maximum Federal purchase incentive of $7,500 is available on cars priced up to $55,000 and on vans, SUVs, and pickups up to $80,000 depending on the buyer's income. For used vehicles, the maximum Federal purchase incentive of $4,000 is available on vehicles priced up to $25,000 depending on the buyer's income.
[60] The ability to charge at home with at most behavior modification (i.e., electrical access with [at most] behavior modification) varies among individual households with patterns emerging among housing types and between owners and renters. The National Renewable Energy Laboratory (NREL) estimates home charging is currently feasible without any upgrades (i.e., no cost) for 28 to 72% of single dwelling structures (i.e., attached and detached single family and mobile homes) and for 11 – 40% of multiple dwelling structures (i.e., apartments) (Ge, et al. 2021).
[61] Using a different metric, the levelized cost of charging (LCOC), Bourlag, Salisbury, Gerdes, and Muratori (2020) estimate that "an upgrade to [Level 2] for residential charging adds more than $0.04/kWh to the cost to charge when levelized over a 15 year period (a 37% increase compared to use of [Level 1])"

	Sedan/ Wagon	CUV/SUV	Pickup
Savings on Net Purchase Price Including Maximum Purchase Incentive	2,300	400	4,000
8 -year Operating Savings	9,040	10,560	12,880
Residential Charging Expense	0 - 3,700	0 - 3,700	0 - 3,700
Total Savings with Max Residential Charging Expense	7,640	7,260	13,180
Total Savings without Residential Charging Expense	11,340	10,960	16,880

In concluding this summary of consumer savings and expenses for new MY2032, we again note that this is not a total costs analysis. According to the criteria that we specified above, we have excluded expenses that consumers customarily incur that are typically included in a total cost of ownership analysis. For example, we exclude vehicle sales tax and property tax since these quantities depend on the value of the vehicle and vary across locations. A national average, though meaningful in a total costs analysis for some audiences,[62] is not sufficiently precise to be useful for a given individual and instead can be calculated for a specific person based on readily available information. For similar reasons, we acknowledge but exclude cost associated with financing. While many buyers finance, loan principle, interest rate, and loan period differ substantially across individuals. We also exclude regional-, state- and local-level monetary purchase incentives as well as other regional-, state- and local-level monetary and non-monetary, “perks”/policies associated with PEV ownership. Regional-, state-, and local-level incentives and policies take many forms across the U.S., differing in source (e.g., governments, utilities), amount, and eligibility (Wakefield 2023) (Bui, Slowik and Lutsey 2020) (Greschak, Kreider and Legault 2022), and some may not persist into the timeframe represented in Table 4-7. Lastly, we exclude insurance and depreciation as recent evidence shows that these are quite similar for similarly valued BEVs and ICE vehicles.

4.2.3 Other Ownership Considerations

In addition to ownership savings and expenses experienced under the proposed standard provided above in Chapter 4.2.24.2.2 and impacts of the proposed standards on consumers quantified in benefit costs analysis below in Chapter 4.3 and in Chapter 10, we also consider the effects of the proposed standards on low-income households and on consumers of low-priced new vehicles and used vehicles. These effects depend, in large part, on countervailing elements of vehicle ownership experience under the proposed standards, namely a) higher up front, net purchase prices,[63] b) net fuel savings,[64] and c) maintenance and repair. The net effect varies across households and as demonstrated above across vehicle types. However, net fuel savings may be especially relevant for low-income households and consumers in the used and low-priced new vehicle markets. First, fuel, maintenance, and repair expenditures are a larger portion of expenses for low-income households compared to higher income households (Hardman,

[62] Burnham et al. (2021, 8-14) provide an excellent summary and critique of "literature related to a holistic TCO calculation" as well as their own comprehensive analysis.
[63] Per vehicle compliance costs are $1,400 including IRA producer incentives (See Chapter 13).
[64] By net fuel savings, we are referring to fuel costs and time spent refueling.

Fleming, et al. 2021).[65] Second, lower-priced new vehicles have historically been more fuel efficient. Third, fuel economy, and therefore fuel savings, do not decline as vehicles age even though the price paid for vehicles typically declines as vehicles age and are resold. Fourth, low-income households are more likely to purchase lower-priced new vehicles and used vehicles (Hutchens, et al. 2021).

Additionally, BEV purchase incentives are available for new and used vehicles. For new vehicles, the maximum Federal purchase incentive of $7,500 is available on cars priced up to $55,000 and on vans, SUVs, and pickups up to $80,000 depending on the buyer's income. For used vehicles, the maximum Federal purchase incentive of $4,000 is available on vehicles priced up to $25,000 depending on buyer's income. Lower priced new vehicles and many used vehicles meet the criteria for the maximum incentive and low-income buyers are more likely, by definition, to qualify for maximum incentives. Furthermore, the IRA purchase incentives for BEVs not only lowers the net purchase price, in some cases, the net price of some BEVs will be lower than that of comparable ICE vehicles, as demonstrated in Chapter 4.2.2. Finally, we also show that maintenance and repair costs for BEVs are lower than that of comparable ICE vehicles, also demonstrated in Chapter 4.2.2 above and Chapter 4.3 below. (See also DRIA Chapter 11.2.3.1).

Furthermore, most vehicle consumers finance, making access to credit for vehicle purchases essential. The ability to finance may be of particular concern for low-income households. As above, the effects of the standards on access to credit is influenced by the potentially countervailing forces of vehicle purchase and other ownership costs. However, the degree of influence and the net effect is not clear (See Chapter 8.4 of the 2021 rule). Increased purchase price and presumably higher loan principal may, in some cases, discourage lending, while reduced fuel costs may, in some cases, improve lenders' perceptions of borrowers' repayment reliability.

Finally, while access to conventional fuels can be assumed for the most part, the number and density of charging stations varies considerably (U.S. Department of Energy 2022). The expansion of public and private charging infrastructure has been keeping up with PEV adoption and is generally expected to continue to grow, particularly in light of very large public and private investments (See DRIA Chapter 5) and local level priorities (Bui, Slowik and Lutsey 2020) (Greschak, Kreider and Legault 2022). This includes home charging events, which are likely to continue to grow with PEV adoption but are also expected to represent a declining proportion charging events as PEV share increases (Ge, et al. 2021). Thus, publicly accessible charging is an important consideration, especially among renters and residents of multi-family dwellings and others who charge away from home (Consumer Reports 2022). Households without access to charging at home or the workplace will likely incur additional charging costs. Thus, among consumers who rely upon public charging, the higher price of public charging is especially important. Please see Chapter 5 of this DRIA for a more detailed discussion of public and private investments in charging infrastructure, and our assessment of infrastructure needs and costs under this proposal. See also, Chapter 4.2.2 for information on home charging

[65] In the U.S., according to (Hardman, Fleming, et al. 2021), the lowest income households spend 11.2 percent of their annual income on fuel, maintenance, and repairs of vehicles compared to all other households that spend 4.5 percent of their annual income on these expenses.

equipment and installation costs as well as Chapter 11.2.3.1 for a discussion of charging and home charging installation for low-income households.

4.3 Consumer-Related Social Benefits and Costs

4.3.1 Vehicle Technology Cost Impacts

Table 4-9 shows the estimated annual vehicle technology costs of the proposal and each alternative, estimated in OMEGA, for the indicated calendar years (CY). The table also shows the present-values (PV) of those costs and the equivalent annualized values (EAV) for the calendar years 2027–2055 using both 3 percent and 7 percent discount rates.[66]

Table 4-9: Vehicle technology costs, light-duty and medium-duty (billions of 2020 dollars)

Calendar Year	Proposal	Alternative 1	Alternative 2	Alternative 3
2027	7.5	7.9	5.5	2.6
2028	6.8	10	5	2.3
2029	6.6	14	5.8	1.8
2030	8.7	17	6.1	4.9
2031	13	20	11	12
2032	17	23	15	18
2035	22	24	17	24
2040	19	20	15	18
2045	13	13	10	13
2050	12	13	10	12
2055	10	11	8.8	11
PV3	280	330	230	270
PV7	180	220	140	170
EAV3	15	17	12	14
EAV7	15	18	12	14

We expect the technology costs of the program will result in a rise in the average purchase prices for consumers, for both new and used vehicles. While we expect that vehicle manufacturers will strategically price vehicles (e.g., subsidizing a lower price for some vehicles with a higher price for others), we assume in our modeling that increased vehicle technology costs will be fully reflected in higher average purchase prices paid by consumers. Note that these technology cost increases are offset by fuel, maintenance and repair costs, discussed in Chapter 4.3.4 and Chapter 4.3.6.

4.3.2 Value of Rebound Driving

As discussed above, the assumed rebound effect might occur when an increase in vehicle fuel efficiency leads people to choose to drive more because of the lower cost per mile of driving. When we estimate fuel expenditures, we multiply the number of miles driven on a given fuel by its price per unit, i.e., dollars per gallon for liquid fuels and dollars per kWh for electricity. Therefore, any reductions in fuel expenditures (fuel savings) associated with a policy include additional fuel expenditures associated with rebound driving. If we ignored those rebound miles,

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[66] For the estimation of the stream of costs and benefits, we assume that after implementation of the MY 2027 and later standards, the MY 2032 standards apply to each year thereafter.

the fuel savings would be calculated using the same number of miles in both the policy and no-action cases but with a lower fuel cost per mile in the policy case.

However, drivers would drive those additional rebound miles only if they find value in them. The increase in travel associated with the rebound effect produces additional benefits to vehicle drivers, which reflect the value of the added social and economic opportunities that become accessible with additional travel. This analysis estimates the economic benefits from increased rebound-effect driving as the sum of the fuel costs paid to drive those miles and the drive surplus, which is the additional value that drivers derive from those miles.

The value of the rebound miles driven is simply the number of rebound miles multiplied by the cost per mile of driving them.

$$Value\ of\ Rebound\ VMT = VMT_{rebound} \times \left(\frac{\$}{mile}\right)_{action}$$

The economic value of the increased owner/operator surplus provided by added driving, the drive surplus, is estimated as one half of the product of the decline in vehicle operating costs per vehicle-mile and the resulting increase in the annual number of miles driven.

$$DriveSurplus = \frac{VMT_{rebound} \times \left[\left(\frac{\$}{mile}\right)_{NoAction} - \left(\frac{\$}{mile}\right)_{Action}\right]}{2}$$

Thus, the economic benefits from increased rebound driving, called Drive Value, is then calculated as below.

$$DriveValue = Value\ of\ Rebound\ VMT + DriveSurplus$$

Drive value depends on the extent of improvement in fuel consumption and fuel prices, which depend upon vehicle model year, the calendar year, and the standards being analyzed. Thus, the value of benefits from increased vehicle use also depends upon model year and calendar year, and it varies among alternative standards.

4.3.3 Fuel Consumption

Overall, the proposed standards are projected to reduce liquid fuel consumption while simultaneously increasing electricity consumption as shown in Table 4-10 and Table 4-11, respectively. These values are generated in OMEGA and used in the benefit cost analysis described in DRIA Chapter 10.

Table 4-10: Liquid-fuel consumption impacts, light-duty and medium-duty (billion gallons)

Calendar Year	Liquid-Fuel Impacts, Proposal	Liquid-Fuel Impacts, Alternative 1	Liquid-Fuel Impacts, Alternative 2	Liquid-Fuel Impacts, Alternative 3
2027	-0.89	-0.93	-0.65	-0.53
2028	-2.2	-2.5	-1.6	-1.3
2029	-4	-4.4	-3.2	-2.3
2030	-6.1	-7	-4.9	-3.9
2031	-8.6	-9.8	-7	-6.3

2032	-12	-13	-9.6	-9.3
2035	-21	-23	-19	-19
2040	-34	-38	-31	-33
2045	-42	-47	-38	-42
2050	-48	-52	-43	-48
2055	-49	-54	-44	-49
sum	-900	-1,000	-810	-870

Table 4-11 Electricity consumption impacts, light-duty and medium-duty (terawatt hours)

Calendar Year	Electricity Impacts, Proposal	Electricity Impacts, Alternative 1	Electricity Impacts, Alternative 2	Electricity Impacts, Alternative 3
2027	8.9	9.3	6.4	5.4
2028	21	23	15	13
2029	38	39	29	22
2030	56	61	44	36
2031	78	84	64	58
2032	100	110	86	85
2035	190	200	170	170
2040	300	330	280	290
2045	380	420	350	380
2050	430	470	390	430
2055	440	490	400	440
sum	8,100	8,900	7,400	7,900

4.3.4 Monetized Fuel Savings

Table 4-12 shows the undiscounted annual monetized fuel savings associated with the proposal and each alternative as well as the present value (PV) of those costs and equivalent annualized value (EAV) for the calendar years 2027–2055 using both 3 percent and 7 percent discount rates. In Chapter 10, we present pretax fuel savings which are used in the benefit cost analysis. In Chapter 10 we also present transfers, or taxes, associated with fuel expenditure changes and battery and vehicle purchase credit incentives.

Table 4-12: Retail fuel expenditure savings, light-duty and medium-duty (billions of 2020 dollars)*

Calendar Year	Retail Fuel Savings, Proposal	Retail Fuel Savings, Alternative 1	Retail Fuel Savings, Alternative 2	Retail Fuel Savings, Alternative 3
2027	1.2	1.3	0.9	0.7
2028	3.2	3.7	2.4	1.9
2029	6	7	4.8	3.5
2030	10	12	8.1	6.5
2031	14	17	12	11
2032	20	23	17	16
2035	39	44	34	35
2040	69	77	61	66
2045	89	98	80	87
2050	100	110	93	100
2055	110	120	98	110
PV3	1,100	1,200	950	1,000
PV7	550	610	490	520
EAV3	56	62	50	54
EAV7	45	50	40	42
* Positive values indicate savings in fuel expenditures.				

4.3.5 Costs Associated with the Time Spent Refueling

More stringent GHG standards have traditionally resulted in lower fuel consumption by liquid fueled vehicles. Provided fuel tanks on liquid fueled vehicles retain their capacity (i.e., gas tanks don't change volume), the lower fuel consumption would be expected to reduce the frequency of refueling events. However, if manufacturers choose to maintain traditional range (i.e., miles traveled on a full tank of fuel), then the possibility exists that tank capacities would become smaller and, therefore, the frequency of refueling events would not change, although time spent at the fuel pump may be reduced. There are indications that both outcomes are happening, with some vehicles reducing tank sizes while others are maintaining them.

Of course, electric vehicles are not fueled in the same way. Many refueling events for electric vehicles would be expected to occur either overnight where the vehicle is parked or during the workday using an employer owned charge point, neither of which require extra time from the driver, especially compared to refueling a liquid fueled vehicle. However, some recharging events will undoubtedly occur in public places, especially when drivers are in the midst of an extended road trip. These mid-trip charging events are the focus of this analysis. For purposes of this analysis, we have made the simplifying assumption that PHEVs will not make use of mid-trip charging since the vehicle can continue to operate on gasoline once the battery is depleted.

To estimate the refueling costs associated with liquid-fueled vehicles, we have borrowed heavily from the approach used by EPA in the December 2021 GHG final rule (U.S. EPA 2021) (U.S. DOT 2021) with updated inputs developed in support of the 2022 CAFE final rule (NHTSA 2022). The refueling costs for liquid-fueled vehicles are calculated on a cost per gallon basis while for BEVs it is calculated on a cost per mile basis. The calculations used are shown in the equation immediately below for liquid-fueled vehicles and in the subsequent equation for BEVs with a discussion following.

$$\frac{Cost}{Gallon} = \frac{1}{Tank\ Size \times Share\ Filled} \times \frac{Fixed\ Time + \frac{Tank\ Size \times Shared\ Filled}{Fill\ Rate}}{60} \times Time\ Value \times 0.6$$

Where,

Cost/Gallon = the refueling cost per gallon of fuel consumed,

Tank Size = the volume, in gallons, of the liquid fuel tank,

Share Filled = the typical share of the tank volume filled during a refill event,

Fixed Time = the fixed time, in minutes, between deciding to refill and returning to the trip,

Fill Rate = the fuel dispense rate, in gallons per minute, of liquid fuel pumps,

60 converts minutes to hours

Time Value = the value of the time for the occupants of the vehicle,

0.6 = a scalar value to count only 60 percent of refueling events

We have estimated tank sizes the same way it was done in our 2021 GHG final rule, which was based on a 2016 internal Department of Transportation (DOT) memorandum. (CAFE TSD 2021) (White September 27, 2016) The most recent data reported was for the 2016 model year and showed that the average tank sizes of some of the most popular vehicles in the United States were 15.7, 18.7 and 27.3 for cars, vans and SUVS, and pickup trucks, respectively, all in gallons. We have used those values for all vehicles in each of those categories.

The share filled values are consistent for all vehicles at 0.65, meaning that the typical refill event includes filling 65 percent of the capacity of the tank.

The fixed time value is also consistent for all vehicles at 3.5 minutes per event, while the fill rate is held constant at 7.5 gallons per minute reflecting the legal restriction of 10 gallons per minute and the fact that not all people refill at that maximum rate.

The time value has been extensively analyzed by DOT for use in regulatory analyses. The values, which account for wage rates, miles driven in urban and rural settings, the different uses of vehicles whether it be personal or commercial use, and the typical number of occupants over the age of 5 years for different vehicles. The hourly values ($/hour) derived and which we use are $25.55 and $30.75 for passenger cars and light-trucks, respectively, both in 2018 dollars (NHTSA 2022).

As described by NHTSA, the 0.6 scaling factor is meant to capture those drivers whose primary reason for the refueling trip was due to a low reading on the gas gauge. Such drivers experience a cost due to added mileage driven to detour to a filling station, as well as added time to refuel and complete the transaction at the filling station. Drivers who refuel on a regular schedule or incidental to stops they make primarily for other reasons (e.g., using restrooms or buying snacks) do not experience the cost associated with detouring to locate a station or paying for the transaction, because the frequency of refueling for these reasons is unlikely to be affected by fuel economy improvements. This restriction was imposed to exclude distortionary effects of those who refuel on a fixed (e.g., weekly) schedule and may be unlikely to alter refueling patterns due to increased driving range (NHTSA 2022).

To estimate the refueling costs associated with BEVs, we calculate cost per mile.

$$\frac{Cost}{Mile} = \left(\frac{Fixed\ Time}{Charge\ Frequency} \times \frac{1}{60} + \frac{Share\ Charged}{Charge\ Rate}\right) \times Time\ Value$$

Where,

Cost/Mile = the refueling cost per mile driven

Fixed Time = the fixed time, in minutes, between deciding to refill and returning to the trip,

Charge Frequency = the cumulative number of miles driven before a mid-trip charging event is triggered,

Share Charged = the share of miles that will be charged mid-trip,

Charge Rate = the typical recharge rate, in miles per hour of charging,

Time Value = the value of the time for the occupants of the vehicle.

The fixed time value is taken to be equal to that for liquid-fueled vehicles, at 3.5 minutes per event, and the time value is equal to those stated above for liquid-fueled vehicles.

The charge rate reflects the number of miles of driving provided by a one hour charging session. Different BEVs have different limits on how much energy can be delivered to the battery pack, and other factors – ambient conditions, the power level of the charging equipment, on-vehicle accessory loads during charging – impact the energy transfer. For our analysis, we use the same value of 100 miles of driving added for each hour of charging and use that value for all BEVs.[67]

For the charge frequency and share charged parameters, we have used values developed by NHTSA and presented in the CCEMS input files used in support of their September 2021 proposal. (U.S. DOT 2021) In their analysis, NHTSA estimated the frequency of mid-trip charging events and the share of miles driven that require mid-trip charging as shown in Table 4-13. As Table 4-13 shows, cars would be expected to require less frequent mid-trip charges and a smaller share of miles driven with mid-trip charge events. Pickups and vans/SUVs have fairly similar measures, with vans and SUVs requiring slightly more mid-trip charging than pickups.

[67] Charging equipment is available in a variety of power levels (see DRIA Ch. 5.3.1.2), with higher-power equipment generally able to charge vehicles more quickly. To the extent mid-trip charging occurs at a higher charge rate, the resulting cost per mile for time spent charging electric vehicles would be lower. To illustrate the lower potential time needed to recharge mid-trip, vehicles using DC fast charging equipment can add 200 or more miles per hour.

Table 4-13: BEV recharging thresholds by body style and range

	Cars	Vans & SUVs	Pickups
Miles to mid-trip charging event, BEV200	2,000	1,500	1,600
Miles to mid-trip charging event, BEV300	5,200	3,500	3,800
Miles to mid-trip charging event, BEV400	10,400	7,000	7,600
Miles to mid-trip charging event, BEV500	20,800	14,000	15,200
Share of miles charged mid-trip, BEV200	0.06	0.09	0.08
Share of miles charged mid-trip, BEV300	0.03	0.04	0.04
Share of miles charged mid-trip, BEV400	0.015	0.02	0.02
Share of miles charged mid-trip, BEV500	0.0075	0.01	0.01

Using the values in Table 4-13, EPA has developed curves for each body style as a function of range. These curves are second order polynomials as a function of BEV range. These curves and their coefficient values are shown in Figure 4-6 and Figure 4-7.

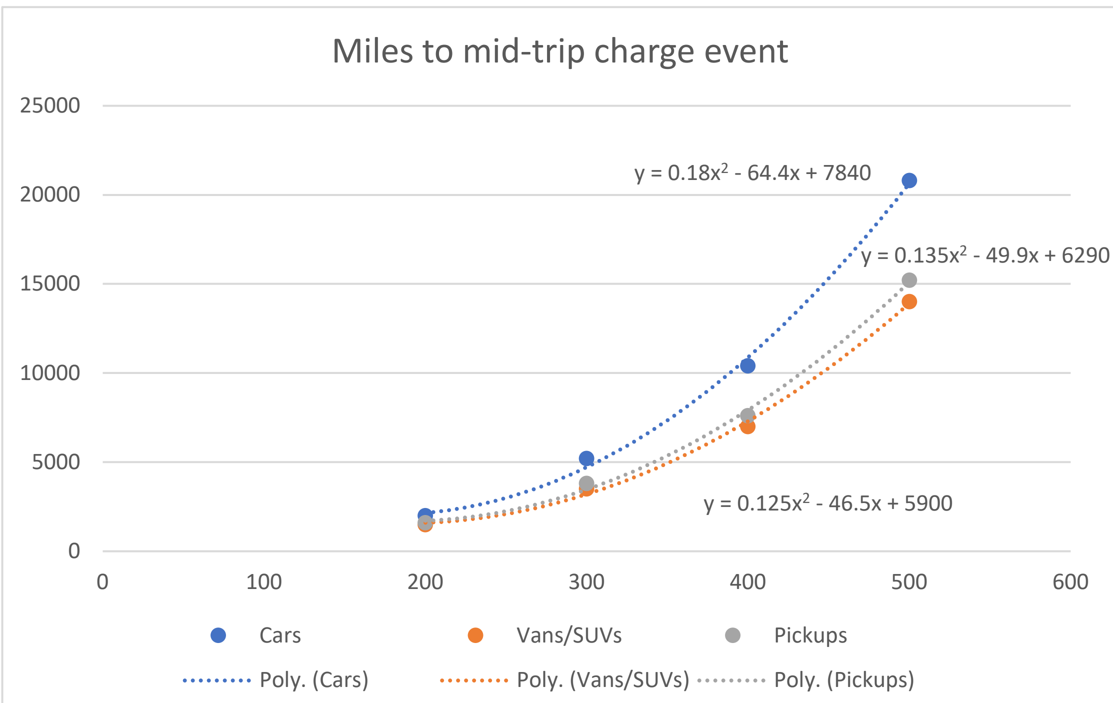

Figure 4-6: Curve fits for miles driven to a mid-trip charge event.

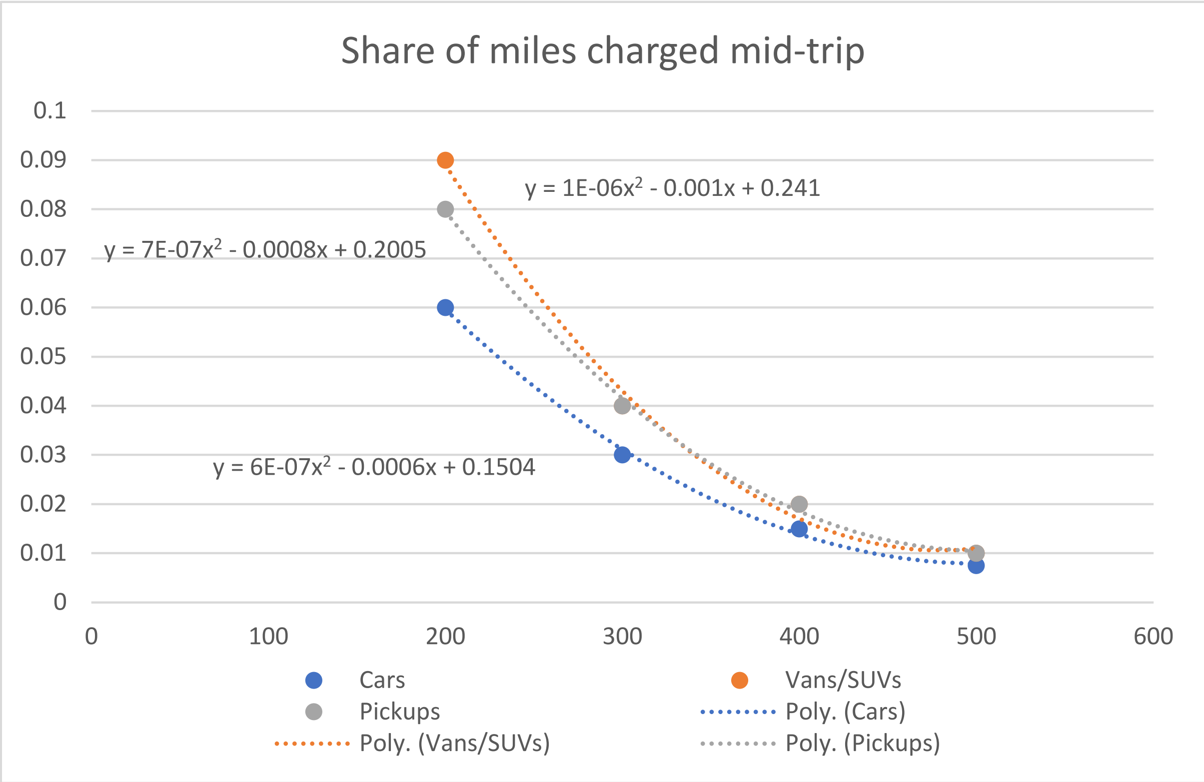

Figure 4-7: Curve fits for the share of miles charged in mid-trip events.

The curve fits shown in these figures are shown in Table 4-. These coefficients are used to calculate the charge frequency and share charged parameters of the Cost/Mile equation above using the functional form shown in the equation below.

$$Charge\ Frequency; Share\ Charged = A \times Range^2 + B \times Range + C$$

Where,

A, *B* & *C* are the applicable coefficient values shown in Table 4-14,

Range = the range of the given BEV.

Table 4-14: Curve coefficients used to estimate charge frequency and share charged

	A	B	C
Miles to mid-trip charge, Car	0.18	-64.4	7840
Miles to mid-trip charge, Van/SUV	0.125	-45.5	5900
Miles to mid-trip charge, Pickup	0.135	-49.9	6290
Share of miles charged mid-trip, Car	0.0000006	-0.0006	0.1504
Share of miles charged mid-trip, Van/SUV	0.000001	-0.001	0.241
Share of miles charged mid-trip, Pickup	0.0000007	-0.0008	0.2005

4.3.6 Maintenance and Repair Costs

Maintenance and repair (M&R) are large components of vehicle cost of ownership for any vehicle. According to Edmunds, maintenance costs consist of two types of maintenance: scheduled and unscheduled. Scheduled maintenance is the performance of factory-recommended actions at periodic mileage or calendar intervals, like oil changes. Unscheduled maintenance includes wheel alignment and the replacement of items such as the battery, brakes, headlights, hoses, exhaust system parts, taillight/turn signal bulbs, tires, and wiper blades/inserts. (Edmunds 2023) Repairs, in contrast, are done to fix malfunctioning parts that inhibit the use of the vehicle. The differentiation between the items that are included in unscheduled maintenance versus repairs is likely arbitrary, but the items considered repairs seem to follow the systems that are covered in vehicle comprehensive (i.e., “bumper-to-bumper”) warranties offered by automakers, which exclude common “wear” items like tires, brakes, and starter batteries. (Muller 2017)

To estimate maintenance and repair costs, we have used the data gathered and summarized by Argonne National Laboratory (ANL) in their look at the total cost of ownership for vehicles of various sizes and powertrains (Burnham, Gohlke, et al. 2021).

4.3.6.1 Maintenance Costs

Maintenance costs, and differences between more traditional ICE vehicles and HEVs versus BEVs and PHEVs, are an importance consideration in not only the full accounting of social benefits and costs, but also the consumer decision making process when comparing ICE/HEV technology versus BEV/PHEV technology. If BEVs and PHEVs are less costly to maintain, a consumer might find the potentially higher purchase price of the vehicle to be “worth it” given the possibly lower fuel and maintenance costs over time. The reverse is also true – more costly BEV/PHEV maintenance relative to ICE/HEV might make the potentially higher purchase price even less appealing, even if the fueling costs are lower.

In their study, ANL developed a generic maintenance service schedule for various powertrain types using owner’s manuals from various makes and models including the Toyota Yaris, Camry, Camry HEV, Prius, and Prius Prime; Chevrolet Cruze, Volt, and Bolt; Nissan Sentra, Kicks, and Leaf; Kia Optima, Optima HEV, and Optima PHEV; Kia Soul and Soul EV; Tesla Model 3 and Model S, Ford Focus; Lincoln MKZ; BMW i3; VW Golf and e-Golf; and Fiat 500 and 500e. The analysis assumed that drivers would follow the recommended service intervals. The authors noted that, in practice, not everyone follows the recommended service intervals but also noted that owners likely do so at the expense of either future repair costs or the early scrappage of the vehicle (Burnham, Gohlke, et al. 2021, 81). The authors also noted that estimates were made for certain “wear items” that might not normally be included in a recommended maintenance schedule (e.g., brake pads and rotors) for which they estimated average lifetimes based on guidance from several experts and from automotive websites (Burnham, Gohlke, et al. 2021, 81).

After developing the maintenance schedules, the authors collected national average costs for each of the preventative and unscheduled services. The authors noted that service cost varies by several factors, including the type of mechanic (dealership vs. chain vs. independent), part quality (OEM vs. aftermarket), and make and model cost characteristics (domestic vs. import and mass market vs. luxury). The authors did not assume drivers would perform any of their own maintenance services, stating a lack of data available on how often drivers do so. The authors noted that “do it yourself” maintenance would reduce costs, though depending on the service would require investment in both tools and skill development (Burnham, Gohlke, et al. 2021, 81).

The authors noted that vehicle type (sedan, SUV, pickup) may influence maintenance costs as some part sizes and fluid capacities can be larger for bigger vehicles (e.g., larger tires needed for a pickup). However, when examining the data at their disposal, the authors found no significant difference over 10 years of ownership. But total maintenance and repair costs of medium-duty diesel vehicles were about 34% higher than that of their gasoline counterparts. The authors attributed that difference to repairs rather than maintenance, since the most obvious maintenance difference between the vehicles is that diesels do not have spark plugs which is a relatively small cost. The authors acknowledge that their dataset had a very limited number of diesel vehicles and there appeared to be no clear trend regarding higher or lower maintenance costs for diesel fueled vehicles.

Specific to tires and tire replacement, an issue often cited with respect to BEVs versus ICE vehicles, the authors noted that their analysis assumed that tire life and replacement costs are the same for all powertrains. However, advanced powertrain vehicles often are equipped with specially designed tires that provide low rolling resistance (LRR) to improve fuel efficiency (Burnham, Gohlke, et al. 2021, 83). Presumably, the authors are speaking of tires on BEV, and maybe PHEV, powertrains when speaking of “advanced powertrain vehicles.” EPA believes that most new vehicles are equipped and sold with low rolling resistance tires. That said, some BEVs are equipped with tires that differ from those on typical ICE vehicles to address tread wear and the instant torque of BEVs making the issue raised by the authors a valid issue for consideration. The authors point to several studies looking into the issue with no clear conclusion being drawn about tire and tire replacement costs for BEVs versus ICE vehicles. The authors did reiterate a Goodyear claim that traditional tires wear 30 percent faster when installed on BEVs (Burnham, Gohlke, et al. 2021, 83).

Regarding brake-related maintenance, the authors assumed that brake pad, rotor, and caliper replacement intervals could be extended by 33% for HEVs and by 50% for PHEVs and BEVs, relative to ICE vehicles, due to less friction wear that would result from the use of regenerative braking. Further, they assumed that PHEVs and BEVs would have more regenerative braking capabilities than HEVs and, therefore, that their service intervals could be extended longer than HEVs due to their larger battery capacity and electric motor (Burnham, Gohlke, et al. 2021, 84). Table 4-16 shows the maintenance costs used as inputs to OMEGA.

Table 4-15: Maintenance service schedule by powertrain

Service	Miles per Event ICE	Miles per Event HEV	Miles per Event PHEV	Miles per Event BEV	Cost per Event (2019 dollars)
Engine Oil	7,500	7,500	9,000	n/a	$65
Oil Filter	7,500	7,500	9,000	n/a	$20
Tire Rotation	7,500	7,500	7,500	7,500	$50
Wiper Blades	15,000	15,000	15,000	15,000	$45
Cabin Air Filter	20,000	20,000	20,000	20,000	$50
Multi-Point Inspection	20,000	20,000	20,000	20,000	$110
Engine Air Filter	30,000	66,667	83,333	n/a	$40
Brake Fluid	37,500	37,500	37,500	37,500	$150
Tires Replaced	50,000	50,000	50,000	50,000	$525
Brake Pads	50,000	66,667	75,000	75,000	$350
Starter Battery	50,000	50,000	50,000	50,000	$175
Spark Plugs	60,000	120,000	120,000	n/a	$225
Oxygen Sensor	80,000	80,000	80,000	n/a	$350
Headlight Bulbs	80,000	80,000	80,000	80,000	$90
Transmission Service	90,000	110,000	110,000	n/a	$200
Timing Belt	90,000	110,000	110,000	n/a	$750
Accessory Drive Belt	90,000	110,000	110,000	n/a	$165
HVAC Service	100,000	100,000	100,000	100,000	$50
Brake Rotors	100,000	125,000	150,000	150,000	$500
Shocks and Struts	100,000	100,000	100,000	100,000	$1,000
Engine Coolant	125,000	125,000	125,000	n/a	$190
EV Battery Coolant	n/a	125,000	125,000	125,000	$210
Fuel Filter	150,000	150,000	200,000	n/a	$110
Brake Calipers	150,000	187,500	225,000	225,000	$1,000

Using the schedules and costs shown in Table 4-15, OMEGA then calculates the cumulative maintenance costs from mile zero through mile 225,000. For example, the cumulative costs for an ICE vehicle at 15,000 miles would be 2 x ($65+$20+$50) + $45, or $315. The cumulative costs can then be divided by the cumulative miles to determine the average maintenance cost per mile at any given odometer reading in a vehicle's life. However, that average cost, while informative, suggests that the first mile incurs the same cost as the last mile. This does not seem appropriate, especially considering that the cumulative costs for ICE vehicles, $20,050, divided by 225,000 cumulative miles results in an average cost per mile of $0.09. If that vehicle had a fuel economy of 35 miles per gallon, assuming $3 per gallon of gasoline, its fuel costs would also be $0.09 per mile. Over 15,000 first year miles, the fuel costs and maintenance costs would both be $1,350. Compare this to the $315 estimate of maintenance costs over the first 15,000 miles. Clearly, while the average cost per mile of $0.09 is valid and informative, it is not the best valuation for our purpose. Instead, we have estimated the cost per mile at a constant slope with an intercept set to $0 per mile such that the cumulative costs after 225,000 miles would equal the $20,050 (for an ICE vehicle) included in the suggested maintenance schedule. Following this approach, the maintenance cost per mile curves calculated within OMEGA are as shown in Figure 4-8.

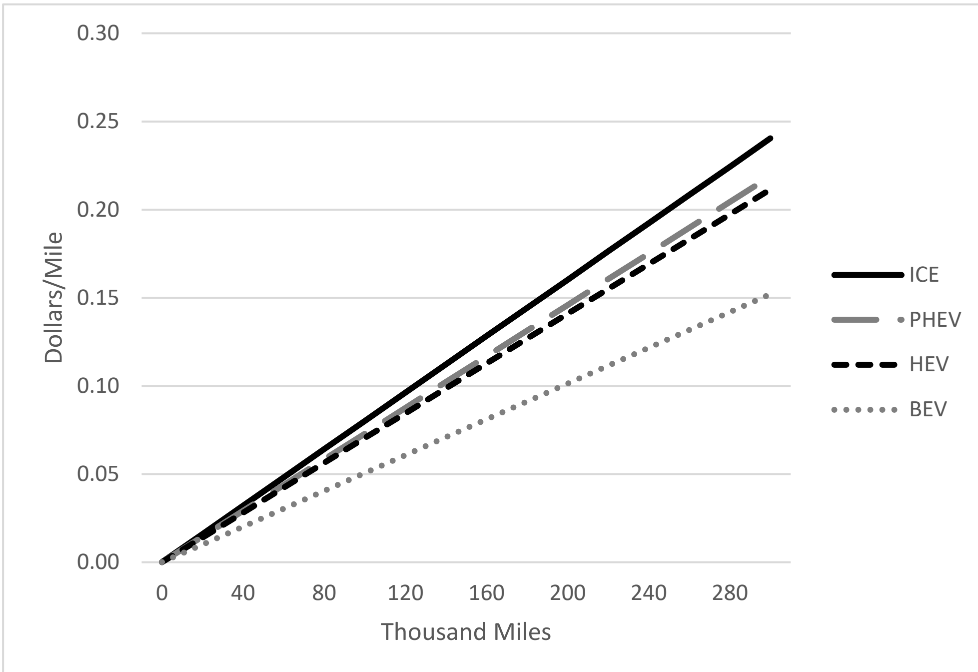

Figure 4-8: Maintenance cost per mile (2019 dollars) at various odometer readings.

Using these maintenance cost per mile curves, OMEGA then calculates the estimated maintenance costs in any given year of a vehicle's life based on the miles traveled in that year. For example, an ICE vehicle having an odometer reading of 120,000 miles would have a maintenance cost per mile of $0.10 (see Figure 4-8). If that vehicle travels 10,000 miles in the given year, then its estimated maintenance costs would be $1,000 in that year. If that vehicle were to instead travel 15,000 miles in that year, its estimated maintenance costs would be $1,500.

OMEGA uses these maintenance costs for light-duty and for medium-duty vehicles. The maintenance costs are included in the benefit and cost analysis. Note that these maintenance costs differ from those presented in Chapter 4.1 and Chapter 4.2. Chapter 4.1 costs are meant to reflect the thought process of a potential new vehicle purchaser. Chapter 4.2 amounts are estimated average expenses per vehicle over the first 8 years of vehicle life. Costs presented here, in Chapter 4.3 are meant to estimate the actual effects of the proposal.

4.3.6.2 Repair Costs

Repairs are done to fix malfunctioning parts that inhibit the use of the vehicle and are generally considered to address problems associated with parts or systems that are covered under typical manufacturer bumper-to-bumper type warranties. In the ANL study, the authors were able to develop a repair cost curve for a gasoline car and a series of scalers that could be applied to that curve to estimate repair costs for other powertrains and vehicle types. The repair cost curve developed in the ANL study is shown in the equation below (Burnham, Gohlke, et al. 2021).

$$Repair_i = vpa_i e^{bx}, i = 1, \ldots, 15$$

Where,

$Repair_i$ = the repair cost per mile at age i,

v = the appropriate vehicle type multiplier (see Car/SUV/Truck entries in Table 4-16),

p = the appropriate powertrain type multiplier (see ICE/HEV/PHEV/BEV/FCV entries in Table 4-16),

a_i = gasoline car repair cost coefficient at age i,

b = exponential constant of 0.00002,

x = the MSRP of the car when sold as new.

Table 4-16: Repair cost per mile coefficient values[a]

Item	Value
Car multiplier	1.0
SUV multiplier	0.91
Truck multiplier	0.7
ICE multiplier	1.0
HEV multiplier	0.91
PHEV multiplier	0.86
BEV multiplier	0.67
FCV multiplier	0.67
a_0	0
a_1	0
a_2	0.00333
a_3	0.01
a_4	0.0167
a_{add-on}	0.00333

[a] These coefficient values come from Burnham, Gohlke, et al. (2021)

OMEGA makes use of the equation developed in the ANL study along with the coefficient values shown in Table 4-16 to estimate repair costs per mile at any age in a given vehicle's life. In place of the MSRP[68] of the new vehicle, OMEGA uses the estimated technology cost for the vehicle as described above. Further, OMEGA makes use of this equation for all ages of a vehicle's life (OMEGA estimates a 30/40-year lifetime) using the a_{add-on} value for every age beyond the first five years. In other words, the a_x value for age 7 would be 0.0167 + 3 x 0.00333 = 0.02669 (note that, in OMEGA, age=7 is the 8th year of a vehicle's life). The resultant repair

[68] Manufacturer suggested retail price

cost per mile values at all ages are shown in Figure 4-9. Note that the new vehicle cost (used in place of the MSRP value) is held constant at $35,000 in Figure 4-9, regardless of vehicle type (car, van/SUV, pickup) and powertrain (ICE vehicle, HEV or MHEV, PHEV, BEV) which is not likely, but is presented here for illustration only.

OMEGA uses these repair costs for both light-duty and medium-duty. Repair costs are included in the benefit-cost analysis.

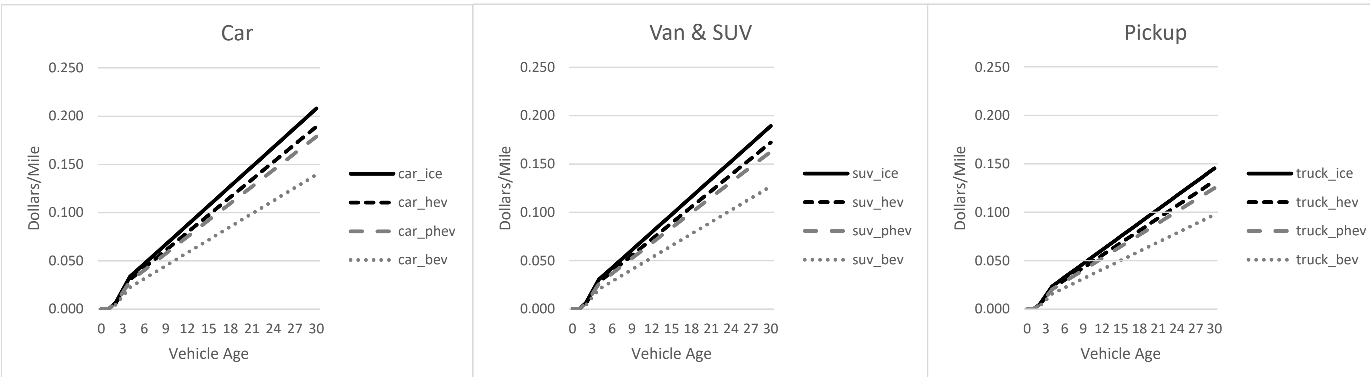

Figure 4-9: Repair cost per mile (2019 dollars) for a $35,000 Car, Van/SUV and Pickup with various powertrains.

4.3.7 Costs Associated with Noise and Congestion

If consumers choose to drive more, they benefit from the utility derived from those additional miles, as described in Chapter 4.3.2. In contrast to the benefits associated with additional driving, there are also costs. Increased vehicle use associated with a positive rebound effect also contributes to increased traffic congestion and highway noise. Depending on how the additional travel is distributed throughout the day and where it takes place, additional vehicle use can contribute to traffic congestion and delays by increasing traffic volumes on facilities that are already heavily traveled during peak periods. These added delays impose higher costs on other road users in the form of increased travel time and operating expenses. Because drivers do not take these external costs into account in deciding when and where to travel, we account for them separately as a cost of addition driving associated with a positive rebound effect.

EPA relies on congestion and noise cost estimates developed by the Federal Highway Administration to estimate the increased external costs caused by added driving due to a positive rebound effect. EPA employed estimates from this source previously in the analysis accompanying the light-duty 2010, 2012 and 2021 final rules. We continue to find them appropriate for this analysis after reviewing the procedures used by FHWA to develop them and considering other available estimates of these values.

FHWA's congestion cost estimates focus on freeways because non-freeway effects are less serious due to lower traffic volumes and opportunities to re-route around the congestion. EPA has applied the congestion cost to the overall VMT therefore the results of this analysis potentially overestimate the congestion costs associated with increased vehicle use, and thus lead to a conservative estimate of net benefits.

EPA uses FHWA's "Middle" estimates for marginal congestion and noise costs caused by increased travel from vehicles. This approach is consistent with the methodology used in our prior analyses. The values used are shown in Table 4-17.

These congestion costs are consistent with those used in the 2021 final rule. These values are used as inputs to OMEGA and adjusted within the model to the dollar basis used in the benefit and cost analysis.

Table 4-17: Costs associated with congestion and noise (2018 dollars per vehicle mile)

	Sedans/Wagons	CUVs/SUVs/Vans	Pickups
Congestion	0.0634	0.0634	0.0566
Noise	0.0009	0.0009	0.0009

4.4 New Vehicle Sales

The topic of the "energy paradox" or "energy efficiency gap" has been extensively discussed in previous analyses of vehicle GHG standards. The idea of the energy efficiency gap is that existing fuel saving technologies were not widely adopted even though they reduced fuel consumption enough to pay for themselves in short period of time. Conventional economic principles suggest that because the benefits to vehicle buyers of the new technologies would outweigh the costs to those buyers, automakers would provide them and people would buy them.

As described in previous EPA GHG vehicle rules (most recently in the 2021 rule), engineering analyses identified technologies (such as downsized-turbocharged engines, gasoline direct injection, and improved aerodynamics) where the additional cost of the technology is quickly covered by the fuel savings it provides, but they were not widely adopted until after the issuance of EPA vehicle standards. Research also suggests that the presence of fuel-saving technologies do not lead to adverse effects on other vehicle attributes, such as performance and noise. Instead, research shows that there are technologies that exist that provide improved fuel economy without hindering performance, and in some cases, while also improving performance (Huang, Helfand, et al. 2018) (Watten, Helfand and Anderson 2021). Additionally, research demonstrates that, in response to the standards, automakers have improved fuel economy without adversely affecting other vehicle attributes (Helfand and Dorsey-Palmateer 2015). Lastly, while the availability of more fuel efficient vehicles has increased steadily over time, research has shown that the attitudes of drivers towards those vehicles with improved fuel economy has not been affected negatively (Huang, Helfand, et al. 2018) (Huang, Helfand and Bolon 2018a). In summary, it appears that in the absence of the standards, markets have not led to the adoption of fuel efficient technologies with short payback periods and no discernible tradeoffs. Thus, an energy efficiency gap appears to have existed, especially in the absence of the standards, and may still exist.

There are a number of hypotheses in the literature that attempt to explain the existence of this apparent market failure, including both consumer and producer side reasons, though the literature has not settled on a single explanation (National Academies of Science, Engineering, and

Medicine 2021). In fact, the gap likely exists due to a combination of consumer- and producer-side characteristics.[69]

Consumer-side hypotheses include:

- Consumers might lack information, not have a full understanding of this information when it is presented, not have correct information, not have the ability to process the information, or not trust the presented information.

- Consumers might weigh the present or present circumstances (e.g., current costs) more heavily than future opportunities (e.g., long term savings, changing circumstances) in their purchase decisions due to, for example, uncertainty about the future, a lack of foresight, an aversion to short term losses relative to longer term gains, or a preference for the status quo.

- Consumers might prioritize other vehicle attributes over fuel economy in their vehicle purchase process.

- Consumers might associate higher fuel economy with lower quality vehicles.

In addition to the research discussed above indicating that fuel-saving technologies are not likely to be associated with adverse effects on other vehicle attributes, EPA has explored evidence on how consumers evaluate fuel economy in their vehicle purchase decisions. Overall, the research has not reached a consensus; results and estimates vary across a range of data types and statistical models. Thus, it is not clear how consumers incorporate fuel economy in their purchase decision, nor how consumer behavior might contribute to the energy efficiency gap.

Part of the uncertainty surrounding the reasons behind the energy efficiency gap is that most of the technology applied to existing ICE vehicles may have been "invisible" to the consumer. This is for a few reasons, including that the technology itself was not something the mainstream consumer would know about, or because it was applied to a vehicle at the same time as multiple other changes, therefore making it unclear to the consumer what changes in vehicle attributes, if any, could be attributed to a specific technology.

Much less research has been conducted to evaluate the producer side of the market, though three interrelated themes arise: market structure, business strategy, and technological innovation. The structure of the automobile industry may inefficiently allocate car attributes, fuel economy among them, which may contribute to the existence of an energy efficiency gap. Specifically, vehicle production involves significant fixed costs in which automakers strive to differentiate their products from each other. In that context, fuel economy of a vehicle could be a just another factor in a company's product differentiation strategy. Product differentiation can lead to an under-supply of fuel economy relative to what is cost-effective to consumers in some segments,

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[69] For simplicity, we present consumer- and producer-side hypotheses for the "energy efficiency gap", consistent with traditional economy theory. Analogously but somewhat differently, we could have presented these hypotheses organized according to individual and institutional characteristics, behaviors, and biases. Under that organization structure, some of the hypotheses we present, such as myopia, uncertainty aversion, loss aversion, asymmetric information, and status quo bias, could apply to both consumer and producers.

and an over-supply of fuel economy in other sectors (Fischer 2005). Automobile manufacturers may adopt a "wait and see" strategy regarding the costs associated with investing in and commercializing new technologies.

In the absence of standards, automakers have seemed willing to invest in small improvements upon existing technologies (Helfand and Dorsey-Palmateer 2015) and more reluctant to invest in major innovations in the absence of standards. This may be a result of first-mover disadvantages to investing in and commercializing new technologies. 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. 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 can create conditions under which companies invest in major innovations. Because all companies (both auto firms and auto suppliers) have incentives to find better, less expensive ways of meeting the standards, the possibilities for synergistic interactions may increase. Thus, the standards, by focusing all companies on finding more efficient ways of achieving the standards, may lead to better outcomes than if any one company operated on its own.

A combination of theories may best explain why there was limited adoption of cost-effective fuel-saving technologies before the implementation of more stringent standards. However, it does appear that, while addressing externalities like pollution, regulation has appeared to also help correct such market failures without serious disruption to vehicle markets. We do not reject the observation that the energy efficiency gap has existed and may still exist. However, the availability of more fuel efficient vehicles has increased steadily over time, thus narrowing or closing the energy efficiency gap, and research has shown that the attitudes of drivers towards those vehicles with improved fuel economy has not been negatively affected (Huang, Helfand, et al. 2018) (Huang, Helfand and Bolon 2018a). In addition, research has shown that automakers have improved fuel economy in response to the standards without adverse effects on other vehicle attributes (Helfand and Dorsey-Palmateer 2015) (Watten, Helfand and Anderson 2021). Thus, EPA does not model tradeoffs between fuel economy and performance as a path to achieving the proposed standards.

Though a slight gap in ICE vehicle purchases may still exist due to uncertainty surrounding new fuel savings technologies, it becomes less of an issue with the increasing prevalence of BEVs in the market, as the changes in vehicle attributes due to this technology are clearly evident to consumers. There is uncertainty in the historical literature regarding consumer acceptance and adoption of electric vehicles, as described in Chapter 4.1 and Jackman et al. (2023), however recent research suggests that the demand for electric vehicles is robust, and adoption is constrained, at least in part, by limited supply. Gillingham et al. (2023) examine all new LD vehicles sold in the U.S. between 2014 and 2020, focusing on comparisons of existing electric vehicles to their most similar ICE vehicle counterpart, finding that EVs are preferred to the ICE counterpart in some segments (Gillingham, et al. 2023). In the paper, the authors show that, compared to ICE counterparts, EVs have seen relative sales shares of over 30%, which indicates that the share of PEVs in the marketplace is, at least partially, constrained due to the lack of offerings needed to convert existing demand into market share. In addition, a survey from

Consumer Reports in early 2022 shows that more than one third of Americans would either seriously consider or definitely buy or lease a BEV today, if they were in the market for a vehicle. (Bartlett 2022).

The rest of this chapter will discuss how sales effects were modeled in OMEGA, as well the total change in sales estimated due to this proposed rule.

4.4.1 How Sales Impacts Were Modeled

EPA has updated its OMEGA model, in part, to increase the model's useability and transparency. In addition, the model has been updated to allow for interactions in producer and consumer decisions in estimating total sales and the share of ICE vehicles and BEVs in the market that both meet the standard being analyzed and will be accepted by consumers. More about the updated OMEGA model, including detailed information on the structure and operations, can be found in DRIA Chapter 2. As in previous rulemakings, the sales impacts are based on a set of assumptions and inputs, including assumptions about the role of fuel consumption in vehicle purchase decisions described in Chapter 4.1, and assumptions on consumers' demand elasticity discussed in below.[70]

At a high level, OMEGA estimates the effects of a policy on new vehicle sales volumes as a deviation from the sales that would take place in the absence of the standards.[71] This calculation is based on applying a demand elasticity to the change in new vehicle net price, the price that incorporates the fact that vehicle buyers are expected to take fuel consumption into consideration in the purchase process. The modeled BEV shares, as described in Chapter 4.1, are then applied to the estimated total sales volumes to estimate further effects of the rule, including costs, emissions and benefits.

4.4.1.1 The Role of Fuel Consumption in Vehicle Sales Estimates

In the 2021 rule, as well as in this proposed rule, EPA assumed that producers account for 2.5 years of fuel consumption in their assessment of the consumer's purchase decision. However, as discussed in detail in the 2021 rule, there is not a consensus around the role of fuel consumption in vehicle purchase decisions. Greene, et al. provides a reference value of $1,150 for the value of reducing fuel costs by $0.01/mile over the lifetime of an average vehicle; for comparison, 2.5 years of fuel savings is only about 30 percent of that value, or about $334. (Greene, et al. 2018) This $334 is within the large standard deviation in Greene, et al. (2018) for the willingness to pay to reduce fuel costs, but it is far lower than both the mean of $1,880 (160 percent of that value) and the median of $990 (85 percent of that value) per one cent per mile in the paper. On the other hand, the 2021 NAS report, citing the 2015 NAS report, observed that automakers "perceive that typical consumers would pay upfront for only one to four years of fuel savings" (pp. 9-10), which is also within the range of values identified in Greene, et al. (2018) for consumer response, but also well below the median or mean. Based on these results, it appears

[70] The demand elasticity is the percent change in quantity associated with a one percent increase in price. For price, we use net price, where net price is the difference in technology costs less an estimate of the change in fuel costs over the number of years we assume fuel costs are taken into account. We also reduce BEV prices in all scenarios, including the No Action case, due to the IRA BEV purchase and battery tax incentives.

[71] We calibrate the sales in OMEGA that would take place in the absence of the standards to data from the U.S. Energy Information Administration.

possible that automakers operate under a different perception of consumer willingness to pay for additional fuel economy than how consumers actually behave. In comments on the 2021 rule, some commenters suggested that new vehicle buyers care more about fuel consumption than the use of 2.5 years suggests, and that EPA should model automaker adoption of fuel-saving technologies based on historical actions. EPA notes that the data, methods and ideas discussed here are based on historical data, and therefore focus on ICE sales. Consumer response to fuel savings, and the amount of fuel savings considered in the purchase decision, may be different with electric vehicles and in an era of high BEV sales.

Chapter 4.1 above describes how OMEGA incorporates fuel costs in consumer purchase decisions. OMEGA also incorporates fuel cost savings in producer assumptions. Specifically, we assume producers account for 2.5 years of consumer fuel consumption. To do this, OMEGA calculates a baseline estimate of the fuel consumption over a user-specified number of years (we assume 2.5), using AEO projections of fuel cost, the expected vehicle miles traveled by year (VMT), and the vehicle's survival schedule. The same fuel costs and expected VMT are then used to calculate fuel consumption in the proposal and alternative scenarios for the same user-specified number of years, using the revised expected fuel consumption.

4.4.1.2 Elasticity of Demand

By definition, a new vehicle demand elasticity relates the percent change in new vehicle price to the percent change in new vehicle sales:

$$\eta = \frac{\Delta Q/Q}{\Delta P/P}$$

Where η is the demand elasticity, Q is the quantity of new vehicles sold, P is the price of new vehicles, and Δ refers to the change in the value. Rearranging this equation produces the sales effect:

$$\Delta Q = \eta * Q * \Delta P/P$$

As described in Chapter 2.6.3, the baseline quantity, Q, comes from EIA's projections of vehicle sales. For this proposed rule, the EIA projection includes effects of the 2021 rule, but not the IRA. The price, P, is proxied with the OMEGA estimated technology costs. The change in price is the difference between new vehicle net price under this EIA projection, and the net price under the OMEGA projected scenarios, where net price is new vehicle purchase price including 2.5 years of fuel consumption. The OMEGA projected scenarios for this rule, the No Action scenario, the Proposed alternative, the more stringent alternative (Alternative 1), and the two less stringent alternatives (Alternative 2 and Alternative 3), all include the effects of the 2021 rule and the IRA. The Proposed scenario, and all three alternatives are described in Preamble Section III.B and III.E.

For durable goods, such as vehicles, people are generally expected to have more flexibility about when they purchase new vehicles than whether they purchase new vehicles; thus, their behavior is more inflexible (less elastic) in the long run than in the short run. For this reason, estimates for long-term elasticities for durable goods are expected to be smaller (in absolute value) than short-run elasticities. At a market level, short-run responses typically focus entirely on the new-vehicle market; longer time spans allow for adjustments between the new and used vehicle markets, and even adjustments outside those markets, such as with public transit.

Because this rule has effects over time and could have effects related to the used vehicle market, long-run elasticities that account for effects in the used vehicle market are more appropriate for estimating the impacts of standards in the new vehicle market than short-run elasticities.

Continuing the approach used in the final 2021 rule, EPA is using a demand elasticity of -0.4 for LD vehicles based on an EPA peer reviewed report (U.S. EPA 2021). However, as noted in EPA's report and by public commenters on the proposed 2021 rule, -0.4 appears to be the largest estimate (in absolute value) for a long-run new vehicle demand elasticity in recent studies. EPA's report examining the relationship between new and used vehicle markets shows that, for plausible values reflecting that interaction, the new vehicle demand elasticity varies from -0.15 to -0.4. A smaller elasticity does not change the direction of sales effects, but it does reduce the magnitude of the effects. Using the value of -0.4 is conservative, as the larger estimate yields a larger change in sales.

The literature used to estimate this elasticity measure is focused on light-duty vehicles, which are primarily purchased and used as personal vehicles by individuals and households. The medium-duty vehicle market, in contrast, largely serves commercial applications. The assumptions in our analysis of the LD sales response are specific to that market, and do not necessarily carry over to the MD vehicle market. Commercial vehicle owners purchase vehicles based on the needs for their business, and we believe they are less sensitive to changes in vehicle price than personal vehicle owners. Though there are not many studies focused on what affects purchase decisions of medium-duty, or commercial, vehicle buyers, especially in the US, there are many articles discussing the importance of fuel efficiency, warranty considerations, maintenance cost, and replacement part availability in choosing which commercial vehicle to buy.[72] In addition, a working paper published by Resources for the Future reports that commercial vehicle buyers are not sensitive to fuel price changes, likely due to specialized vehicle needs. (Leard, McConnell and Zhou 2017) For this proposal, we are assuming an elasticity of 0 for the MD vehicle sales impacts estimates and we are not projecting any differences in the number of MD vehicles sold between the No Action and the Proposal or Alternative scenarios. This implicitly assumes that the buyers of MD vehicles are not going to change purchase decisions if the price of the vehicle changes, all else equal. In other words, as long as the characteristics of the vehicle do not change, commercial buyers will still purchase the vehicle that fits their needs. The rest of this chapter focuses on the LD vehicle market.

4.4.2 New LD Vehicle Sales Estimates

For this proposed rule, EPA is maintaining the previous assumptions of 2.5 years of fuel savings and a new LD vehicle demand elasticity of -0.4 for its modeling.

Table 4-18 shows results for total new LD vehicle sales impacts due to the proposed option. There is a very small change in total new LD vehicle sales projected in the proposed option compared to the No Action case. Sales fall in the first two years, increase slightly for the next

[72] See, for example: https://www.fleetmaintenance.com/equipment/chassis-body-and-cab/article/21136479/considerations-for-purchasing-new-and-used-trucks ; https://www.automotive-fleet.com/159336/10-factors-driving-commercial-fleet-vehicle-acquisitions ; https://www.mwsmag.com/commercial-vehicle-demand-is-rising-and-so-are-prices/ . These webpages are saved to the docket for this rule.

two, and then fall again. The largest sales effect in the Proposal is a very small in magnitude decrease of less than 0.4% in 2027. The fall in sales in the early and later years is expected given that 1) supply and demand theory tell us that quantity falls as costs/prices rise, and 2) we have seen decreased sales due to increased costs in previous EPA LD rule analyses. However, the increase in sales in 2029 and 2030 may be unexpected at first. Though average per vehicle costs are increasing, the estimated 2.5 years of fuel savings offset the additional vehicle cost enough to lead to increasing demand in those years.[73] For more information on fuel prices used in OMEGA, see DRIA Chapter 2.6.6. For more information on the estimated fuel savings in this rule, see DRIA Chapter 10.2.

Table 4-18: LD sales impacts in the Proposal scenario

Year	No Action	Proposal	
	Total Sales	**Total Sales**	**Change from No Action (%)**
2027	15,487,827	15,432,908	-54,919 (-0.35%)
2028	15,637,207	15,616,676	-20,531 (-0.13%)
2029	15,770,260	15,781,094	10,834 (0.07%)
2030	15,807,049	15,814,296	7,247 (0.05%)
2031	15,884,729	15,860,358	-24,370 (-0.15%)
2032	15,880,160	15,834,010	-46,150 (-0.29%)

Table 4-19 shows results for new LD sales impacts under the three alternative option scenarios as described in Preamble Section II.E. Alternative 1 (-10) is more stringent than the proposed scenario, and Alternative 2 (+10) and Alternative 3 (Linear Phase-in) are less stringent. The results under the most stringent alternative, Alternative 1 (-10) project decreasing sales in all 6 years compared to the No Action case. Alternative 2 (+10) shows results directionally similar to the proposal, above. Alternative 3 (linear) projects one additional year of increasing sales than is seen in the Proposal. The results under Alternative 1 are the largest in magnitude, with the largest result projecting a decrease of less than 0.8 percent in 2032. Alternative 3 projects the smallest change, in magnitude, in the first two years, with Alternative 2 projecting the smallest change, in magnitude, in the last two years. Results in 2029 through 2032 are very similar for the Proposal and the two less stringent scenarios.

Table 4-19: LD sales impacts in the alternative scenarios

Year	Alternative 1 (-10)		Alternative 2 (+10)		Alternative 3 (Linear)	
	Total Sales	**Change from No**	**Total Sales**	**Change from No**	**Total Sales**	**Change from No**

[73] All scenarios, including the No Action scenario, account for purchase and battery production incentives in the IRA, which further reduce the cost of BEVs. For more information on the BEV purchase and battery production incentives included in the consumer generalized cost estimates in OMEGA, see Chapter 2.6.8.

		Action (%)		Action (%)		Action (%)
2027	15,429,939	-57,889 (-0.37%)	15,447,829	-39,998 (-0.26%)	15,476,391	-11,436 (-0.07%)
2028	15,582,224	-54,983 (-0.35%)	15,624,158	-13,048 (-0.08%)	15,643,941	6,734 (0.04%)
2029	15,690,100	-80,160 (-0.51%)	15,778,412	8,153 (0.05%)	15,795,393	25,133 (0.16%)
2030	15,732,702	-74,347 (-0.47%)	15,821,919	14,871 (0.09%)	15,823,563	16,514 (0.10%)
2031	15,774,869	-109,860 (-0.69%)	15,864,090	-20,639 (-0.13%)	15,857,727	-27,001 (-0.17%)
2032	15,758,885	-121,275 (-0.76%)	15,834,633	-45,527 (-0.29%)	15,818,292	-61,868 (-0.39%)

As an alternative representation of results, Figure 4-10 shows the percent change in total new LD vehicle sales compared to the No Action case for all 4 scenarios.

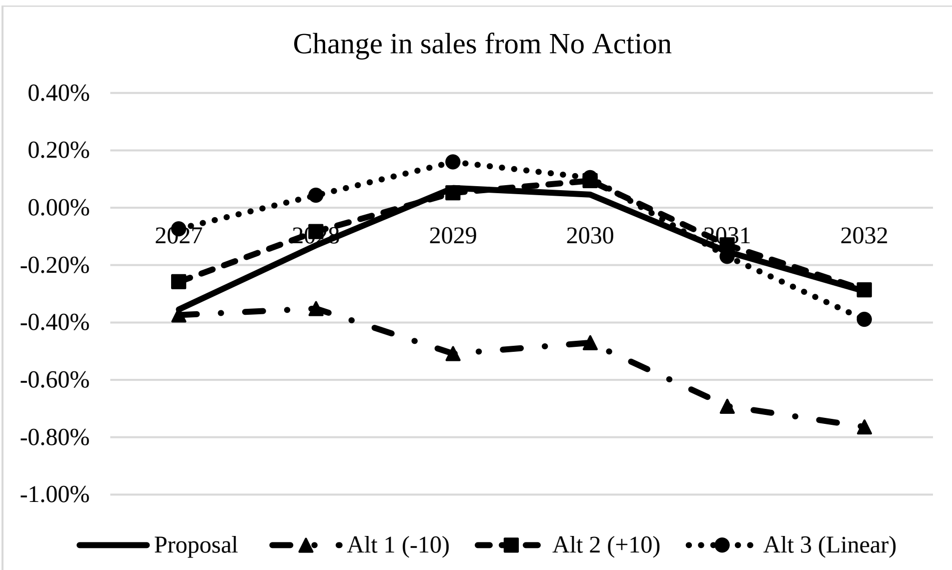

Figure 4-10: Total new LD vehicle sales impacts, percent change from the No Action case.

The results discussed here focus on sales of new LD vehicles, which does affect the total size and make-up of the onroad fleet over time.[74] In addition to new sales, the analysis for the effects of this proposed rule also include estimates of which vehicles are re-registered. Re-registered vehicles are used vehicles that remain on the road and are registered for onroad use for that year. This is the flip side to scrappage, which estimates the vehicles that are taken out of the total onroad fleet. For information on estimates of vehicles re-registered in our analysis, see Chapter 9.3.

[74] The onroad fleet consists of the total count and types of vehicles on the road, and their characteristics including transmission type and age

4.5 Employment

This chapter explains the methods and estimates of employment impacts due to this proposal. The rule primarily affects LD and MD vehicles, suggesting that there may be employment effects in the motor vehicle and parts sectors due to the effects of the standards on sales. Thus, we focus our assessment on the motor vehicle manufacturing and the motor vehicle parts manufacturing sectors, with some assessment of impacts on additional closely related sectors likely to be most affected by the standards.

When the U.S. economy is at full employment, 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.

Chapter 4.5.1 offers a brief, high-level explanation of employment impacts due to environmental regulation and discusses a selection of the peer-reviewed literature on this topic. Chapter 4.5.2 focuses on potential impacts from growing electrification, and Chapter 4.5.3 qualitatively discusses possible employment impacts of this rule on regulated industries. Chapter 4.5.4 presents a quantitative estimate of partial employment impacts that may occur due to this proposed rule. In previous rules, we have quantitatively estimated a cost effect, which should be estimated holding vehicle sales constant. However, the cost estimates come from OMEGA, which estimates the costs of the proposed rule inclusive of the effects of changes in vehicles sold. Therefore, the quantitative partial employment analysis for this rule is a combined cost and demand effect. Chapter 4.5.5 qualitatively discuss potential impacts on related sectors.

4.5.1 <u>Background and Literature</u>

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 channels by which 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 (especially the state of the macroeconomy) and business decisions that affect employment, 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 demand effect, caused by higher production costs increasing market prices and decreasing demand; 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; and a factor shift effect, in which post-regulation production technologies may have different labor intensities than their pre-regulation counterparts. These effects are outlined in a paper by Morgenstern et al., which provides the theoretical foundation for EPA's analysis of the impacts of this regulation on labor (Morgenstern, Pizer and Shih 2002). Due to data limitations, EPA is not quantifying the impacts of the final regulation on firm-level employment for affected companies. Instead, we 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 model two components that drive changes in firm-level labor demand: output effects and substitution effects (Berman and Bui 2001).[75] Deschênes describes environmental regulations as requiring additional capital equipment for pollution abatement that does not increase labor productivity (Deschenes 2018). For an overview of the neoclassical theory of production and factor demand, see Chapter 9 of Layard and Walters' Microeconomic Theory (Layard and Walters 1978). Ehrenberg and Smith 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 (Ehrenberg and Smith 2000).

Arrow et al. 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 (Arrow, et al. 1996). Even if they are mitigated by long-run market adjustments to full employment, many regulatory actions have transitional effects in the short run (Smith 2015) (U.S. OMB 2015). 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 (Curtis 2018) and Hafstead and Williams (Hafstead and Williams III 2018)).

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[75] 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.

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. Consequently, employment impacts are hard to disentangle from other economic changes and business decisions that affect employment, over time and across regions and industries.

4.5.2 Potential Employment Impacts from the Increasing Penetration of Electric Vehicles

In addition to the employment effects we have discussed in previous rules (for example the 2021 rule), the increasing penetration of electric vehicles in the market is likely to affect both the number and the nature of employment in the auto and parts sectors and related sectors, such as providers of battery charging infrastructure. Over time, as BEVs become a greater portion of the new vehicle fleet, the kinds of jobs in auto manufacturing are expected to change: for instance, there will be no need for engine and exhaust system assembly for BEVs, while many assembly tasks will involve electrical rather than mechanical fitting. In addition, 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-assembled modules or packs, from suppliers whose employment will thereby be affected. Employment in building and maintaining battery charging infrastructure needed to support the ever-increasing number of BEVs on the road is also expected to affect the nature of employment in automotive and related sectors. For much of these effects, there is considerable uncertainty in the data to quantitatively assess how employment might change as a function of the increased electrification expected to result under the proposed standards. Some suggest that fewer workers will be needed because BEVs have fewer moving parts (Krisher and Seewer 2021), while others estimate that the labor-hours involved in BEVs is almost identical to that for ICE vehicles (Kupper, et al. 2020).

Prior analyses of employment in the auto sector conducted outside of EPA have estimated a range of impacts. Results from California's ACC II program analysis seem to suggest that there may be a small decrease, not exceeding 0.3 percent of baseline California employment in any year, in total employment across all industries in CA through 2040 (California Air Resources Board 2022). A report by the Economic Policy Institute suggests that US employment in the auto sector could increase if the share of vehicles, or powertrains, sold in the US that are produced in the US increases. The BlueGreen Alliance also states that though BEVs 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 (BlueGreen Alliance 2021). They go on to state that if the US does not become a major producer for these components, there is risk of job loss.

The UAW states that re-training programs will be needed to support auto workers in a market with an increasing share of electric vehicles in order to prepare workers that might be displaced by the shift to the new technology (UAW 2020). 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 (Herrmenn, et al. 2020). Research from the Seattle Jobs Initiative indicates that employment in a collection of sectors related to both BEV and ICE vehicle manufacturing is expected to grow slightly through 2029 (Seattle Jobs Initiative 2020). Climate Nexus also indicates that transitioning to 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 (Climate Nexus 2022). This expected investment 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. (Infrastructure Investment and Jobs Act 2021). [76] The CHIPS Act, signed in August, 2022, invests in expanding America’s manufacturing capacity for the semiconductors used in electric vehicles and chargers (CHIPS Act of 2022 2022). [77] The IRA provides incentives for producers to expand domestic manufacturing of BEVs and domestic sourcing of components and critical minerals needed to produce them (117th Cong. 2022). The IRA also provides incentives for consumers to purchase both new and used BEVs. 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 reliable EV battery supply chains.[78] The BlueGreen Alliance and PERI estimate that IRA will create over 9 million jobs over the next decade, with about 400,000 of those jobs being attributed directly to the battery and fuel cell vehicle provisions in the act (Political Economy Research Institute 2022).

The U.S. Bureau of Labor Statistics (BLS) recently published an article which identifies three key occupational areas they expect to be affected by growth in the BEV market, as well as estimates a change in employment in those sectors between 2021 and 2031 (Colato and Ice 2023). This outlook from the BLS indicates that the increasing prevalence of BEVs in the market can lead to growth in employment in a range of sectors, including sectors beyond those discussed in this analysis. The authors note that though it is expected that these sectors will be significant in BEV production and deployment, they include estimates of the total employment change across all sectors, not just those related to BEV production and deployment. For example, the estimates for the change in employment of construction laborers is the effect from all construction sectors, not just those related to the construction of BEV charging infrastructure. In the report, BLS estimated employment changes related to occupations employed in the design and development of electric vehicles, including software developers, electrical engineers, electronics engineers, and chemical engineers; battery manufacturing, including electrical, electronic and electromechanical assemblers, and miscellaneous assemblers and fabricators; and

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[76] 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/

[77] 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/

[78] 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

charging network development and maintenance, including urban and regional planners, electrical, electrical power-line installers and repairers, and construction laborers. With the exception of the sector miscellaneous assemblers and fabricators, BLS is forecasting an increase in employment across the board, with the smallest increase, in percentages, being 1.6 percent (electrical engineers), and the largest increase (software developers) being 26 percent.[79] BLS states that though total employment in the miscellaneous assemblers and fabricators sector is projected to fall, they do expect a number of job openings in the sector each year to replace workers who transfer to different occupations or exit the work force. Again, it is difficult to separate out the effect that the increase in BEV production will have on these sectors from the macroeconomic effects, or the effects from non-BEV related production activity.

4.5.3 Potential Employment Impacts of the Proposed Standards

Because it is challenging to know the state of the macroeconomy when these standards become effective, the changing nature of auto manufacturing employment due to the transition to electric vehicles, and the difficulties of modeling impacts on employment in a complex national economy, we focus our analysis on the direct impacts in closely affected sectors. In the next sections, we discuss potential impacts of industry-level employment effects of the proposed rule. We qualitatively describe the employment impacts due to the factor shift, demand effects and cost effect, following the structure of Morgenstern et al., as described above. Then we present a quantitative estimate of partial employment effects of the proposed standards, followed by a discussion of possible employment impacts on related sectors.

4.5.3.1 The Factor Shift Effect

The factor shift effect reflects employment changes due to changes in labor intensity of production resulting from compliance activities. A factor shift effect of this rule might occur if this proposed regulation affects the labor intensity of production of ICE vehicles. It may also occur if a BEV 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. There is ongoing research on the different labor intensity of production between ICE and BEV production, with inconsistent results. Some research indicates that the labor hours needed to produce a BEV are fewer than those needed to produce an ICE vehicle, while other research indicates there are no real differences. EPA is currently working with a research group to produce a peer-reviewed tear-down study of a BEV to its comparable ICE counterpart. For more information on this study, see Chapter 2.5.2.2.3. For information on the early indications of labor differences in ICE and BEV production, see Chapter 4.5.4. As part of this study, we will receive estimates of labor intensity needed to produce each vehicle. We hope to use this information in additional analytical discussions in the final rule. Given the current lack of data and inconsistency in the existing literature, we are unable to estimate a factor shift effect in ICE vehicle production, nor of increasing relative BEV production as a function of this rule.

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[79] The urban and regional planners sector is forecast to have the smaller increase in number of employees, with an increase of about 1,600 employees between 2021 and 2031.

4.5.3.2 The Demand Effect

Demand effects on employment are due to changes in labor that result from changes in total new vehicle sales. In previous EPA LD regulations, like the 2021 rule, we have used the CAFE model to estimate effects of a change in ICE vehicle demand on labor. The model uses a method of estimating a demand effect on employment through the relationship of hours involved in a new vehicle sale (for the effect on automotive dealers) or average labor hours per vehicle at a sample of US assembly plants (for the effect on the final assembly industry) to the change in the number of vehicles sold due to the regulation. This rule, however, uses EPA's OMEGA model. We currently do not have the data to estimate these effects in OMEGA.

In general, if the proposed regulation causes total sales of new vehicles to decrease, keeping the share of BEVs in the new vehicle fleet constant, fewer workers will be needed to assemble vehicles and manufacture their components. If BEVs and ICE vehicles have different labor intensities of production, the relative change in BEV and ICE sales will impact the demand effect on employment. If, for example, total new BEV sales increase more than total new ICE sales falls, a portion of the change in employment, where the new BEVs replace ICE vehicles, would be attributed to factor shifts. The additional new BEV sales would increase labor needs by the labor intensity of BEV production. Due to lack of data, as discussed in the Chapter 4.5.3.1, we are unable to estimate a change in the employment due to a relative shift in BEV and ICE vehicle demand, or a change in employment due to a change in demand.

4.5.3.3 The Cost Effect

The cost effects on employment are due to changes in labor associated with increases in costs of production. In general, if a regulation leads firms to invest in lower-emitting vehicles, we expect an increase in the labor used to implement those technologies. In previous LD and heavy-duty (HD) rules, we have estimated a partial employment effect due to the change in costs of production, where the change in costs of production were assumed to be the change in technology costs estimated as a result of the rule being analyzed. We estimated the cost effect using the historic share of labor in the cost of production to extrapolate future estimates of impacts on labor due to new compliance activities in response to the regulations. Specifically, we multiplied the share of labor in production costs by the production cost increase estimated as an impact of the rule. This provided a sense of the magnitude of potential impacts on employment. For this rule, we estimate partial employment effects using this same basic method. However, as explained further in Chapter 4.5.4, the impacts estimated in this proposed rule are a combined cost and demand effect due to how costs are estimated in OMEGA.

The use of the ratio of the share of labor in production costs to estimate a cost effect on employment has both advantages and limitations. It is often possible to estimate these ratios for detailed sector definitions, for example, the average number of workers in the automobile and light-duty motor vehicle manufacturing sector per $1 million spent in that sector, rather than using ratios from more aggregated sectors, such as the motor vehicle manufacturing sector. This would avoid extrapolating employment ratios from less closely related sectors. On the other hand, 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 vehicles 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 industries that supply these sectors, such as steel or electronics producers. The effects estimated with this method can be viewed as effects on employment in the sectors included in the analysis due to the changes in expenditure in that sector, rather than as an assessment of all employment changes due to the standards being analyzed. In addition, labor intensity is held constant in the face of increased expenditures; this approach does not take changes in labor intensity due to changes in the nature of production (the factor shift effect) into account, which could either increase or decrease the employment impacts estimated using this method.

BEVs and ICE vehicles require different inputs and have different costs of production, though there are interchangeable, common, parts as well. We used a recent report from the Seattle Jobs Initiative, which identified sectors most strongly associated with ICE and BEV automotive production, to determine a list of sectors that may be directly affected by our proposed rule (Seattle Jobs Initiative 2020). Sectors that are mainly associated with BEV production include electrical equipment and manufacturing and other electrical equipment and component manufacturing. Sectors that include employment related to both EV and ICE manufacturing include motor vehicle manufacturing, motor vehicle body and trailer manufacturing, and motor vehicle parts manufacturing. A sector that is only associated with ICE vehicle manufacturing is motor vehicle gasoline engine and engine parts 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 2021 (Bureau of Labor Statistics 2023). Over time, the amount of labor needed in the motor vehicle industry has changed: automation and improved methods have led to significant productivity increases. This is supported by this historical data. In Figure 4-11, we can see that the workers per $1 million in sales for all five of these sectors has, generally, decreased over time. For instance, in 1997, about 1.2 workers in the Motor Vehicle Manufacturing sector were needed per $1 million, but only 0.5 workers by 2021 (in 2020$). The three sectors mainly associated with BEV manufacturing show an increase in recent years, with the 2020 ratios for electrical equipment manufacturing and other electrical equipment and component manufacturing surpassing those estimated in 2005. This indicates that these sectors have become more labor intensive over time.

Figure 4-11 shows the estimates of employment per $1 million of expenditure for each sector, adjusted to 2020 dollars using the U.S. Bureau of Economic Analysis Gross Domestic Product Implicit Price Deflator. The values are adjusted to remove effects of imports through the use of a ratio of domestic production to domestic sales of 0.81.[80]

[80] 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 2009-2021, the proportion averages 0.83 percent. From 2016-2021, the proportion average is slightly lower, at 0.81 percent.

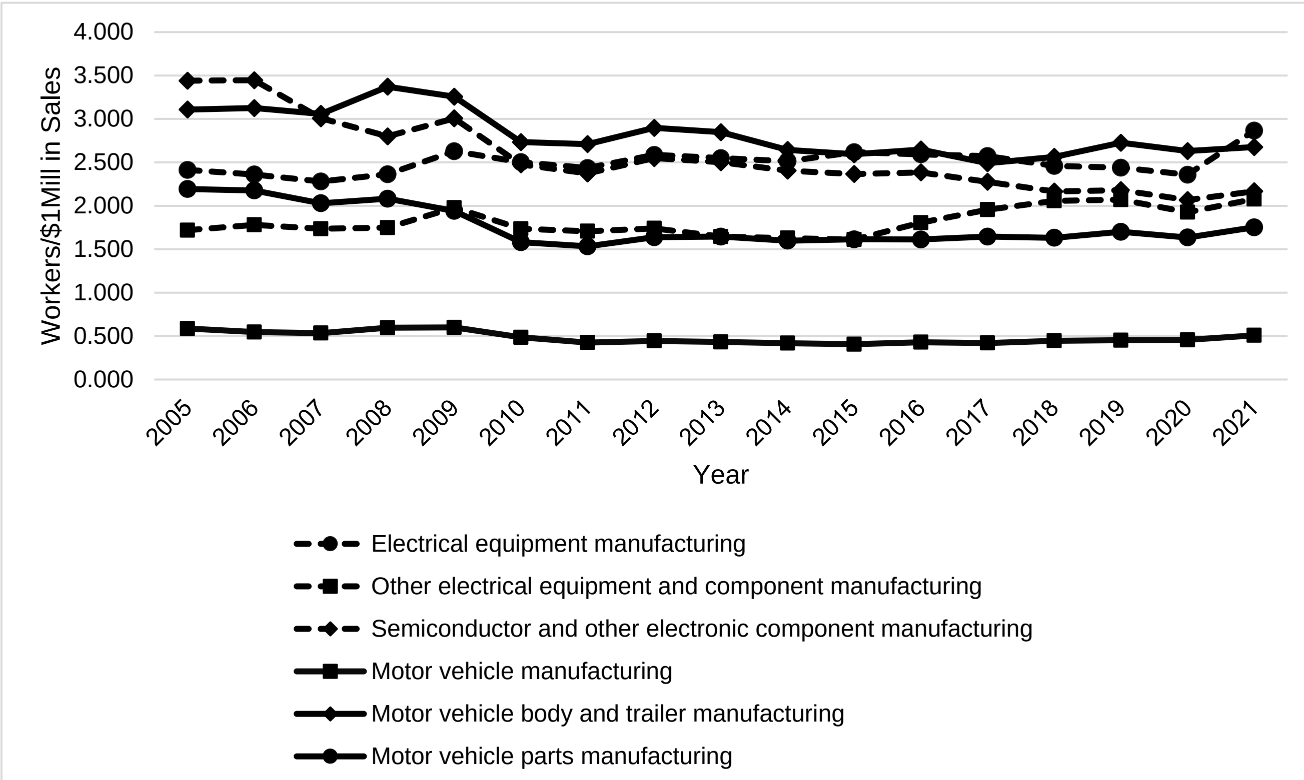

Figure 4-11: Workers per million dollars in sales, adjusted for domestic production.

4.5.4 Partial Employment Effects of the Proposed Standards

In previous LD rules, EPA has estimated a cost effect on employment holding sales constant, and assuming labor intensity is held constant in the face of increasing expenditures. However, the costs in this proposal are estimated in OMEGA, which works iteratively to estimate a vehicle fleet that will meet the regulatory standards, as well as be accepted by consumers. The model estimates this by both changing the number of new vehicles sold, as well as changing the penetration of BEVs in the market between the No Action and Action cases. Therefore, though the method used, described in this Chapter 4.5.4, is the same as that in previous rules, we are unable to estimate a cost employment effect due to this rule while holding sales constant. Therefore, the partial employment analysis presented here is a change in employment due to the change in costs, allowing sales to change as well. In other words, it is a combined cost and demand effect.

We estimate the partial employment effect using the historic share of labor in the cost of production for a set of sectors affected by this rule. We use these historic shares to extrapolate estimates of future shares of labor in the cost of production for each of those sectors. We then multiply the estimated share of labor in production costs by the change in production costs estimated as an impact of this proposed rule. This provides a sense of the magnitude of potential impacts on employment. The advantages and limitations of this method are described in Chapter 4.8.3.3.

We rely on three different public sources to get a range of estimates of employment per $1 million expenditures: the Economic Census (EC) and the Annual Survey of Manufactures (ASM), both provided by the U.S. Census Bureau, and the Employment Requirements Matrix (ERM) provided by the U.S. Bureau of Labor Statistics (BLS). The EC is conducted every 5 years, most recently in 2017.[81] The ASM is an annual subset of the EC and is based on a sample of establishments. The latest set of data from the ASM is from 2021. The EC and ASM have more sectoral detail than the ERM, providing estimates out to the 6-digit North American Industry Classification System (NAICS) code level. They provide separate estimates of the number of employees and the value of shipments, which we convert to a ratio for this employment analysis.[82] The ERM 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 it provides data through 2020.

We estimate cost effects on employment by separating out costs mainly associated with BEV production, costs mainly associated with ICE vehicle production, and costs that are common to ICE and BEV production due to this rule, applying the BEV cost increases to data from sectors that primarily include BEV production, ICE costs to the sectors that primarily include ICE production, and common costs to a set of sectors that include both BEV and ICE manufacturing. We use the sum of the estimated BEV, ICE and common costs for both LD and MD vehicles. We used a report from the Seattle Jobs Initiative to identify sectors most strongly associated with

[81] Though the Economic Census was conducted in 2022, data from 2022 will not begin to be released until March 2024.

[82] The total employment across the NAICS code sectors used in this analysis (see Table 10-6) as reported in the ASM and the EC ranges from about 1,052,500 to about 1,053,800 depending on which data source is used; as noted above the most recent data for ASM and EC are from 2021 and 2017, respectively.

ICE or BEV automotive production and sectors that are common between them (Seattle Jobs Initiative 2020).

Table 4-20 below shows the sector definition, the NAICS code, and the ERM sector number EPA used to estimate employment effects in this analysis. It also provides the estimates of employment per $1 million of expenditure for each sector for each data source, adjusted to 2020 dollars using the U.S. Bureau of Economic Analysis Gross Domestic Product Implicit Price. The values are adjusted to remove effects of imports through the use of a ratio of domestic production to domestic sales of 0.81.[83] While the estimated labor ratios differ across data sources, they are fairly similar, and mainly exhibit a similar pattern across the ICE and common sectors. Within the BEV focused sectors, the ASM and EC are very similar, while the order of most intensive to least intensive as estimated by the ERM differs. This may be due to the inclusion of additional NAICS sectors within the larger ERM sectors.[84] Within the ASM and EC data, Other Electronic Component Manufacturing seems to be the most labor-intensive sector, while ERM indicates Motor and Generator Manufacturing is the most labor-intensive. All three data sets agree that Automobile and Light-Duty Motor Vehicle Manufacturing is the least labor-intensive.

Table 4-20: Sectors and associated workers per million dollars in expenditures used in this analysis

	Sector	**NAICS Code**	**ERM Sector**	**Ratio of Workers per $1 Million Expenditures[a]**		
				ASM (2018)	**EC (2017)**	**ERM (2021)**
BEV Sectors	Other electronic component manufacturing	334419	73	3.4	3.3	2.2
	Motor and generator manufacturing	335312	78	2.2	2.2	2.9
	Battery manufacturing	33591	79	2.6	2.5	2.1
	All other miscellaneous electrical equipment and component manufacturing	335999	79	2.6	2.5	
Sectors Common to ICE and BEV	Automobile and light duty motor vehicle manufacturing	33611	80	0.5	0.5	0.5
	Motor vehicle body and trailer manufacturing	3362	81	2.6	2.3	2.7
	Motor vehicle parts manufacturing (not gasoline engines)	3363*	82	1.9	1.8	1.8
	Motor vehicle electrical and electronic equipment manufacturing	33632	82	2.0	1.9	
ICE Sectors	Motor vehicle gasoline engine and engine parts manufacturing	33631	82	1.3	1.2	

[a] Values are adjusted for domestic vs. foreign production
* In our analysis, 3363 excludes estimates for NAICS code 33631. NAICS code 33631 only includes ICE vehicle manufacturing, so we subtract those data out from the main sector, NAICS code 3363, and apply ICE costs to that sub-sector.

Because the ERM is available annually for 1997-2021, we use these data to estimate productivity improvements over time. We regress logged ERM values on a year trend for each

[83] 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 2009-2021, the proportion averages 83 percent. From 2016-2021, the proportion average is slightly lower, at 81 percent.
[84] ERM sectors are based on the 4-digit level for NAICS code sectors. For example, ERM sector 73, consists of results from manufacturers in NAICS code 3344.

sector.[85] We use this approach because the coefficient describing the relationship between time and productivity is a direct measure of the average percent change in productivity per year. The results show productivity changes in Semiconductor and Other Electronic Component Manufacturing (ERM sector 73) of almost -6 percent per year, Electrical Equipment Manufacturing (ERM sector 78) of about -0.5 percent per year, Other Electrical Equipment and Component Manufacturing (ERM sector 79) of about 0.1 percent per year, Motor Vehicle Manufacturing (ERM sector 80) of almost -3 percent per year, Motor Vehicle Body and Trailer Manufacturing (ERM sector 81) or almost -1.5 percent per year, and Motor Vehicle Parts Manufacturing (ERM sector 82) of about -2.6 percent per year. These figures coincide with the general fall in workers per million dollars in sales as seen in Figure 4-11.

We then use those estimated percent improvements in productivity to project the number of workers per $1 million of production expenditures through 2032. The results provided in Table 4-21 below represent an order of magnitude effect, rather than definitive impacts. We calculate separate sets of projections (adjusted to 2020$) for each set of data (ERM, EC, and ASM) for all sectors described above. The ERM projections are calculated directly from the fitted regression equations used to estimate the projected productivity growth, since the regressions themselves used ERM data. For the ASM and EC projections of the number of workers needed per $1 million of expenditures (in 2020$), we apply ERM's ratio of projected annual productivity growth to the projected production expenditure value in 2021 for the ASM and 2017 for the EC (the base years in our data). In other words, we apply the projected productivity growth estimated using the ERM data to the ASM and EC numbers.

To simplify the results, we compare the projected employment across data sources and report only the maximum and minimum (in absolute terms) effects in each year across all sectors.[86] We provide a range rather than a point estimate because of the inherent difficulties in estimating employment impacts as well as the uncertainty over how the costs are expended. The reported ranges provide an estimate of the expected magnitude of the effect. The employment effect estimated here includes the costs of this rule for both LD and MD vehicles, as well as the change in new vehicles sales for LD vehicles due to this rule. There are no estimated changes in MD vehicle sales. See Chapter 4.4.2 for more information on the estimates of new vehicle sales effects due to this rule.

Vehicle technology cost estimates for this rule were developed in OMEGA. Chapter 10 provides information on the total and per-vehicle costs estimated. For this analysis, we use detailed OMEGA results to get estimates of the costs of manufacturing LD and MD vehicles separated out by costs expected to apply only to BEVs, those expected to only apply to ICE vehicles, and those expected to apply to both BEV and ICE vehicles. These costs (in $ million) are multiplied by the estimates of workers per $1 million in costs. The projected estimates of technology costs and corresponding minimum and maximum estimated employment impacts for each year are shown in Table 4-21, below. The effects are shown in job-years, where a job-year

[85] Details and results are found in the file LMDV_NPRM_EmploymentImpactsCalculations.xlsx, which is in the docket for this rule.

[86] To see details, as well as results for all sources, see "LMDV_NPRM_EmploymentImpactsCalculations.xlsx" in the docket.

is, for example, one year of full-time work for one person or two years of half-time work for two workers.

Increased technology costs of vehicles and parts is, allowing for the estimated change in sales due to the proposal, expected to increase employment over the 2027-2032 time frame under the assumptions of the maximum estimated effects, with the increase coming from the sectors common to BEV and ICE production. Changes in ICE and BEV focused manufacturing are expected to lead to a decrease in job-years in the sector included in this analysis. Under the assumptions of the minimum estimated effects, we are estimating a net negative employment effect. In addition, though the range of possible net effects includes zero, the net maximum impact is larger, in absolute value, than the net minimum impact.[87]

It should be noted that these results are exclusive of any changes in employment in related sectors, such as charging infrastructure. While we estimate employment impacts, measured in job-years, beginning with program implementation, some of these employment gains may occur earlier as vehicle manufacturers and parts suppliers hire staff in anticipation of compliance with the standards, or in anticipation of ramping up BEV production.

Table 4-21: Estimated partial employment effects in job-years for BEV and ICE sectors, sectors common to BEV and ICE, and the net minimum and maximum across all sectors

	Common to BEV and ICE		BEV only		ICE only		Net	
Year	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**
2027	7,620	54,000	-9,800	-11,700	-10,200	-11,500	-12,380	30,800
2028	8,600	61,600	-9,100	-11,600	-13,900	-15,700	-14,400	34,300
2029	10,300	75,200	-9,000	-12,100	-19,200	-21,600	-17,900	41,500
2030	11,700	86,900	-9,100	-12,800	-21,600	-24,300	-19,000	49,800
2031	14,600	109,900	-10,100	-15,100	-26,100	-29,300	-21,600	65,500
2032	17,500	133,300	-11,100	-17,500	-30,500	-34,300	-24,100	81,500

EPA contracted with FEV to perform a detailed tear-down study comparing two similar vehicles, a 2021 Volkswagen ID.4 (BEV) and a 2021 Volkswagen Tiguan (ICE) (see DRIA Chapter 2.5.2.2.3 for more details on this study). In the process of compiling the detailed information, FEV estimated the number of labor hours it takes to build each of the two vehicles. Under a realistic scenario of assembly based on what OEMs are currently doing, their results suggest that the labor hours needed to assemble the BEV and ICE vehicles are very similar.[88] This indicates that changes in employment in the auto manufacturing sectors from increasing

[87] Comparing the net results in Table 4-21 to the lower estimate of total employment across all sectors found in footnote 82 (1,052,500), net employment effects estimated under the Proposal scenario for 2032 range from -2.3% to 7.7% of total employment across the sectors.

[88] In the realistic scenario, FEV assumes that the automakers purchase EV battery modules and assemble the pack. Under assumptions that the auto manufacturers provide the least amount of added value in assembly, the Tiguan (ICE) is estimated to require more man hours to assemble than the ID.4 (BEV). Under assumptions that the auto manufacturers perform most of the sub system manufacturing and assembly, including the engine, transmission and battery pack modules, the ID.4 (BEV) is estimated to take more man hours per vehicle than the Tiguan (ICE).

electrification will not come from the assembling of the vehicles at the auto manufacturer, but from changing sales.

4.5.4.1 Partial Employment Effects of the Alterative Scenarios

The estimated partial effect on employment for the three alterative scenarios are in Table 4-22 through Table 4-24, below. Results are directionally similar across all scenarios. Similar to the results for the proposal, job-years in BEV and ICE related sectors are estimated to fall, while job-years in sectors common to BEV and ICE are expected to increase. Also like the Proposed scenario, though the range of possible net effects includes zero, the net maximum impact is larger, in absolute value, than the net minimum impact for all alternative scenarios.

Table 4-22: Estimated partial employment effects in job-years for BEV and ICE sectors, sectors common to BEV and ICE, and the net minimum and maximum across all sectors for Alternative 1 (-10)

	Common		BEV		ICE		Net	
Year	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**
2027	8,000	56,600	-10,000	-12,000	-10,700	-12,100	-12,700	32,500
2028	10,100	73,000	-8,100	-10,300	-16,000	-18,000	-14,000	44,700
2029	11,600	84,500	-7,100	-9,500	-17,400	-19,500	-12,900	55,500
2030	15,000	111,000	-9,000	-12,700	-24,200	-27,200	-18,200	71,100
2031	16,500	124,100	-9,100	-13,500	-25,900	-29,200	-18,500	81,400
2032	19,200	146,400	-10,500	-16,500	-30,600	-34,500	-21,900	95,400

Table 4-23: Estimated partial employment effects in job-years for BEV and ICE sectors, sectors common to BEV and ICE, and the net minimum and maximum across all sectors for Alternative 2 (+10)

	Common		BEV		ICE		Net	
Year	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**
2027	5,500	38,700	-7,500	-9,000	-6,900	-7,800	-8,900	21,900
2028	5,800	42,000	-6,300	-8,000	-9,100	-10,300	-9,600	23,700
2029	9,000	65,800	-8,100	-10,900	-16,700	-18,800	-15,800	36,100
2030	9,200	68,000	-7,800	-11,000	-17,200	-19,300	-15,800	37,700
2031	12,500	94,200	-9,200	-13,800	-22,200	-25,000	-18,900	55,400
2032	15,500	117,900	-10,200	-16,200	-26,600	-29,900	-21,300	71,800

Table 4-24: Estimated partial employment effects in job-years for BEV and ICE sectors, sectors common to BEV and ICE, and the net minimum and maximum across all sectors for Alternative 3 (Linear)

	Common		BEV		ICE		Net	
Year	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**
2027	4,100	29,000	-7,300	-8,800	-5,800	-6,500	-9,000	13,700
2028	4,800	34,700	-7,400	-9,400	-8,100	-9,200	-10,700	16,100

2029	5,200	37,800	-6,300	-8,500	-10,100	-11,400	-11,200	17,900
2030	8,300	61,700	-7,900	-11,200	-15,700	-17,700	-15,300	32,800
2031	14,000	105,500	-10,800	-16,100	-24,900	-28,000	-21,700	61,400
2032	18,100	137,800	-12,300	-19,300	-30,900	-34,800	-25,100	83,700

4.5.5 Employment Impacts on Related Sectors

Economy-wide impacts on employment are generally driven by broad macroeconomic effects. However, employment impacts, both positive and negative, in sectors upstream and downstream from the regulated sector, or in sectors producing substitute or complementary products, may also occur as a result of this rule.

For example, as described in DRIA Chapter 9.5, we expect the proposed rule to cause a small decline in liquid fuel consumption and a small increase in electricity generation which may have consequences for labor demand in those upstream industries, as well as associated industries such as extracting, refining, transporting, and storing of petroleum fuels. The lower per-mile fuel costs could lead to increases in demand for ride-hailing services and cause increases in demand for drivers in those jobs. Firms producing substitutes or complements to the goods produced by the regulated industry may also experience changes in demand for labor. For example, the expected decline in gas station visits may lead to reduced demand for labor in that sector. Although gasoline stations will sell less fuel, the fact that many provide other goods, such as food or car washes, moderates possible losses in this sector. There will also likely be an increase in demand for labor in sectors that build and maintain charging stations. The magnitude of these impacts depends on a variety of factors including the labor intensities of the related sectors as well as the nature of the linkages between them and the regulated firms.

Expected petroleum fuel consumption reductions found in Chapter 9.5 represent fuel savings for purchasers of fuel, however they also represent a potential loss in value of output for the petroleum refining industry, fuel distributors, and gasoline stations. The loss of expenditures to petroleum fuel suppliers throughout the petroleum fuel supply chain, from the petroleum refiners to the gasoline stations, could result in reduced employment in these sectors. Because the fuel production sector is material-intensive, the employment effect is not expected to be large. It may also be difficult to distinguish these effects from other trends, such as increases in petroleum sector labor productivity that may also lower labor demand. In addition, there is uncertainty about the impact of reduced domestic demand for petroleum fuels on the petroleum fuel supply chain. For instance, refineries might export the volumes of gasoline and diesel fuel that would otherwise have been consumed in light- and medium-duty vehicles, absent this rulemaking. In that scenario there would be no impact on employment at refineries.

As discussed in Chapter 4.5.2, above, electrification of the vehicle fleet is likely to affect both the number and the nature of employment in the auto and parts sectors and related sectors, such as providers of charging infrastructure. In addition, the type and number of jobs related to vehicle maintenance are expected to change, though we expect this to happen over a longer time span due to the nature of fleet turnover. Though we expect the sale of new BEVs to increase over the time span of this proposed rule, both new and used ICE vehicles will persist in the fleet for many years. As vehicles age, they generally require greater amounts of maintenance, possibly mitigating the expected reduction in the number of ICE vehicles in the onroad fleet over time.

Over this same time span, though we estimate less maintenance needs for BEVs compared to ICE vehicles, the total employment related to BEV maintenance is expected to increase due to the increase in number of BEVs in the onroad fleet. Even if the increase in BEV maintenance-related employment is smaller than the decrease in ICE vehicle maintenance-related employment over time, we expect opportunities for workers to retrain to other positions, for example within BEV maintenance, charging station infrastructure, or elsewhere in the economy.

Effects in the supply chain depend on where goods in the supply chain are developed. Commenters on the 2021 LD rule argue that developing EVs in the U.S. is critical for domestic employment, and for the global competitiveness of the U.S. in the future auto industry: as other countries are moving rapidly to develop EVs, the U.S. auto industry risks falling behind. As discussed in Preamble Section I.A.2.iii and DRIA 4.5.2, there have been several legislative and administrative efforts enacted several acts since 2021 aimed at improving the domestic supply chain for electric vehicles, including electric vehicle chargers, critical minerals, and components needed by domestic manufacturers of EV batteries. These actions are also expected to provide opportunities for domestic employment in these associated sectors.

The standards may affect employment for auto dealers through a change in vehicles sold, with increasing sales being associated with an increase in labor demand. However, vehicle sales are also affected by macroeconomic effects, and it is difficult to separate out the effects of the standards on sales from effects due to macroeconomic conditions. In addition, auto dealers may be affected by changes in maintenance and service costs. Increases in those costs are likely to increase labor demand in dealerships, and reductions are likely to decrease labor demand. Auto dealers may also be affected by changes in the maintenance needs of the vehicles sold. For example, reduced maintenance needs of BEVs could lead to reduced demand for maintenance labor for dealers that sell BEVs.

As a result of these standards, consumers will likely pay higher up-front costs for the vehicles, but they are expected to recover those costs through reduced fuel, maintenance, and repair costs, as well as due to the IRA tax incentives for BEV purchase and battery manufacturing leading to reduced up-front costs for BEVs. As a result, consumers are expected to have additional money to spend on other goods and services, though the timing of access to that additional money depends on aspects including whether the consumer borrows money to buy the vehicle. These increased expenditures could support employment in those sectors where consumers spend their savings. If the economy is at full employment, any change in consumer expenditures would primarily represent a shift in employment among sectors. If, on the other hand, the economy has substantial unemployment, these expenditures would contribute to employment through increased consumer demand.

Chapter 4 References

Arrow, R.G., M.L. Cropper, G.C. Eads, R.W. Hahn, L.B. Lave, R.G. Noll, P.R. Portney, et al. 1996. "Is There a Role for Benefit-Cost Analysis in Environmental, Health, and Safety Regulation?" Science 272 (5259): 221-222.

Autolist. 2022. How Long Should I Keep My Car. June 24. Accessed February 07, 2023. https://www.autolist.com/guides/how-long-should-i-keep-my-car.

Bartlett, Jeff. 2022. More Americans Would Buy and Electric Vehicle, and Some Consumers Would Use Low-Carbon Fuels, Survey Shows. Consumer Reports. July 7. Accessed March 2, 2023. https://www.consumerreports.org/hybrids-evs/interest-in-electric-vehicles-and-low-carbon-fuels-survey-a8457332578/.

Bauer, Gordon, Chih-Wei Hsu, Mike Nicholas, and Nic Lutsey. 2021. Charging Up America: Assessing the Growing Need for U.S. Charging Infrastructure through 2030. The International Council on Clean Transportation. https://theicct.org/sites/default/files/publications/charging-up-america-jul2021.pdf.

Berman, E., and L.T.M. Bui. 2001. "Environmental Regulation and Labor Demand: Evidence from the South Coast Air Basin." Journal of Public Economics 79 (2): 265-295.

Blackley, Julie. n.d. How Long Do People Keep Their Cars? Accessed 02 07, 2023. https://www.iseecars.com/how-long-people-keep-cars-study.

BlueGreen Alliance. 2021. "Backgrounder: EVs are Coming. Will They be Made in the USA?" https://www.bluegreenalliance.org/wp-content/uploads/2021/04/Backgrounder-EVs-Are-Coming.-Will-They-Be-Made-in-the-USA-vFINAL.pdf.

Borlaug, Brennan, Shawn Salisbury, Mindy Gerdes, and Matteo Muratori. 2020. "Levelized Cost of Charging Electric Vehicles in the United States." Joule 4: 1470-1485. doi:https://doi.org/10.1016/j.jopule.2020.05.013.

Bui, Anh, Peter Slowik, and Nic Lutsey. 2020. Update on electric vehicle adoption across U.S. cities. International Council on Clean Transportation. https://theicct.org/wp-content/uploads/2021/06/EV-cities-update-aug2020.pdf.

Bureau of Labor Statistics. 2023. Real Domestic Employment Requirements. Accessed January 2023. http://www.bls.gov/emp/ep_data_emp_requirements.htm.

Burlig, Fiona, James Bushnell, David Rapson, and Catherine Wolfram. 2021. "Low Energy: Estimating Electric Vehicle Electricity Use." AEA Papers and Proceedings 111: 430-435.

Burnham, Andrew, David Gohlke, Luke Rush, Thomas Stephens, Yan Zhou, Mark A Delucchi, Alicia Birly, et al. 2021. Comprehensive Total Cost of Ownership Quantification for Vehicles with Different Size Classes and Powertrains. ANL/ESD-21/4, Energy Systems Division, Lemont, IL: Argonne National Laboratory. https://publications.anl.gov/anlpubs/2021/05/167399.pdf.

2021. "CAFE TSD." Technical Support Document: Proposed Rulemaking for Model Years 2024-2026 Light-Duty Vehicle Corporate Average Fuel Economy Standards. NHTSA, Department of Transportation, August.

California Air Resources Board. 2022. "Public Hearing to Consider the Proposed Advanced Clean Cars II Regulations Staff Report: Initial Statement of Reasons." https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2022/accii/isor.pdf.

Chakraborty, Debapriya, Scott Hardman, and Gil Tal. 2022. "Integrating plug-in electric vehicles (PEVs) into household fleet- foactors influencing miles traveled by PEV owners in California." Travel Behavior and Society 26: 67-83.

CHIPS Act of 2022. 2022. H.R. 4346 (117th Cong. Sess. 2).

Climate Nexus. 2022. "Job Impacts From the Shift to Electric Cars and Trucks." Accessed December 2022. https://climatenexus.org/climate-issues/energy/ev-job-impacts/.

Colato, J, and L Ice. 2023. "Charging into the Future: The Transition to Electric Vehicles." Beyond the Numbers: Employment & Unemployment (U.S. Bureau of Labor Statistics) 12 (4). https://www.bls.gov/opub/btn/volume-12/charging-into-the-future-the-transition-to-electric-vehicles.htm.

Consumer Reports. 2022. "Survey Says: Considerable Interest in Electric Vehicles Across Racial, Ethnic Demographics."

Curtis, M.E. 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.

Davis, Lucas W. 2022. "Electric vehicles in multi-vehicle households." Applied Economics Letters. doi:https://doi.org/10.1080/13504851.2022.2083563.

Davis, Lucas W. 2019. "How much are electric vehicles driven?" Applied Economics Letters 26 (18): 1497-1502. doi:https://doi.org/10.1080/13504851.2019.1582847.

Deschenes, O. 2018. "Balancing the Benefits of Environmental Regulations for Everyone and the Costs to Workers and Firms." IZA World of Labor. Vol. 22v2. https://wol.iza.org/uploads/articles/458/pdfs/environmental-regulations-and-labor-markets.pdf.

Edmunds. 2023. Cost of Car Ownership. Accessed January 6, 2023. Edmunds.com/tco.html.

Ehrenberg, R.G., and R.S. Smith. 2000. Modern Labor Economics: Theory and Public Policy. Addison Wesley Longman, Inc.

ERM. 2022. "Electric Vehicle Market Update: Manufacturer Commitments and Public Policy Initiatives Supporting Electric Mobility in the U.S. and Worldwide. Contract Report to the Environmental Defense Fund." Accessed 12 16, 2022. https://blogs.edf.org/climate411/files/2022/04/electric_vehicle_market_report_v6_april2022.pdf.

Fischer, Carolyn. 2005. "On the Importance of the Supply Side in Demand-Side Management." Energy Economics 17: 165-180.

Fujita, K Sydny, Hung-Chia Yang, Margaret Taylor, and Dana Jackman. 2022. "The Green Light on Buying a Car: How Consumer Decision Making Interacts with Environmental Attributes in the New Vehicle Purchase Process." Transportation Research Record 2676 (7): 743-762.

GCAM. n.d. GCAM v6 Documentation: Economic Choice in GCAM. Accessed 03 05, 2023. https://jgcri.github.io/gcam-doc/choice.html.

Ge, Yanbo, Christina Simeone, Andrew Duvall, and Andrew Wood. 2021. There's No Place Like Home: Residential Parking, Electrical Access, and Implications for the Future of Electric Vehicle Charging Infrastructure. NREL/TP-5400-81065, Golden, CO: National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy22osti/81065.pdf.

Gillingham, K, A van Benthem, S Weber, D Saafi, and X He. 2023. "Has Consumer Acceptance of Electric Vehicles Been Increasing? Evidence from Microdata on Every New Vehicle Sale in the United States." American Economics Association: Papers & Proceedings, forthcoming. https://resources.environment.yale.edu/gillingham/GBWSH_ConsumerAcceptanceEVs.pdf.

Greene, D., A. Hossain, J. Hofmann, G. Helfand, and R. Beach. 2018. "Consumer Willingness to Pay for Vehicle Attributes: What Do We Know?" Transportation Research Part A 118: 258-279.

Greschak, Tressa, Matilda Kreider, and Nathan Legault. 2022. "Consumer Adoption of Electric Vehicles: An Evaluation of Local Programs in the United States." School for Environment and Sustainability, University of Michigan, Ann Arbor, MI. https://deepblue.lib.umich.edu/handle/2027.42/172221.

Hafstead, M.A.C., and R.C. Williams III. 2018. "Unemployment and Environmental Regulation in General Equilibrium." Journal of Public Economics 160: 50-65.

Hardman, Scott, and Gil Tal. 2021. "Understanding Discontinuance among California's Electric Vehicle Owners." Nature Energy 6 (5): 538-545. doi:https://doi.org/10.1038/s41560-021-00814-9.

Hardman, Scott, Kelly L Fleming, Eesha Khare, and Mahmoud M Ramadan. 2021. "A perspective on equity in the transition to electric vehicles." MIT Science Policy Review 2: 46-54. doi:10.38105/spr.e10rdoaoup.

Helfand, G, and R Dorsey-Palmateer. 2015. "The Energy Efficiency Gap in EPA's Benefit-Cost Analysis of Vehicle Greenhouse Gas Regulations: A Case Study." Journal of Benefit-Cost Analysis 6 (2): 432-454.

Herrmenn, F., W. Beinhauer, D. Borrmann, M. Hertwig, J. Mack, T. Potinecke, C-P. Praeg, and P. Rally. 2020. Employment 2030: Effect of Electric Mobility and Digitalization on the Quality and Quantity of Employment at Volkswagen. Fraunhofer Institute for Industrial Engineering IAO. https://www.volkswagenag.com/presence/stories/2020/12/frauenhofer-studie/6095_EMDI_VW_Summary_um.pdf.

Huang, H, G Helfand, and K Bolon. 2018a. "Consumer Satisfaction with New Vehicles Subject to Greenhouse Gas and Fuel Economy Standards." Society for Benefit-Cost Analysis Annual Conference.

Huang, H, G Helfand, K Bolon, R Beach, M Sha, and A Smith. 2018. "Re-searching for hidden costs: Evidence from the adoption of fuel-saving technologies in light-duty vehicles." Transportation Research Part D 65: 194-212.

Hutchens, Andrew, Alecia Cassidy, Geoffrey Burmeister, and Gloria Helfand. 2021. Impacts of Light-Duty Greenhouse Gas Emission Standards on Vehicle Affordability. U.S. Environmental Protection Agency.

IHS Markit. 2021. "US EPA Proposed Greenhouse Gas Emissions Standards for Model Years 2023-2026; What to Expect." https://www.spglobal.com/mobility/en/research-analysis/us-epa-proposed-greenhouse-gas-emissions-standards-my2023-26.html.

Inflation Reduction Act of 2022. 2022. H.R. 5376 (117th Cong., 2nd sess.).

Infrastructure Investment and Jobs Act. 2021. H.R. 3684 (117th Cong., 1st sess.).

Jackman, D K, K S Fujita, H C Yang, and M Taylor. 2023. Literature Review of U.S. Consumer Acceptance of New Personally Owned Light Duty Plug-in Electric Vehicles. Washington, D.C.: U.S. Environmental Protection Agency.

Krisher, T., and J. Seewer. 2021. Autoworkers face uncertain future in an era of electric cars. ABC News. February 11. Accessed March 1, 2023. https://www.abc27.com/news/us-world/business/autoworkers-face-dimmer-future-in-a-new-era-of-electric-cars/.

Kupper, D., K. K. Kuhlmann, A. Tominaga, and J. Schlageter Arora. 2020. Shifting Gears in Auto Manufacturing. September 28. Accessed October 20, 2021. https://www.bcg.com/publications/2020/transformative-impact-of-electric-vehicles-on-auto-manufacturing.

Layard, R., and A. Walters. 1978. "Microeconomic Theory." Chap. 9. London: McGraw-Hill.

Leard, B., V. McConnell, and Y. C. Zhou. 2017. "The Effect of Fuel Price Changes on Fleet Demand for New Vehicle Fuel Economy." Working Paper (Resources For the Future). https://media.rff.org/documents/RFF20WP2017-25.pdf .

M.J. Bradley and Assoc. 2021. "Electric Vehicle Market Status – Update, Manufacturer Commitments to Future Electric Mobility in the U.S. and Worldwide. Contract Report to Environmental Defense Fund." https://www.erm.com/globalassets/documents/mjba-archive/reports/2021/edf_ev_market_report_april_2021_update.pdf

Morgenstern, R.D., W.A. Pizer, and J.-S. Shih. 2002. "Jobs Versus the Environment:" An Industry-Level Perspective." Journal of Environmental Econometrics and Management 43: 412-436.

Muller, D. 2017. "Warranties Defined: The Truth behind the Promises." Car and Driver, May 29.

National Academies of Science, Engineering, and Medicine. 2021. Assessment of Technologies for Improving Light-Duty Vehicle Fuel Economy 2025-2035. Washington, DC: The National Academies Press. doi:https://doi.org/10.17226/26092.

Nehiba, Cody. 2022. "Electric vehicle usage, pollution damages, and the electricity price elasticity of driving."

NHTSA. 2022. Technical Support Document: Final Rulemaking for Model Years 2024-2026 LightDuty Vehicle Corporate Average Fuel Economy Standards. U.S. Department Of Transportation, National Highway Traffic Safety Administration. Accessed March 7, 2023. https://www.nhtsa.gov/sites/nhtsa.gov/files/2022-04/Final-TSD_CAFE-MY-2024-2026.pdf.

Nicholas, Michael. 2019. Estimating electric vehicle charging infrastructure costs across major U.S. metropolitan areas. The International Council on Clean Transportation.

Political Economy Research Institute. 2022. Job Creation Estimates Through Proposed Inflation Reduction Act. University of Massachusetts Amherst. https://www.bluegreenalliance.org/site/9-million-good-jobs-from-climate-action-the-inflation-reduction-act/.

Raghavan, Seshadri Srinivasa, and Gil Tal. 2021. "Behavioral and technology implications of electromobility on household travel emissions." Transportation Research Part D 94 (102792). doi:https://doi.org/10.1016/j.trd.2021.102792.

S&P Global Mobility. 2021. Average age of cars and light trucks in the US rises to 12.1 years, accelerated by COVID-19. June 14. Accessed 03 14, 2023. https://www.spglobal.com/mobility/en/research-analysis/average-age-of-cars-and-light-trucks-in-the-us-rises.html.

Seattle Jobs Initiative. 2020. "Amping Up Electric Vehicle Manufacturing in the PNW: Opportunities for Business, Workforce, and Education." https://www.seattle.gov/Documents/Departments/OSE/ClimateDocs/TE/EV%20Field%20in%20OR%20and%20WA_February20.pdf.

Slowik, Peter, Aaron Isenstadt, Logan Pierce, and Stephanie Searle. 2022. Assessment of Light-Duty Electric Vehicle Costs and Consumer Benefits in the United States in the 2022-2035 Time Frame. International Council on Clean Transportation. Accessed 12 16, 2022. https://theicct.org/publication/ev-cost-benefits-2035-oct22/.

Smith, V.K. 2015. "Should Benefit-Cost Methods Take Account of High Unemployment?" Review of Environmental Economics and Policy 9 (2): 165-178.

Taylor, Margaret. 2023. Draft of "Modeling the Future of Electric Vehicles to Support U.S. Public Policy: A Comparison of Leading Approaches". Lawrence Berkeley National Laboratory.

Taylor, Margaret, and K Sydny Fujita. 2018. Consumer Behavior and the Plug-in Electric Vehicle Purchase Decision Process: A Research Synthesis. Berkeley, CA: Lawrence Berkeley National Laboratory.

U.S. Department of Energy (DOE). 2020. Alternative fuels data center: develoing infrastructure to charge plug-in electric vehicles. Accessed 2020. https://afdc.energy.gov/fuels/electricity_infrastructure.html.

U.S. Department of Energy. 2022. Electric Vehicle Charging Station Locations. Accessed March 8, 2022. https://afdc.energy.gov/fuels/electricity_locations.html.

U.S. DOE and U.S. EPA. 2015. "Model Year 2015 Fuel Economy Guide." Accessed January 10, 2023. https://www.fueleconomy.gov/feg/pdfs/guides/feg2015.pdf.

U.S. DOE and U.S. EPA. 2021. "Model Year 2021 Fuel Economy Guide." Accessed January 10, 2023. https://fueleconomy.gov/feg/pdfs/guides/FEG2021.pdf.

U.S. DOT. 2021. "86 FR 49602." Corporate Average Fuel Economy Standards for Model Years 2024-2026 Passenger Cars and Light Trucks. September 3.

U.S. EPA. 2021. "86 FR 74434." Revised 2023 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions Standards. December 30.

U.S. EPA. 2021. The Effects of New-Vehicle Price Changes on New- and Used-Vehicle Markets and Scrappage. EPA-420-R-21-019. https://cfpub.epa.gov/si/si_public_record_Report.cfm?dirEntryId=352754&Lab=OTAQ.

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." https://obamawhitehouse.archives.gov/sites/default/files/omb/inforeg/2015_cb/2015-cost-benefit-repot.pdf/.

UAW. 2020. "Taking the High Road: Strategies for a Fair EV Future." https://uaw.org/wp-content/uploads/2019/07/190416-EV-White-Paper-REVISED-January-2020-Final.pdf.

Wakefield, Chantel. 2023. Electric Car Rebates and Incentives: What to Know by State. February 02. Accessed February 02, 2023. https://www.kbb.com/car-advice/electric-vehicle-rebates-by-state/.

Watten, A, G Helfand, and S Anderson. 2021. "Attribute Production and Technical Change: Rethinking the Performance and Fuel Economy Trade-off for Light-duty Vehicles." Working Paper.

White, Vinn. September 27, 2016. "Revised Departmental Guidance on Valuation of Travel Time in Economic Analysis."

Chapter 5: Electric Infrastructure Impacts

As plug-in electric vehicles (PEVs) are projected to represent a significant share of the future U.S. light- and medium-duty vehicle fleet, EPA has developed new approaches to estimate the power sector emission implications (i.e., from electricity generation, transmission, and distribution system, which typically ends at a service drop; the run of cables from the electric power utility's distribution power lines to the point of connection to a customer's premises) of increased PEV charging. EPA combined the use of three analytical tools to incorporate grid-related emissions from PEV charging demand within the light- and medium-duty vehicle emissions inventory analysis for the proposal:

1) OMEGA
2) A suite of electric vehicle infrastructure modeling tools (EVI-X) developed by the National Renewable Energy Laboratory (NREL)
3) The Integrated Planning Model (IPM)

Chapter 5.1 below provides a summary of EVI-X and how these tools were used together with OMEGA to estimate charge demand inputs for IPM. The IPM modeling results and how the results were incorporated into the emissions inventory analysis are described in Chapters 5-8 and Chapter 9. Chapter 5.3 describes our assessment of PEV charging infrastructure. It should be noted that charging infrastructure is different from the electric power utility distribution system infrastructure, which is comprised of distribution feeder circuits, switches, protective equipment, primary circuits, distribution transformers, secondaries, service drops, etc. The electric power utility distribution system infrastructure typically ends at a service drop (i.e. the run of cables from the electric power utility's distribution power lines to the point of connection to a customer's premises).

Finally, the potential impacts on pending changes to the power sector on grid resiliency are discussed in Chapter 5.4.

5.1 Modeling PEV Charge Demand and Regional Distribution

Under an Interagency Agreement between EPA and the U.S. Department of Energy, NREL has continued its development of a suite of electric vehicle infrastructure modeling tools (EVI-X) and methods for simulating PEV charging infrastructure requirements and associated electricity loads from best available data. EVI-X tools have informed multiple national, state, and local PEV charging infrastructure planning studies (E. Wood, et al. 2017) (E. Wood, C. Rames, et al. 2018) (Alexander, et al. 2021), including a forthcoming national infrastructure assessment through 2030 (Wood, Borlaug, et al. 2023). As noted above, this infrastructure differs from that of electric power utility distribution system infrastructure. Within the emissions inventory analysis for the proposal, EVI-X models are used to translate scenario-specific forecasts of national light-duty vehicle stock and annual energy consumption from the OMEGA model into spatially disaggregated hourly load profiles required for subsequent power sector modeling using the Integrated Planning Model (IPM) (see Chapter 5.2). The primary components of the process flow from OMEGA outputs to IPM inputs as shown in Figure 5-1. IPM outputs also flow back into inventory analyses in OMEGA as PEV emissions factors (see DRIA Chapter 9).

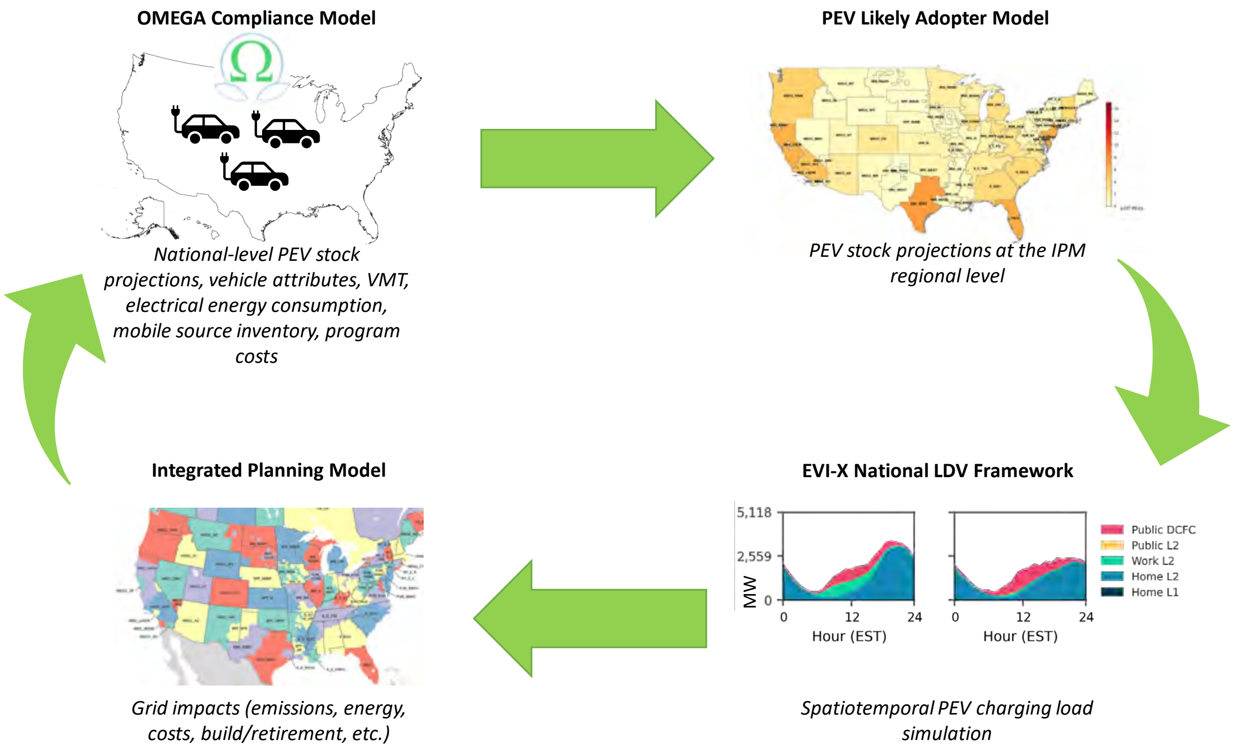

Figure 5-1: Modeling process flow highlighting the primary components for translating OMEGA's national PEV stock projections and PEV attributes into hourly load profiles.

5.1.1 PEV Disaggregation and Charging Simulation

As described in further detail in Chapter 2 of the DRIA, the OMEGA model evaluates the cost of compliance for meeting the standards and options analyzed within the proposed rule. Each OMEGA run produces scenario-specific projections of national vehicle sales, stock, energy consumption, and tailpipe emissions. For PEVs, however, tailpipe emissions are zero in the case of battery electric vehicles (BEVs) and during the charge-depleting operation of plug-in hybrid electric (PHEVs) with resulting emissions occuring upstream at the electricity generation source, thus expanding the requisite analytical boundaries of the system with respect to determination of emissions inventory impacts. To produce estimates of the spatiotemporal charging loads needed for power sector emissions modeling, the national PEV stock from OMEGA must first be disaggregated regionally.

The framework developed for PEV disaggregation leverages a likely adopter model (LAM) adapted by NREL (Ge, et al. 2021) to rank vehicles in the private light-duty fleet for their likelihood to be replaced by a PEV based on publicly available demographic data, including housing type, income, tenure (rent or own), state policies (ZEV states), and population density. The model is trained on the revealed preferences of 3,772 survey respondents (228 PEV owners) across the United States as described in (Ge, et al. 2021). Vehicle registration data from June 2022 (Experian 2022) were used to develop a set of chassis-specific LAMs for disaggregating PEV sedans, S/CUVs, pickups, and vans based on current regional vehicle type preferences. This process is outlined in Figure 2.

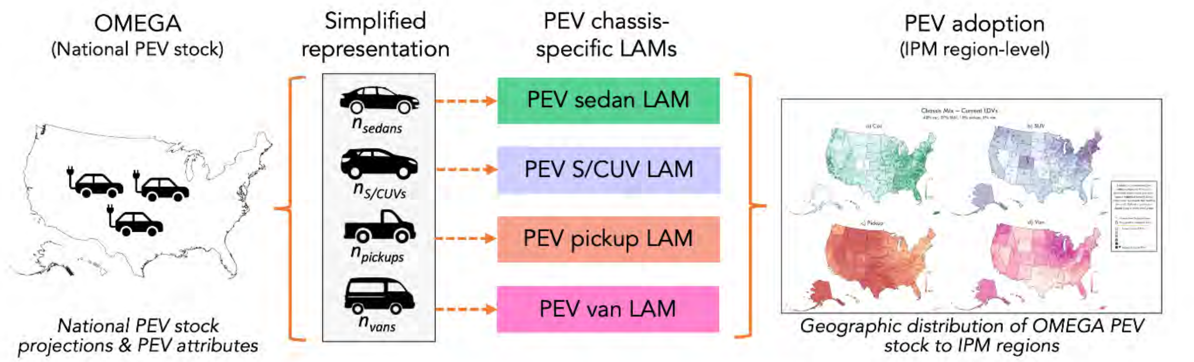

Figure 5-2: Procedure for disaggregating OMEGA national PEV stock projections to IPM regions.

Vehicles modeled within OMEGA were first assigned to a simplified chassis type (i.e., sedan, S/CUV, pickup, van). Next, the total number of vehicles in the simplified chassis types were used as inputs to each of the four chassis-specific LAMs to disaggregate PEVs into IPM regions based on regional vehicle type preferences and the likelihood of PEV adoption.

The OMEGA model generates vehicle adoption projections for thousands of unique PEV models over time. Conducting detailed charging simulations for each of these models would be computationally prohibitive and produce results not expected to meaningfully differentiate from those generated by a reduced set of representative PEV models. Thus, a clustering approach was used to generate these representative PEV models for simulation from the complete set of OMEGA vehicles. K-means clustering was performed over each PEV's respective battery capacity (kWh) and energy consumption rate (kWh/mi.) parameters as specified by OMEGA. A silhouette analysis was used to determine the appropriate number of clusters (k=6 for BEVs, k=2 for PHEVs) and OMEGA vehicles were assigned to clusters that minimize the Euclidean distance to the centroids of the two normalized (Z-score) parameters. These assignments were retained and used to map OMEGA vehicles to the most similar synthetic representative PEV model. The cluster centroids were used to produce the battery capacity and energy consumption rate parameters for the eight representative PEVs required for subsequent PEV charging simulations. An additional parameter, the max DC charge acceptance, was defined as the maximum effective charging rate over a typical 20percent to 80percent SOC DC fast charge (DCFC) window. This was required to simulate DCFC for BEVs and was not directly specified by the OMEGA model. PHEVs were assumed to be incapable of using DCFC equipment. For modeling BEV DCFC, a simple heuristic was applied such that pre-2030 model years (Gen 1 batteries) would be capable of 1.5C charging while model year 2030 and after BEVs would be capable of charging at 3C (Gen 2 batteries).[89] The key parameters for simulating charging for each of the representative PEVs are shown in Table 5-1.

Three separate EVI-X models developed by NREL, namely EVI-Pro (for typical daily travel), EVI-RoadTrip (for long-distance travel), and EVI-OnDemand (for ride-hailing applications)

[89] C-rate is a measure of the rate at which a battery is charged/discharged relative to its maximum energy storage capacity. For example, 1.5C indicates that the battery is fully charged in 40 minutes, while 3C indicates a full charge in 20 minutes

were used to estimate composite PEV charging load profiles under a unified set of assumptions: PEV fleet composition, regional home charging access (Ge, et al. 2021), regional weather conditions, public/workplace infrastructure availability, and charging preferences.

Table 5-1: Representative PEV examples for charging simulations.

Sim vehicle	Vehicle type	Battery capacity [kWh]	Energy cons. rate [kWh/mi.]	Max AC accept. [kW] (Gen 1 / Gen 2)	Max DC accept. [kW] (Gen 1 / Gen 2)
BEV1	BEV	89	0.27	9 / 12	134 / 267
BEV2	BEV	103	0.31	9 / 12	154 / 308
BEV3	BEV	114	0.34	9 / 12	171 / 342
BEV4	BEV	128	0.38	9 / 12	191 / 383
BEV5	BEV	141	0.42	9 / 12	212 / 424
BEV6	BEV	157	0.47	9 / 12	236 / 471
PHEV1	PHEV	18	0.29	9 / 12	-
PHEV2	PHEV	18	0.38	9 / 12	-

Figure 5-3 shows a schematic summary of the EVI-X models. The EVI-X models perform bottom-up simulations of charging behavior by superimposing the use of a PEV over travel data from internal combustion engine vehicles. These independent, but coordinated, simulations produce daily charging demands for typical PEV use, long-distance travel, and ride-hailing electrification, respectively, which are indexed in time (hourly over a representative 24-hr period for weekdays and weekends) and space (county). This process is shown in Figure 3 and described in (Wood, Borlaug, et al. 2023).

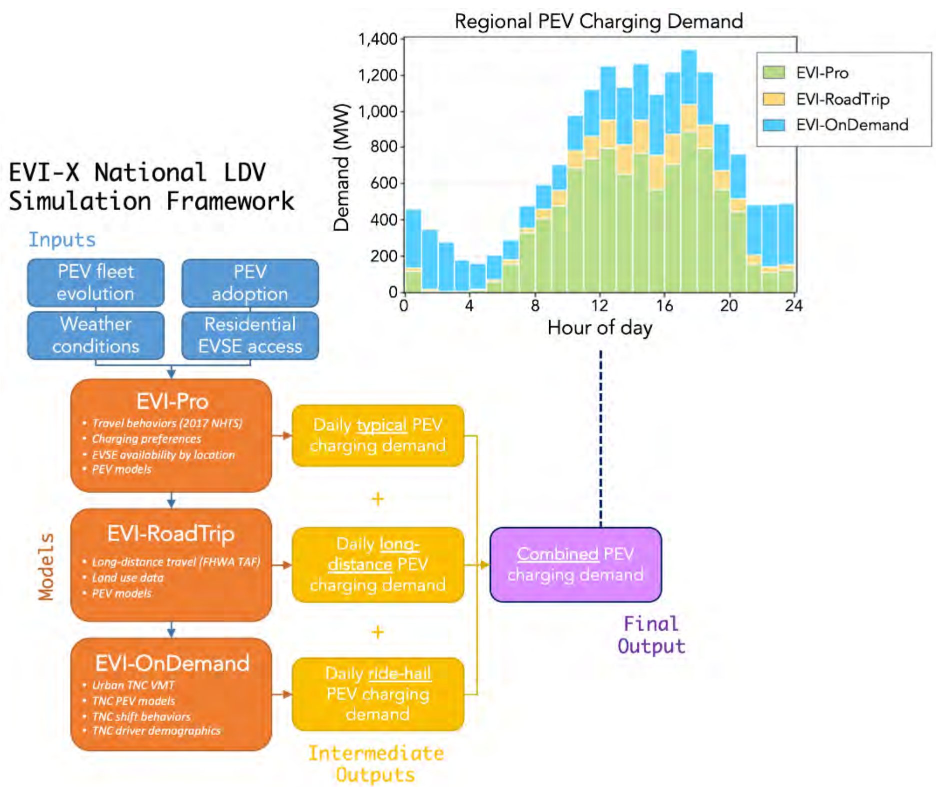

Figure 5-3: EVI-X National light-duty vehicle framework simulation showing spatiotemporal energy demands for three separate use cases: typical daily travel (EVI-Pro), long-distance travel (EVI-RoadTrip), and ride-hailing (EVI-OnDemand).

Following the PEV charging simulations, load profiles were aggregated from the county-level into IPM regions and converted from local time to Eastern Standard Time (EST) for IPM implementation. A final corrective step was taken to ensure that the annual energy consumption estimates supplied by OMEGA were reflected in the PEV load profiles.

For a given OMEGA national PEV stock projection file, the modeling framework produces a typical weekday and weekend 24-hour (EST) load profile for all IPM regions (plus Hawaii, Alaska, and Puerto Rico) and analysis years (2026, 2028, 2030, 2032, 2035, 2040, 2045, 2050, 2055). Load profiles were analyzed using output from four separate OMEGA analytical cases:

1) No-action Case: Vehicle electrification under the existing 2023 through 2026 light-duty vehicle GHG standards as represented by the standards finalized by EPA December 30, 2021 (86 FR 74434 2021), with updated OMEGA compliance modeling (see DRIA Chapter 2).

2) Action Case: Proposed light-and medium-duty vehicle standards

3) High BEV Sensitivity Case

4) Low BEV Sensitivity Case

These analytical cases are described in more detail below. Figure 5-4 provides an example of how specific load profiles may be used to infer annual PEV charging demands for 2030 and 2050 using an example OMEGA analytical scenario (the "Action Case").

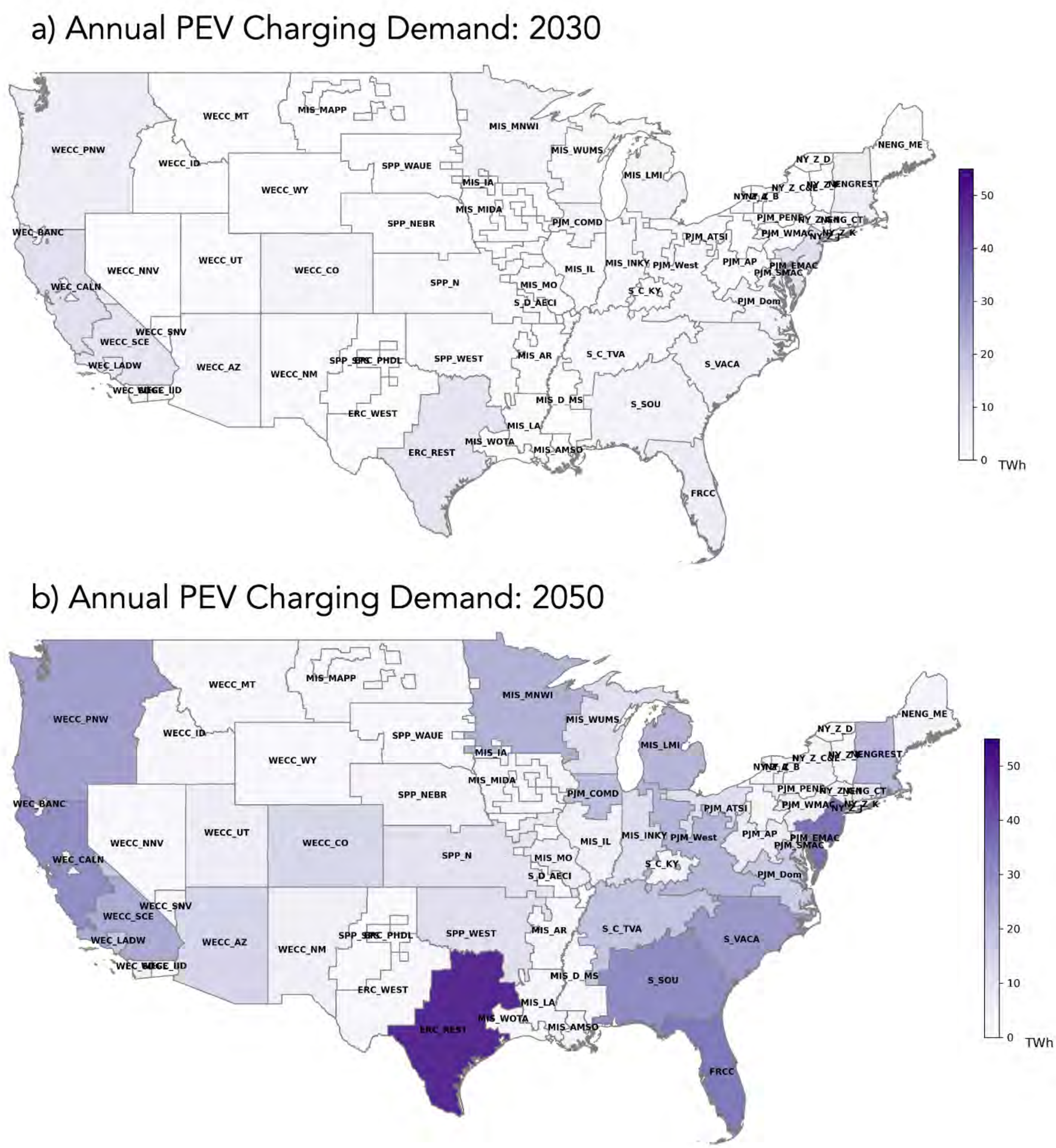

Figure 5-4: Annual PEV charging loads (2030 and 2050 are shown) for each IPM region in the contiguous United States based on OMEGA charge demand for the proposal in 2030 (top) and 2050 (bottom).

In addition to the total hourly energy demands for PEV charging, energy demands were also broken out by the following charger types – home Level 1 (L1), home Level 2 (L2), work L2, public L2, and public DCFC (Figure 5-5). See section 5.3.1.2. for additional discussion. Note that these have been converted to EST and reflect an unmanaged charging scenario where drivers do not prioritize charging at certain times of the day (i.e., charging starts as soon as possible when vehicles are plugged in without consideration of electricity price or other factors).

In Figure 5-5, there are clear differences in the magnitude, shape, and charger types between the West Texas (left–ERC_WEST, containing mostly rural areas and small cities such as Midland and Odessa) and East Texas (right–ERC_REST, including multiple major population centers such as Houston, San Antonio, Austin, and Dallas-Ft. Worth) regions. The EVI-X National light-duty vehicle framework conducts charging simulations that are reflective of the regional differences in EV adoption, vehicle type preferences, home ownership, weather conditions, and travel patterns. These demonstrative results reflect how in ERC_WEST, EV adoption is projected to be low (due to limited population and revealed vehicle preferences) leading to a reduced demand for home-based charging while public DCFC demands for long-distance travel across the region (e.g., road trips) are amplified. This leads to a disproportionate share of public DCFC charging demand along highway corridors within the ERC_WEST region. Alternatively, simulated charging demands in the ERC_REST are dominated by home and workplace charging due to the higher EV adoption and urban travel patterns more common to the region.

The OMEGA national PEV outputs and the resulting regionalized IPM inputs from EVI-X for each of the four analyzed cases, for each IPM region and all analytical years (2026, 2028, 2030, 2032, 2035, 2040, 2045, 2050, 2055) are summarized within a separate PEV Regionalized Charge Demand Report (McDonald 2023).

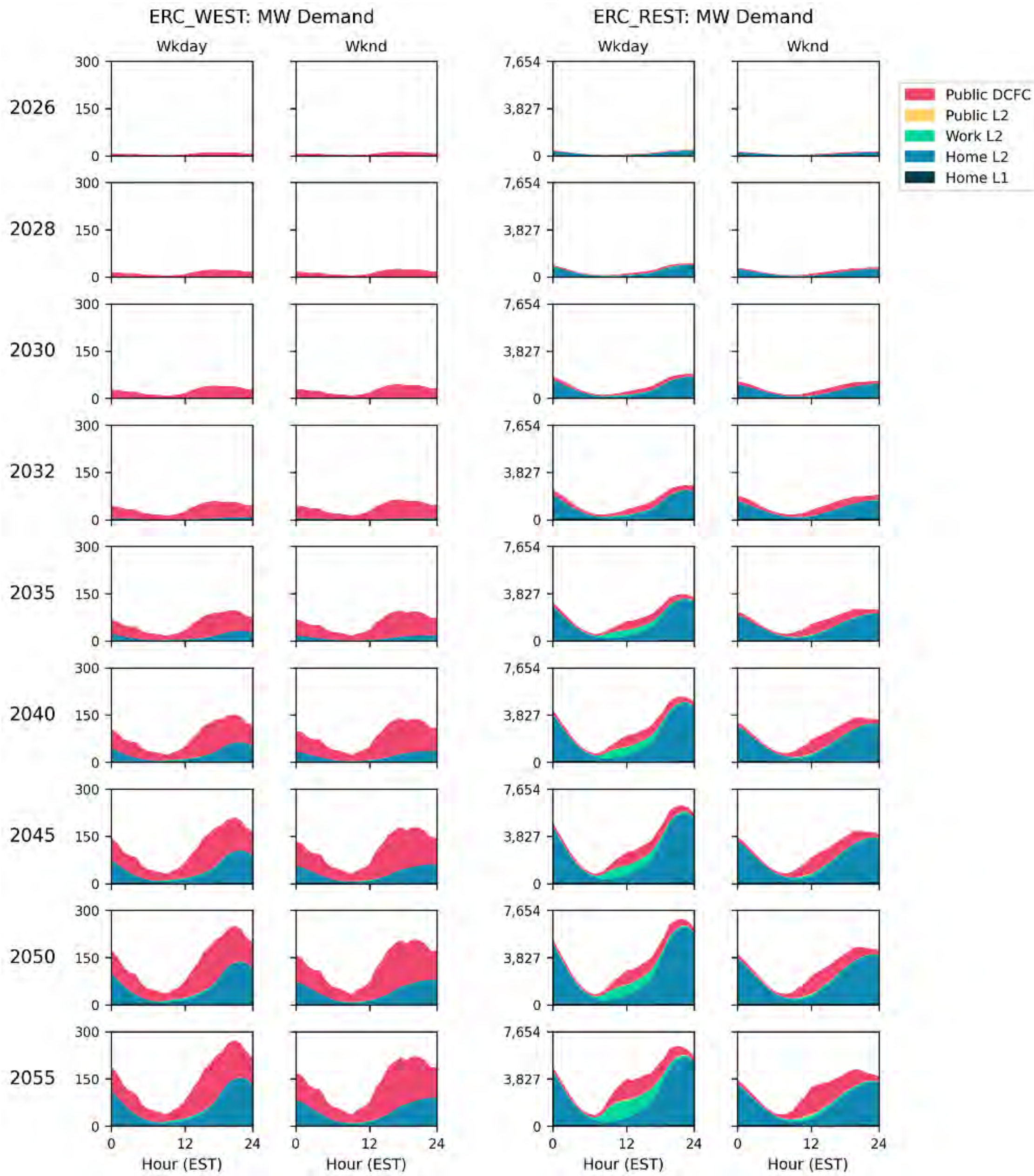

Figure 5-5: Yearly hourly (in EST) weekday and weekend load profiles for two IPM regions (ERC_WEST, west Texas; and ERC_REST, east Texas) broken out by charger type for an example OMEGA analytical scenario.

5.2 Electric Power Sector Modeling

The analyses for the proposal used EPA's Power Sector Modeling Platform, which utilizes the Integrated Planning Model (IPM). IPM is a multi-regional, dynamic, deterministic linear programming model of the U.S. electric power sector. It provides projections of least-cost capacity expansion, electricity dispatch, and emission control strategies for meeting energy demand and environmental, transmission, dispatch, and reliability constraints. IPM can be used to evaluate the cost and emissions impacts of proposed policies to limit emissions of sulfur dioxide (SO_2), nitrogen oxides (NO_X), carbon dioxide (CO_2), hydrogen chloride (HCl), and mercury (Hg) from the electric power sector. Post-processing IPM outputs allows for the processing of other emissions, such as volatile organic compounds (VOC) and non-CO_2 GHGs. The power-sector modeling used for the proposal included power-sector-related provisions of both the Bipartisan Infrastructure Law (BIL) and the Inflation Reduction Act (IRA). Additional information regarding power-sector modeling is available via a report submitted to the docket (U.S. EPA 2023).

5.2.1 Estimating Retail Electricity Prices

The Retail Price Model (RPM) was developed to estimate retail prices of electricity using wholesale electricity prices generated by the IPM. The RPM provides a first-order estimate of average retail electricity prices using information from EPA's Power Sector Modeling Platform v6.21 using the Integrated Planning Model (IPM) and the EIA's Annual Energy Outlook (AEO). This model was developed by ICF a under contract with EPA (ICF 2019).

IPM includes a wholesale electric power market model that projects wholesale prices paid to generators. Electricity consumers—industrial, commercial, and residential customers—face a retail price for electricity that is higher than the wholesale price because it includes the cost of wholesale power and the costs of transmitting and distributing electricity to end-use consumers. The RPM was developed to estimate retail prices of electricity based on outputs of EPA's Base Case using IPM and a range of other assumptions, including the method of regulation and price-setting in each state. Traditionally, cost-of-service (COS) or Rate-of-Return regulation sets rates based on the estimated average costs of providing electricity to customers plus a "fair and equitable return" to the utility's investors. States that impose cost-of-service regulation typically have one or more investor-owned utilities (IOUs), which own and operate their own generation, transmission, and distribution assets. They are also the retail service provider for their franchised service territory in which IOUs operates. Under this regulatory structure, retail power prices are based on average historical costs and are established for each class of service by state regulators during periodic rate case proceedings. Additional documentation on the RPM can be found at on the EPA website.

5.2.2 IPM emissions post-processing

Emissions of non-CO_2 GHG (methane, nitrous oxide), PM, VOC, CO and NH_3 were calculated via post-processing of IPM power sector data and using EPA-defined emissions factors. The EPA GHG Emissions Factors Hub was used to determine fuel-specific emissions factors for methane and nitrous oxide emissions for the electric power sector (U.S. EPA 2022a). Emissions factors used for post-processing of PM, VOC, CO and NH_3 were documented as part of EPA's Power Sector Modeling Platform v6 - Summer 2021 Reference Case (U.S. EPA 2021).

5.2.3 IPM National-level Demand, Generation, Emissions and Costs

As EPA was in the process of developing this proposal in the fall of 2022, EPA's Clean Air Markets Division (CAMD) completed an initial power sector modeling analysis of the BIL and IRA. The IRA provisions modeled within IPM included:

- Clean Electricity Production and Investment Tax Credits
- Existing Nuclear Production Tax Credit

- Carbon Capture and Storage 45Q Tax Credit

This initial modeling did not include other power sector impacts, such as demand impacts from electrification and energy efficiency provisions, however these are likely to be part of future CAMD power sector analyses.

The initial modeling of the IRA showed a 70percent reduction of power sector related CO_2 emissions from current levels by 2055, and that the changes in CO_2 emissions would be driven primarily by increases in renewable generation and enabled by increased use of grid battery storage capacity (see Figure 5-6).

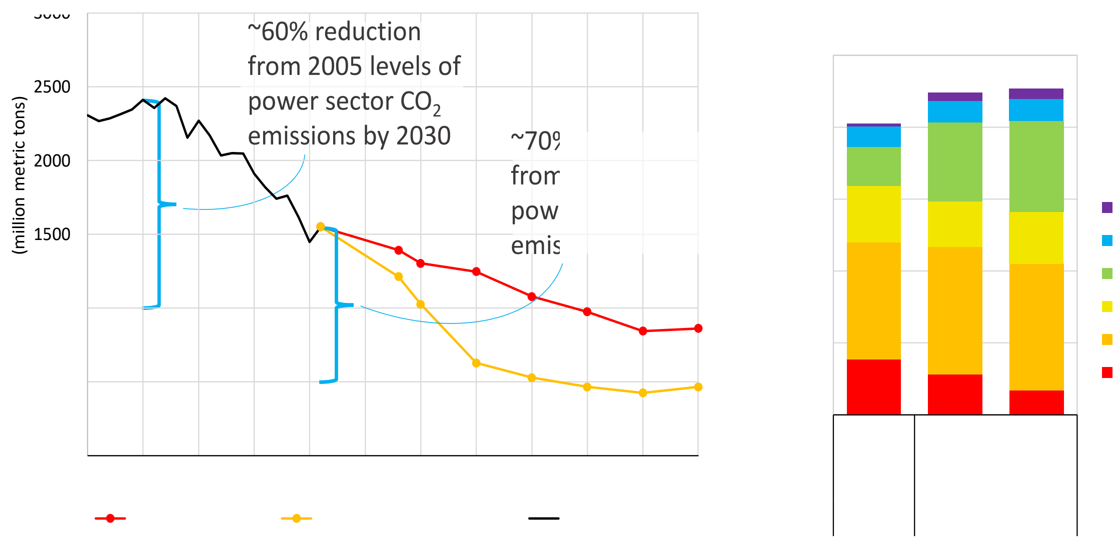

Figure 5-6: Power sector modeling comparing results of the Bipartisan Infrastructure Law (BIL) and the Inflation Reduction Act (IRA)

Similar to CAMD's earlier power sector analysis, the power sector analysis for both the proposal and a no-action case show significant reductions in CO_2 emissions from 2028 through 2050 despite increased generation and largely due to increased use of renewables for generation.

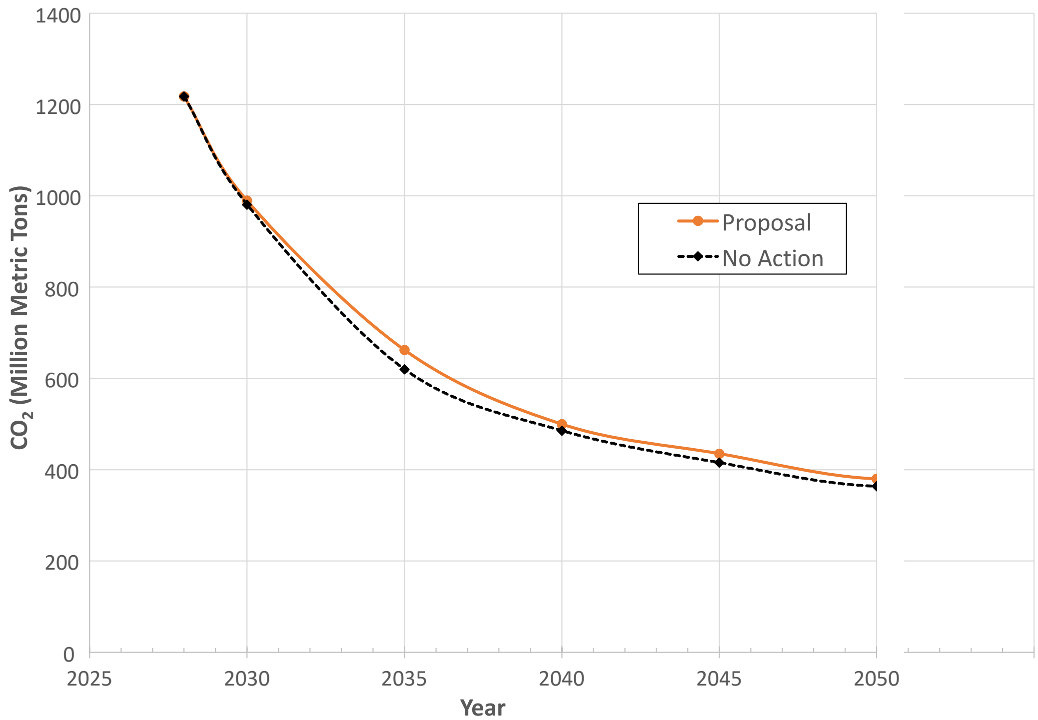

Figure 5-7: 2028 through 2050 power sector CO_2 emissions for the proposal (orange line) and no-action case (dashed line).

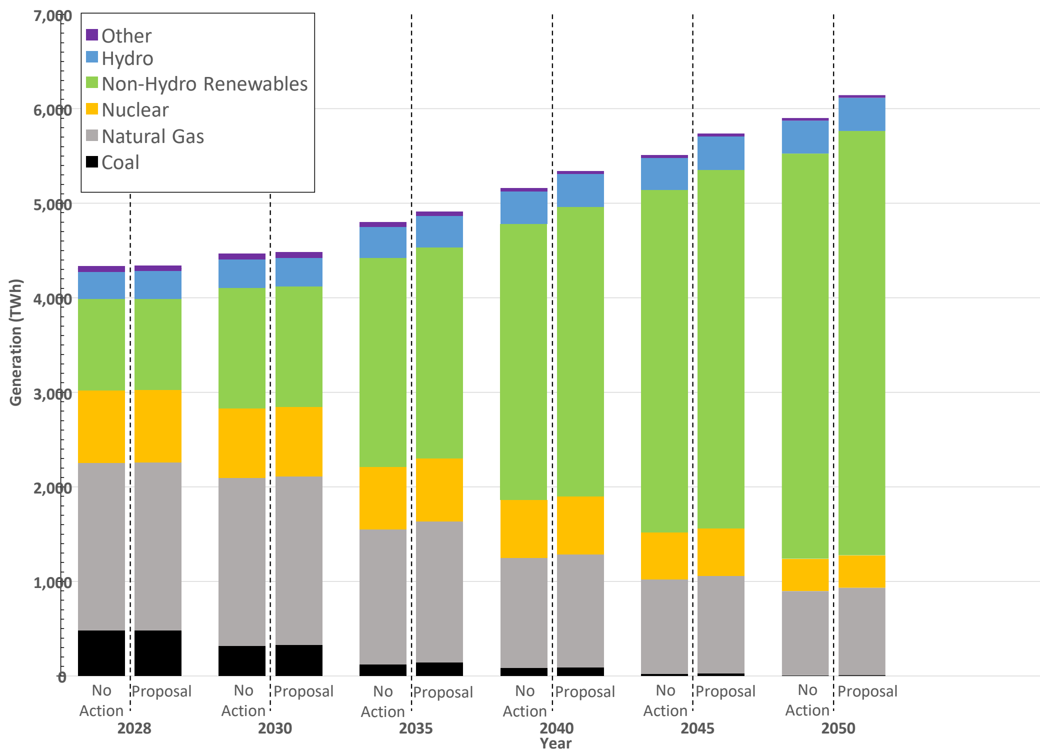

Figure 5-8: 2028 through 2055 power sector generation and grid mix.

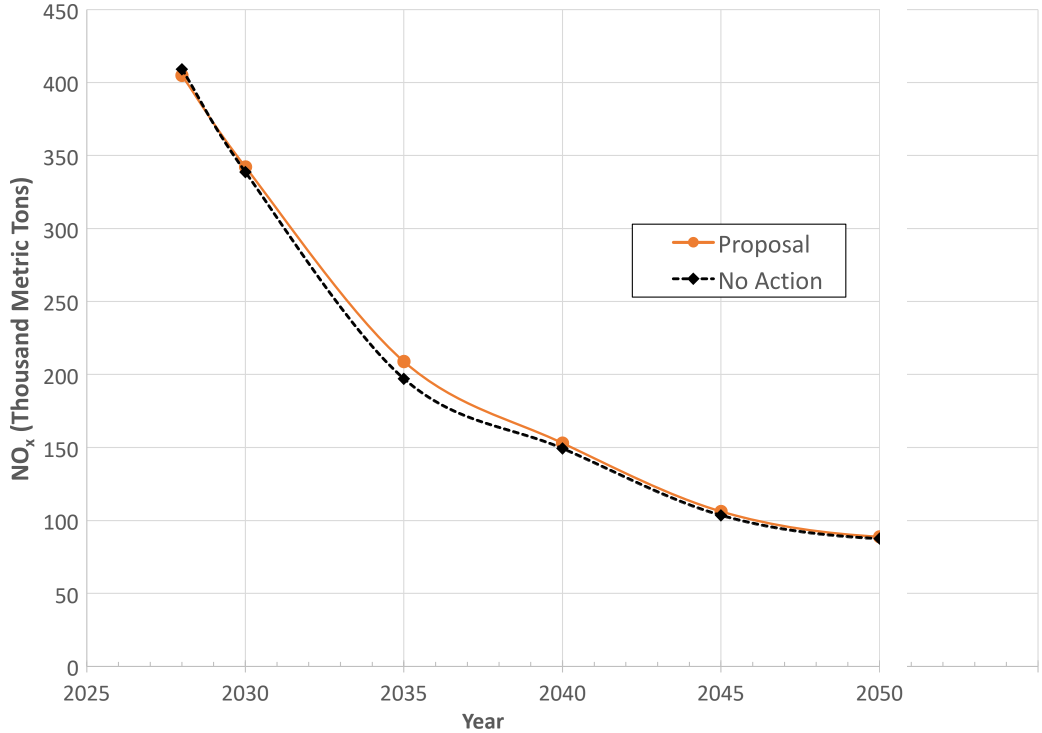

Figure 5-9: 2028 through 2050 power sector NO_X emissions for the proposal (orange line) and no-action case (dashed line).

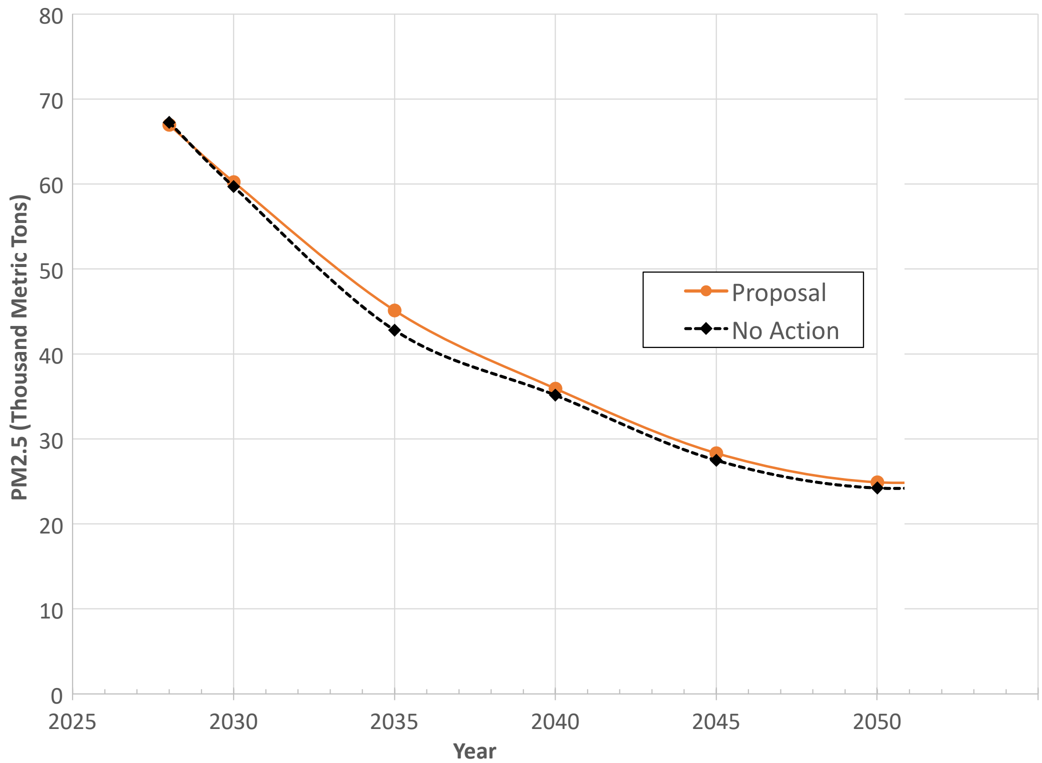

Figure 5-10: 2028 through 2050 power sector $PM_{2.5}$ emissions for the proposal (orange line) and no-action case (dashed line).

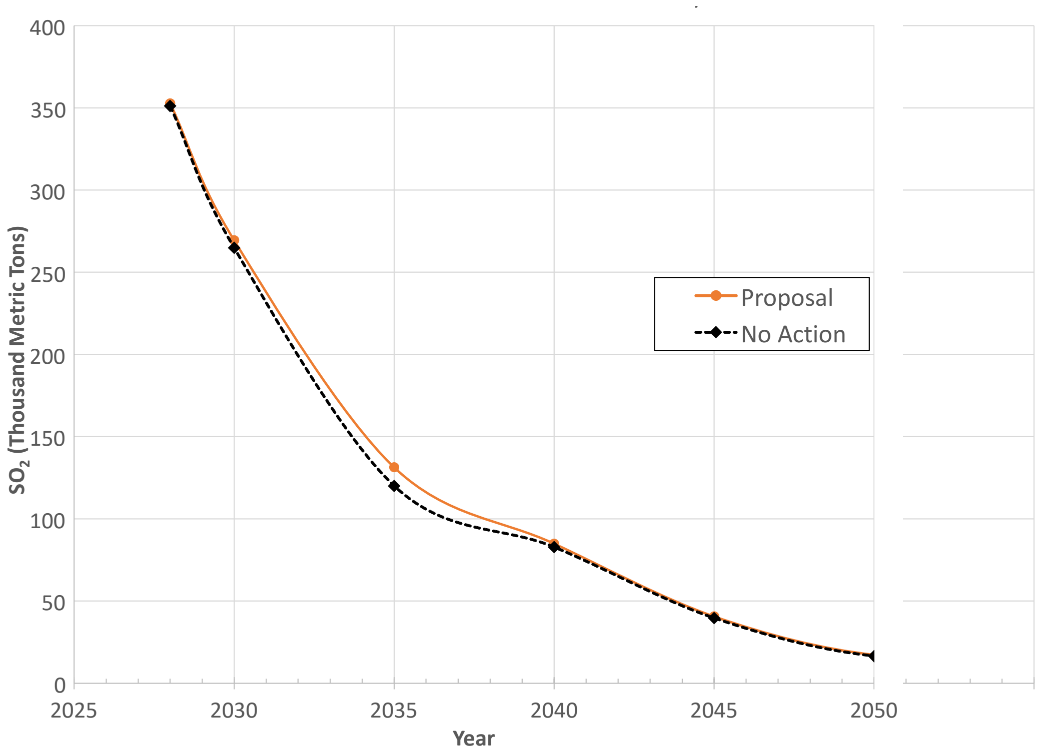

Figure 5-11: 2028 through 2050 power sector SO_2 emissions for the proposal (orange line) and no-action case (dashed line).

A summary of national electric power sector emissions, demand, generation, and cost for the no-action case and for the proposal are presented in Table 5-2 and Table 5-3, respectively. Note that the total costs presented in both tables represent:

- Capital costs for building new power plants as well as retrofits
- Variable and fixed operation and maintenance costs
- Fuel costs
- Cost of transporting and storing CO_2

Table 5-2: National electric power sector emissions, demand, generation and cost for the no-action case

Emission	2028	2030	2035	2040	2045	2050
SO_2 (million metric tons)	0.351	0.265	0.120	0.0828	0.0396	0.0165
$PM_{2.5}$ (million metric tons)	0.0672	0.0597	0.0428	0.0351	0.0275	0.0242
NO_X (million metric tons)	0.409	0.339	0.197	0.149	0.104	0.0875
VOC (million metric tons)	0.0330	0.0291	0.0230	0.0200	0.0169	0.0155
CO_2 (million metric tons)	1,218	980	620	485	415	364
CH_4 (metric tons)	75,270	59,870	36,185	28,218	17,388	13,906
N_2O (metric tons)	10,333	8,050	4,718	3,659	2,136	1,668
Hg (metric tons)	2.27	1.92	1.46	1.32	1.06	0.962
HCL (million metric tons)	2.36	1.66	0.845	0.646	0.215	0.118
Demand (TWh)	4,400	4,528	4,854	5,188	5,533	5,885
Generation (TWh)	4,498	4,670	5,096	5,538	5,951	6,437
Total Cost (Billion $)	132	127	130	141	143	146

Table 5-3: National electric power sector emissions, demand, generation and cost for the proposal

Emission	2028	2030	2035	2040	2045	2050
SO_2 (million metric tons)	0.353	0.269	0.131	0.0849	0.0406	0.0173
$PM_{2.5}$ (million metric tons)	0.0669	0.0602	0.0451	0.0359	0.0283	0.0249
NO_X (million metric tons)	0.405	0.342	0.209	0.153	0.106	0.0888
VOC (million metric tons)	0.0318	0.0292	0.0237	0.0202	0.0173	0.0159
CO_2 (million metric tons)	1,217	989	662	500	435	380
CH_4 (metric tons)	75,340	61,455	39,265	29,323	17,913	14,268
N_2O (metric tons)	10,324	8,281	5,146	3,812	2,200	1,709
Hg (metric tons)	2.28	1.97	1.53	1.36	1.08	0.979
HCL (million metric tons)	2.38	1.74	0.961	0.681	0.224	0.121
Demand (TWh)	4,403	4,545	4,972	5,372	5,753	6,118
Generation (TWh)	4,500	4,688	5,210	5,733	6,184	6,689
Total Cost (Billion $)	132	128	136	147	150	153

5.2.4 Retail Price Modeling Results

EPA estimated the change in the retail price of electricity (2020$) using the Retail Price Model (RPM) and using the same methodology used in recent power-sector rulemakings (U.S. EPA 2022b). The RPM was developed by ICF for EPA (ICF 2019) and uses the IPM estimates of changes in the cost of generating electricity to estimate the changes in average retail electricity prices. The prices are average prices over consumer classes (i.e., consumer, commercial, and industrial) and regions, weighted by the amount of electricity used by each class and in each region. The RPM combines the IPM annual cost estimates in each of the 74 IPM regions with EIA electricity market data for each of the 25 NERC/ISO[90] electricity supply subregions (Table 5-4 and Figure 5-12) in the electricity market module of the National Energy Modeling System (NEMS) (U.S. Energy Information Administraton 2019). Table 5-4 summarizes the projected percentage changes in the retail price of electricity for the proposal versus a no-action case, respectively. Consistent with other projected impacts presented above, average retail electricity price differences at the national level are projected to be small at less than 1percent difference in 2030 and 2050. Regional average retail electricity price differences showed small increases or decreases (less than approximately 1 to 2percent) with the sole exception of PJMC, which is the PJM Commonwealth Edison (Metropolitan Chicago) NERC/ISO subregion.

There is a general trend of reduced national average retail electricity prices from 2021 through 2050, which is largely due to reduced fuel costs from increased use of renewables for generation.

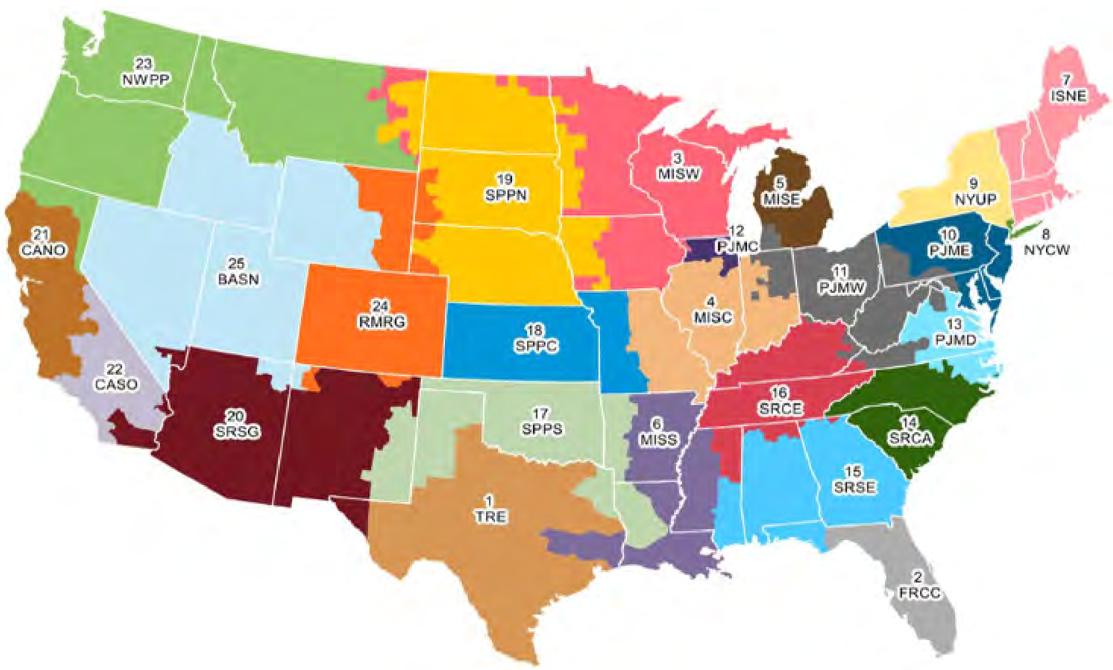

Figure 5-12: Electricity Market Module Regions (U.S. Energy Information Administraton 2019).

[90] NERC is the National Electricity Reliability Corporation. ISO is an Independent System Operator, sometimes referred to as a Regional Transmission Organization.

Table 5-4: National Energy Modeling System's Electricity Market Module regions (U.S. Energy Information Administraton 2019)

Number	Abbreviation	NERC/ISO subregion name	Geographic name
1	TRE	Texas Reliability Entity	Texas
2	FRCC	Florida Reliability Coordinating Council	Florida
3	MISW	Midcontinent ISO/West	Upper Mississippi Valley
4	MISC	Midcontinent ISO/Central	Middle Mississippi Valley
s	MISE	Midcontinent ISO/East	Michigan
6	MISS	Midcontinent ISO/South	Mississippi Delta
7	ISNE	Northeast Power Coordinating Council/ New England	New England
8	NYCW	Northeast Power Coordinating Council/ New York City & Long Island	Metropolitan New York
9	NYUP	Northeast Power Coordinating Council/Upstate New York	Upstate New York
10	PJME	PJM/East	Mid-Atlantic
11	PJMW	PJM/West	Ohio Valley
12-	PJMC	PJM/Commonwealth Edison	Metropolitan Chicago
13	PJMD	PJM/Dominion	Virginia
14	SRCA	SERC Reliability Corporation/East	Carolinas
15	SRSE	SERC Reliability Corporation/Southeast	Southeast
16	SRCE	SERC Reliability Corporation/Central	Tennessee Valley
17	SPPS	Southwest Power Pool/South	Southern Great Plains
18	SPPC	Southwest Power Pool/North	Central Great Plains
19	SPPN	Southwest Power Pool/North	Northern Great Plains
20	SRSG	Western Electricity Coordinating Council/Southwest	Southwest
21	CANO	Western Electricity Coordinating Council/California North	Northern California
22	CASO	Western Electricity Coordinating Council/California South	Southern California
23	NWPP	Western Electricity Coordinating Council/	Northwest
		Northwest Power Pool	
24	RMRG	Western Electricity Coordinating Council/Rockies	Rockies
25	BASN	Western Electricity Coordinating Council/Basin	Great Basin

Table 5-5: Average retail electricity price by region for the proposal and a no-action case in 2030 and 2050 compared to AEO2021

	AEO2021 2020	**No-action** 2030	**Proposal** 2030	**No-action** 2050	**Proposal** 2050	**Percent Change*** 2030	**Percent Change*** 2050
AEO/NEMS Model Regions	2020 mills/kWh†						
TRE	89.4	80.0	80.5	60.9	61.0	0.6%	0.1%
FRCC	98.2	89.9	90.3	78.2	78.8	0.4%	0.7%
MISW	108.4	81.7	82.1	86.9	87.6	0.4%	0.8%
MISC	96.2	90.3	90.8	72.0	72.2	0.5%	0.3%
MISE	116.4	99.2	98.3	83.7	83.7	-0.9%	0.1%
MISS	79.0	90.7	91.0	71.3	71.5	0.4%	0.4%
ISNE	178.3	149.1	149.0	152.5	153.4	-0.1%	0.6%
NYCW	187.5	206.4	201.2	202.2	203.5	-2.5%	0.6%
NYUP	117.8	123.5	120.2	114.2	114.7	-2.6%	0.5%
PJME	109.3	109.1	107.2	103.0	103.5	-1.8%	0.5%
PJMW	103.4	95.4	95.6	78.2	78.8	0.3%	0.8%
PJMC	96.0	80.2	84.8	79.7	83.3	5.8%	4.5%
PJMD	85.4	73.4	73.9	71.8	72.1	0.6%	0.4%
SRCA	102.7	98.0	98.1	89.5	89.5	0.2%	0.0%
SRSE	101.6	91.6	91.8	74.5	74.6	0.3%	0.0%
SRCE	85.0	106.3	106.6	71.7	71.9	0.2%	0.2%
SPPS	79.2	70.6	70.8	65.2	65.6	0.3%	0.5%
SPPC	105.0	81.3	81.5	60.3	60.3	0.3%	0.0%
SPPN	71.5	60.5	60.4	58.7	59.0	-0.1%	0.6%
SRSG	99.2	84.4	84.6	81.3	81.2	0.2%	-0.2%
CANO	151.0	158.6	159.0	150.0	150.0	0.2%	0.0%
CASO	179.4	189.3	189.5	168.6	169.2	0.1%	0.3%
NWPP	87.1	77.5	78.5	78.4	79.3	1.3%	1.2%
RMRG	98.1	87.6	88.0	74.9	74.8	0.4%	-0.1%
BASN	91.4	89.7	90.4	76.2	76.9	0.7%	0.9%
National	105.3	99.6	99.7	87.8	88.3	0.2%	0.6%

Table Notes:
*Percentage increase in average retail electricity price from the Proposal to a no-action case. Negative percentages reflect a decrease in average retail electricity price for the proposal.
†One mill is equal to 1/1,000 U.S. dollar, or 1/10 U.S. cent. 2020 mills per kilowatthour (mills/kWh) are equivalent to 2020 dollars per megawatt-hour ($/MWh)

5.2.5 New Builds, Retrofits and Retirements of EGUs

The electric power sector emissions modeling undertaken in support of this rulemaking, using IPM (described at the beginning of Chapter 5.2), also projects the anticipated mix of electric power plants required to meet the imposed electric power load from vehicle electrification, subject to various constraints. These power plants are referred to here collectively as Electric Generating Units (EGU). This definition includes all types of generating facilities (e.g. fossil fuel-fired combustion, nuclear, hydroelectric, renewable, etc.).

This modeling reveals anticipated EGU retirements, EGU retrofits, and new EGU construction, which are discussed below. EGUs are retired by IPM when announced by their owner and for economic reasons. The IRA and BIL resulted in many EGU retirements. As such, the number and types of EGU retirements associated with the proposed rule when compared to a no-action case are small in comparison to those retirements that occurred as a result of the IRA and BIL.

New EGU capacity modelled by IPM for the no-action case is summarized in Table 5-6. New EGU capacity modelled by IPM for the proposal is summarized in Table 5-7. EGU retirements modelled by IPM for the no-action and for the proposal are summarized in Table 5-8 and Table 5-9, respectively. Incremental EGU retirements and incremental new modeled EGU capacity are summarized in Table 5-10 and Table 5-11, respectively.

For the no-action case, the retirement of coal-fired EGUs account for 81.1%, 80.4%, 75.7%, 74.7%, 65.3%, and 57.4% of all EGU retirements for 2028, 2030, 2035, 2040, 2045, and 2050, respectively (see Table 5-8). For the proposal, the retirement of coal-fired EGUs are very similar to the no-action case at 81.7%, 81.3%, 76.2%, 75.7%, 66.0%, and 57.8% of all EGU retirements for 2028, 2030, 2035, 2040, 2045, and 2050, respectively (see Table 5-9).

For the no-action case, cumulative power generation from new solar EGU builds are expected account for 11.3%, 23.2%, 28.9%, 31.5%, 28.7%, and 29.2% of all new power generation for 2028, 2030, 2035, 2040, 2045, and 2050, respectively. Also, cumulative power generation from new wind-powered EGU builds are expected account for 27.0%, 36.9%, 45.4%, 42.7%, 42.9%, and 40.1% of all new power generation for 2028, 2030, 2035, 2040, 2045, and 2050, respectively. Likewise, cumulative power generation from new energy storage EGU builds are expected account for 31.8%, 24.4%, 15.7%, 13.0%, 10.3%, and 9.2% of all new power generation for 2028, 2030, 2035, 2040, 2045, and 2050, respectively.

New generation for the proposal is similar to the no-action case. For the proposal, cumulative power generation from new solar EGU builds are expected account for 10.9%, 22.8%, 28.8%, 31.8%, 29.2%, and 29.5% of all new power generation for 2028, 2030, 2035, 2040, 2045, and 2050, respectively. Also, cumulative power generation from new wind-powered EGU builds are expected account for 27.3%, 36.7%, 44.1%, 41.6%, 41.6%, and 39.4% of all new power generation for 2028, 2030, 2035, 2040, 2045, and 2050, respectively. Likewise, cumulative power generation from new energy storage EGU builds are expected account for 31.0%, 24.7%,15.8%,12.4%, 9.7%, and 8.8% of all new power generation for 2028, 2030, 2035, 2040, 2045, and 2050, respectively.

Solar-power is expected to become the single largest new source of EGU capacity for 2040, 2045, and 2050, accounting for 34.4%, 35.4%, and 34.0% of overall new EGU capacity, respectively. Wind-driven EGUs are expected to comprise the second largest new source of EGU capacity for 2040 and 2050, accounting for 28.5% and 28.2% of overall new EGU capacity, respectively.

Table 5-6: Newly modeled EGU capacity for the no-action case.

NEW MODELED CAPACITY (Cumulative GW)	2028	2030	2035	2040	2045	2050
Hydro	0.0	1.5	5.8	8.2	8.2	8.2
Non-Hydro Renewables	42.0	131.7	404.4	622.4	831.8	1,050.3
Biomass	0.0	0.0	0.0	0.0	0.0	0.0
Geothermal	0.3	0.3	0.3	0.3	0.3	0.3
Landfill Gas	1.3	1.3	1.3	1.3	1.3	1.3
Solar	11.9	50.2	156.9	263.6	333.2	441.6
Wind	28.5	79.9	245.9	357.2	497.1	607.1
Coal	0.0	0.0	0.0	0.0	0.0	0.0
Coal without Carbon Capture & Sequestration (CCS)	0.0	0.0	0.0	0.0	0.0	0.0
Integrated Gasification Combined Cycle without CCS	0.0	0.0	0.0	0.0	0.0	0.0
Coal with CCS	0.0	0.0	0.0	0.0	0.0	0.0
Energy Storage	33.7	52.8	85.3	108.6	119.3	139.1
Nuclear	0.0	0.0	0.0	0.0	0.0	0.0
Natural Gas	30.0	30.2	46.7	96.5	200.7	315.0
Combined Cycle without CCS	21.1	21.3	25.6	26.2	26.7	30.3
Combustion Turbine	8.9	8.9	21.1	70.3	174.0	284.7
Other	0.0	0.0	0.0	0.0	0.0	0.0
Grand Total	105.7	216.2	542.2	835.7	1,160.0	1,512.5

Table 5-7:Newly modeled EGU capacity for the proposal.

NEW MODELED CAPACITY (Cumulative GW)	2028	2030	2035	2040	2045	2050
Hydro	0.0	1.5	5.8	8.7	8.7	8.7
Non-Hydro Renewables	42.2	131.9	410.9	670.7	889.8	1,114.9
Biomass	0.0	0.0	0.0	0.0	0.0	0.0
Geothermal	0.3	0.3	0.3	0.3	0.3	0.3
Landfill Gas	1.3	1.3	1.3	1.3	1.3	1.3
Solar	11.6	49.9	161.8	290.0	366.5	477.0
Wind	29.0	80.4	247.5	379.1	521.6	636.3
Coal	0.0	0.0	0.0	0.0	0.0	0.0
Coal without CCS	0.0	0.0	0.0	0.0	0.0	0.0
Integrated Gasification Combined Cycle without CCS	0.0	0.0	0.0	0.0	0.0	0.0
Coal with CCS	0.0	0.0	0.0	0.0	0.0	0.0
Energy Storage	32.9	54.0	88.8	113.0	121.9	142.5
Nuclear	0.0	0.0	0.0	0.0	0.0	0.0
Natural Gas	31.2	31.6	56.3	120.0	233.8	350.4
Combined Cycle without CCS	22.0	22.4	29.7	30.2	31.6	35.6
Combustion Turbine	9.2	9.2	26.6	89.8	202.2	314.7
Other	0.0	0.0	0.0	0.0	0.0	0.0
Grand Total	106.2	219.0	561.8	912.4	1,254.2	1,616.4

Table 5-8: EGU retirements for the no-action case.

RETIREMENTS (GW)	2028	2030	2035	2040	2045	2050
Combined Cycle Retirements	1.5	1.5	2.6	2.6	6.2	15.2
Coal Retirements	56.0	80.3	102.5	112.8	126.2	139.3
Combustion Turbine Retirements	0.2	0.8	2.2	2.7	13.7	19.3
Nuclear Retirements	0.0	2.7	9.9	14.5	28.7	48.2
Oil/Gas Steam Retirements	8.1	10.6	14.0	14.0	14.1	16.5
Integrated Gasification Combined Cycle Retirements	0.2	0.6	0.8	0.8	0.8	0.8
Biomass Retirements	3.0	3.2	3.3	3.3	3.3	3.3
Fuel Cell Retirements	0.0	0.0	0.0	0.0	0.0	0.0
Fossil-Other Retirements	0.0	0.0	0.0	0.0	0.0	0.0
Geothermal Retirements	0.0	0.0	0.0	0.0	0.0	0.0
Hydro Retirements	0.0	0.0	0.0	0.0	0.0	0.0
Landfill Gas Retirements	0.0	0.1	0.1	0.1	0.1	0.1
Non-Fossil, Other Retirements	0.0	0.0	0.0	0.0	0.0	0.0
Energy Storage Retirements	0.0	0.0	0.0	0.0	0.0	0.0
Grand Total	69.0	99.9	135.4	150.9	193.1	242.6

Table 5-9: EGU retirements for the proposal.

RETIREMENTS (GW)	2028	2030	2035	2040	2045	2050
Combined Cycle Retirements	1.5	1.5	2.6	2.6	6.2	15.1
Coal Retirements	55.3	79.9	97.9	110.9	125.3	138.2
Combustion Turbine Retirements	0.2	0.8	1.5	1.9	13.0	18.4
Nuclear Retirements	0.0	2.7	9.9	14.5	28.7	48.2
Oil/Gas Steam Retirements	7.3	9.6	12.4	12.4	12.5	14.9
Integrated Gasification Combined Cycle Retirements	0.2	0.5	0.8	0.8	0.8	0.8
Biomass Retirements	3.1	3.2	3.3	3.3	3.3	3.3
Fuel Cell Retirements	0.0	0.0	0.0	0.0	0.0	0.0
Fossil-Other Retirements	0.0	0.0	0.0	0.0	0.0	0.0
Geothermal Retirements	0.0	0.0	0.0	0.0	0.0	0.0
Hydro Retirements	0.0	0.0	0.0	0.0	0.0	0.0
Landfill Gas Retirements	0.1	0.1	0.1	0.1	0.1	0.1
Non-Fossil, Other Retirements	0.0	0.0	0.0	0.0	0.0	0.0
Energy Storage Retirements	0.0	0.0	0.0	0.0	0.0	0.0
Grand Total	67.7	98.2	128.4	146.6	189.9	239.0

Table 5-10: Incremental EGU retirements comparing the proposal to the no-action case.

Incremental Retirements	2028	2030	2035	2040	2045	2050
Biomass [MW]	92.9	0.0	0.0	0.0	0.0	0.0
Landfill Gas [MW]	126.0	0.0	0.0	0.0	0.0	0.0
Total [MW]	218.9	0.0	0.0	0.0	0.0	0.0

Table 5-11: Incremental new EGU capacity comparing the proposal to the no-action case [Cumulative GW].

Incremental New Capacity	2028	2030	2035	2040	2045	2050
Solar (GW)	0.0	0.0	4.8	26.4	33.4	35.3
Wind (GW	0.4	0.5	1.6	21.9	24.5	29.3
Energy Storage (GW)	0.0	1.2	3.6	4.4	2.6	3.4
Hydro (GW)	0.0	0.0	0.0	0.5	0.5	0.5
Other (Geothermal, Biomass, Landfill Gas, GW)	0.0	0.0	0.0	0.0	0.0	0.0
Combined Cycle (GW)	0.8	1.1	4.0	4.0	4.9	5.4
Combustion Turbine (GW)	0.3	0.3	5.5	19.5	28.2	30.0
Grand Total (GW)	1.6	3.1	19.6	76.7	94.2	103.9

When comparing the proposal to the no-action case, only existing coal-fired EGUs were found to receive retrofits. The cumulative capacity modeled by IPM totaled to 1,994.4 MW, 1,891.4 MW, 10,554.4 MW, 3,745.3 MW, 848.5 MW and 2,047.3 MW for the model run years of 2028, 2030, 2035, 2040, 2045, and 2050, respectively.

5.2.6 Interregional Dispatch

IPM results showing international dispatch are summarized for a no-action case and for the proposal in Table 5-8 and Table 5-9, respectively. International dispatch only occurred between Canada and the contiguous United States represented by the IPM regions. Net international dispatch was also very small as a percentage of total U.S. electricity demand, with electricity imports less than 1percent for all years and trending towards zero by 2050 for both the no-action case and proposal.

Table 5-12: IPM results for net export of electricity into the contiguous United States for the no-action case.*,†

	2028	2030	2035	2040	2045	2050
Net US Exports (GWh)*	-28,519	-23,383	-22,661	-7,997	-3,987	-501
US Electricity Demand (GWh)	4,400,402	4,527,705	4,854,351	5,188,357	5,533,316	5,885,168
Net US Exports as a Percentage of Total Demand (%)	-0.65%	-0.52%	-0.47%	-0.15%	-0.07%	-0.01%

Table Notes:
* Negative net exports represent imports of electricity
† International dispatch to the contiguous United States only occurred over the U.S. - Canada border.

Table 5-13: IPM results for net export of electricity into the contiguous United States for the proposal.*,†

	2028	2030	2035	2040	2045	2050
Net US Exports (GWh)	-28,312	-23,879	-24,877	-8,809	-4,453	-22
US Electricity Demand (GWh)	4,403,327	4,545,283	4,971,619	5,371,913	5,753,443	6,117,592
Net US Exports as a Percentage of Total Demand (%)	-0.64%	-0.53%	-0.50%	-0.16%	-0.08%	0.00%

Table Notes:
* Negative net exports represent imports of electricity
† International dispatch to the contiguous United States only occurred over the U.S. - Canada border.

International dispatch only occurred between Canada and the contiguous United States represented by the IPM regions. To estimate interregional dispatch, IPM utilizes Total Transfer Capabilities (TTCs), a metric that represents the capability of the power system to import or export power reliably from one region to another.

The amount of energy and capacity transferred on a given transmission line between IPM regions is modeled on a seasonal basis for all run years in the EPA Platform v6. All the modeled transmission lines have the same TTCs for all seasons. The maximum values for these metrics were obtained from public sources such as market reports and regional transmission plans, wherever available. Where public sources were not available, the maximum values for TTCs are based on ICF's expert view. ICF analyzes the operation of the grid under normal and contingency conditions, using industry-standard methods, and calculates the transfer capabilities between regions. To calculate the transfer capabilities, ICF uses standard power flow data developed by the market operators, transmission providers, or utilities, as appropriate. Additional information regarding power-sector modeling is available via a report submitted to the docket (U.S. EPA 2023).

5.3 Assessment of PEV Charging Infrastructure

As PEV adoption grows, more charging infrastructure will be needed to support the fleet. This section summarizes the status and outlook of U.S. PEV charging infrastructure, how much and what types of charging may be needed to support the level of PEV penetration in the rulemaking, and how we estimated the associated costs.

5.3.1 Status and Outlook for PEV Charging Infrastructure

5.3.1.1 Definitions

Terminology for charging infrastructure varies in the literature with terms like "charger", "plug", "outlet", and "port" sometimes being used interchangeably. Throughout this chapter, we use the following definitions.[91] When referring to public charging, a **station** is the physical location where charging occurs. Each station may have one or more Electric Vehicle Supply Equipment (EVSE) **ports** that provide electricity to a vehicle. 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, e.g., to accommodate vehicles that use different connector types, but each port can only charge one vehicle at a time. While it is less common to refer to the place home charging occurs (e.g., garage or driveway) as a station, we use the term ports in the same way for residential and non-residential charging.

It must be noted that charging infrastructure is different from the electric power utility distribution system infrastructure, which is comprised of distribution feeder circuits, switches, protective equipment, primary circuits, distribution transformers, secondaries, service drops, etc. The electric power utility distribution system infrastructure typically ends at a service drop (i.e. the run of cables from the electric power utility's distribution power lines to the point of connection to a customer's premises).

5.3.1.2 Charging Types

Electric Vehicle Supply Equipment (EVSE) ports can be alternating or direct current (AC or DC); they also vary by power level. Common AC charging types include L1 (up to about 2 kW power) and L2 (up to 19.2 kW power) (U.S. Department of Energy, Alternative Fuels Data Center 2023a) (Schey, Chu and Smart 2022). DC fast charging (DCFC) is available in a range of power levels today, e.g., 50 kW to 350 kW with standards for even higher-powered DCFC such as the Megawatt Charging System (MCS) currently in development (CharIN e.V. 2022).

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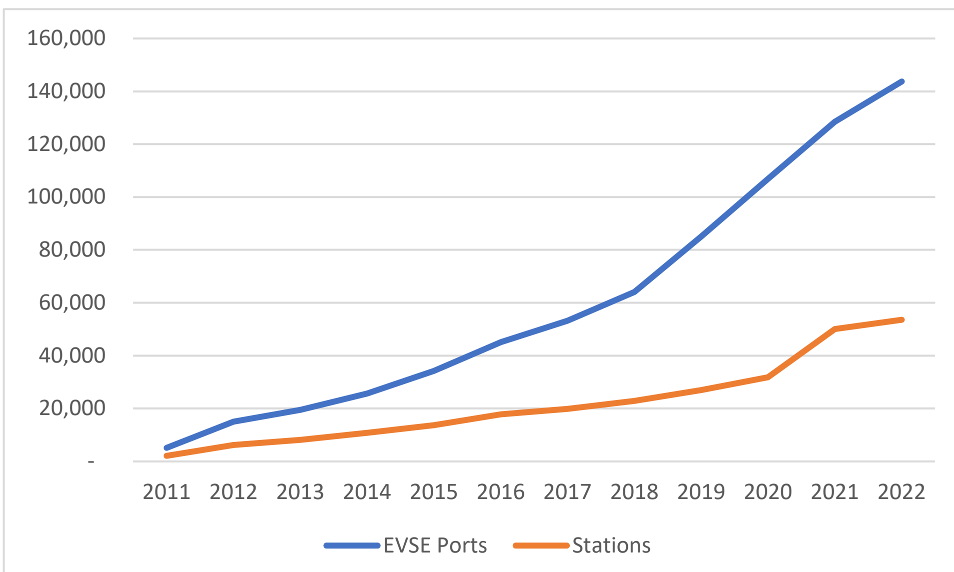
[91] Definitions are consistent with those used by (U.S. Department of Energy, Alternative Fuels Data Center 2023a). A diagram is available at: https://afdc.energy.gov/fuels/electricity_infrastructure.html (last accessed March 8, 2023).

Generally, the use of higher-power EVSE ports corresponds to faster charging[92] though the maximum power that vehicles can accept varies by model.[93]

Wireless or inductive charging systems have also been demonstrated and sold as aftermarket add-ons but have not been widely deployed (U.S. Department of Energy, Alternative Fuels Data Center 2023a). Due to the uncertainty about the timing and uptake of wireless charging, we consider it outside the scope of this analysis.

5.3.1.2.1 PEV Charging Infrastructure Status and Trends

Charging infrastructure[94] has grown rapidly over the last decade (U.S. Department of Energy, Alternative Fuels Data Center 2023b). As shown in Figure 5-13, there are more than 50,000 non-residential charging stations in the U.S. today with over 140,000 EVSE ports.[95] This is an increase from just over 85,000 EVSE ports as of the end of 2019. These include public EVSE ports, as well as some private ports, e.g., at workplaces or for fleet use. About 80 percent of EVSE ports today are L2, however, DCFC deployments have generally experienced faster growth than L2 in the past few years (Brown, et al. 2022). Among DCFC, there is a trend toward higher power levels with more than half of the EVSE ports over 50 kW and 10 percent at 300 kW or more as of the first quarter of 2021 (U.S. Department of Energy 2021).



[92] For example, DCFC can add 200 miles or more of range per hour of charging compared to about 25 miles for L2, depending on power levels (U.S. Department of Energy, Alternative Fuels Data Center 2023a).
[93] Table 5-1 shows the maximum DCFC power levels we assumed for BEV models in our infrastructure cost analysis.
[94] As used herein, "charging infrastructure" refers to EVSE, which is not a part of electric utility distribution infrastructure, which is comprised of distribution feeder circuits, switches, protective equipment, primary circuits, distribution transformers, secondaries, service drops, etc. The electric power utility distribution system infrastructure typically ends at a service drop (i.e. the run of cables from the electric power utility's distribution power lines to the point of connection to a customer's premises).
[95] These counts may include a small number of EVSE ports and stations at multifamily housing.

Figure 5-13: U.S. Non-residential PEV Charging Infrastructure from 2011─2022 (Data Source: (U.S. Department of Energy, Alternative Fuels Data Center 2023b)

While estimates for future infrastructure needs vary widely in the literature, (Brown, et al. 2022) found that the overall ratio of EVSE ports to the number of PEVs on the road today generally compares favorably to projected needs in national assessments by NREL (E. Wood, et al. 2017) and ATLAS (McKenzie and Nigro 2021)[96]. For example, the NREL study estimated a need for 1.8 DCFC ports for every thousand PEVs on the road, while Atlas estimated the need for 4.7 DCFC ports per thousand PEVs. By mid-2022, there were 9.2 DCFC ports per thousand PEVs,[97] well above the projected needs estimated by these studies (Brown, et al. 2022). By mid-2022, there were also 40 public and workplace L2 ports for every thousand PEVs on the road. This is similar to the 40.1 NREL estimated will be needed, and significantly higher than the 5.8 L2 ports per thousand PEVs that Atlas estimated (Brown, et al. 2022). Of course, keeping up with charging needs as PEV adoption grows will require continued expansion of, and investment in, charging infrastructure.

5.3.1.3 PEV Charging Infrastructure Investments

Investments in PEV charging infrastructure have grown rapidly in recent years and are expected to continue to climb. According to BloombergNEF, annual global investment was $62 billion in 2022, nearly twice that of the prior year, and while about 10 years was needed for cumulative global investment to total $100 billion, $200 billion could be reached in just three more years (BloombergNEF 2023). This growth was also seen in U.S. infrastructure spending. Combined investments in hardware and installation for U.S. home and public charging ports was over $1.2 billion in 2021, nearly a three-fold increase from 2017 (BloombergNEF 2022).

The U.S. government is making large investments in infrastructure through the Bipartisan Infrastructure Law (Public Law 117-58 2021) and the Inflation Reduction Act (Public Law 117-169 2022). However, we expect that private investments will also play a critical role in meeting future infrastructure needs. Private charging companies have already attracted billions globally in venture capital and mergers and acquisitions (Hampleton 2023). In the U.S., there was $200 million or more in mergers and acquisition activity in 2022 according to the capital market data provider PitchBook (St. John and Naughton 2022), indicating strong interest in the future of the charging industry. Bain projects that by 2030, the U.S. market for electric vehicle charging will be "large and profitable" with both revenue and profits estimated to grow by a factor of twenty relative to 2021 (Zayer, et al. 2022).[98] Domestic manufacturing capacity is also increasing with over $600 million in announced investments to support the production of charging equipment and components at existing or new U.S. facilities. (Joint Office of Energy and Transportation 2023) (Kempower 2023). These activities along with the large variety of private investments

[96] NREL and ATLAS both assessed future charging infrastructure needs, but under different PEV adoption scenarios. See studies for details. Ratios discussed above are based on projected infrastructure needs in 2030.

[97] Estimates for the number of DCFC and L2 ports available in 2022 include Tesla EVSE ports that are not currently available for use by non-Tesla vehicles.

[98] Estimates account for hardware and installation as well as operations and other charging services such as vehicle-grid integration.

detailed in Chapter 5.3.1.3.4 below suggest that companies are positioning themselves to meet the growing demand for PEV charging.

The following sections outline some current and upcoming investments in charging infrastructure from both public and private sources.

5.3.1.3.1 Bipartisan Infrastructure Law

The Bipartisan Infrastructure Law (BIL)[99] (Public Law 117-58 2021) provides up to $7.5 billion over five years to build out a national network of PEV chargers. Two-thirds of this funding is for the National Electric Vehicle Infrastructure (NEVI) Formula Program (U.S. Department of Transportation, Federal Highway Administration 2022a). The remaining $2.5 billion is for the Charging and Fueling Infrastructure (CFI) Discretionary Grant Program, which is evenly divided between funds for charging and fueling infrastructure along corridors and in communities where fueling infrastructure can include hydrogen, propane, or natural gas (U.S. Department of Transportation, Federal Highway Administration 2022a). These programs are administered under the Federal Highway Administration with support from the Joint Office of Energy and Transportation.

The first phase of NEVI formula funding for states was launched in 2022 and is focused on building out Alternative Fuel Corridors (AFCs) on highways. Charging stations for AFCs are required to have at least four DCFC ports, each 150 kW or higher (88 FR 12724 2023). Per FHWA's guidance to states, stations generally must be located no more than 50 miles apart and one mile from the Interstate (U.S. Department of Transportation, Federal Highway Administration 2022a). Initial plans for all 50 states, DC, and Puerto Rico covering FY22 and FY23 funds were approved in September 2022. Together the $1.5 billion in funding will help deploy or expand charging infrastructure on about 75,000 miles of highway (U.S. Department of Transportation, Federal Highway Administration 2022b). In March 2023, the first funding opportunity was opened under the CFI Program with up to $700 million to deploy PEV charging and hydrogen, propane, or natural gas fueling infrastructure in communities and along corridors (Joint Office of Energy and Transportation 2023b).

In addition to NEVI, there are a variety of other Federal programs that could help reduce State or private costs associated with deploying EVSE. For example, constructing and installing charging infrastructure is an eligible activity for other U.S. Department of Transportation formula programs including the Congestion Mitigation & Air Quality Improvement Program, National Highway Performance Program, and Surface Transportation Block Grant Program, which have a total of more than $40 billion in FY22 funds authorized under the BIL (U.S. Department of Transportation, Federal Highway Administration 2022a).[100] Discretionary grant programs include the Rural Surface Transportation Grant Program, Infrastructure for Rebuilding America Grant Program, and the Discretionary Grant Program for Charging and Refueling Infrastructure (U.S. Department of Transportation, Federal Highway Administration 2022a).

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[99] Signed into law as the "Infrastructure Investment and Jobs Act"

[100] Only a portion is likely to be used to support PEV charging infrastructure, and limits and restrictions may apply.

5.3.1.3.2 Inflation Reduction Act

The Inflation Reduction Act (IRA), signed into law on August 16, 2022, can also help reduce the cost that consumers and businesses pay toward PEV charging infrastructure (Public Law 117-169 2022).

Section 13404 extends the Alternative Fuel Refueling Property Tax Credit through Dec 31, 2032, with modifications. Under the new provisions, consumers in low-income or rural areas would be eligible for a 30 percent credit for the costs of installing a residential charging equipment subject to a $1,000 cap. Businesses would also 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 they meet prevailing wage and apprenticeship requirements. The Joint Committee on Taxation estimates the cost of this tax credit from FY2022─2031 to be $1.738 billion, which reflects a significant level of support for charging infrastructure and other eligible alternative fuel property (Joint Committee on Taxation 2022).

5.3.1.3.3 Equity Considerations in BIL and IRA

The infrastructure funding in the BIL and the IRA tax credit discussed above can help to address equity challenges for PEV charging infrastructure. One of the stated goals of the $7.5 billion in infrastructure funding under the BIL is to support equitable access to charging across the country (U.S. Department of Transportation, Federal Highway Administration 2022a). Accordingly, FHWA instructed states to incorporate public engagement in their planning process for the NEVI Formula program, including reaching out to Tribes, and rural, underserved, and disadvantaged communities among other stakeholders. This funding will also support the Justice40 target that 40 percent of the benefits go to disadvantaged communities (U.S. Department of Transportation, Federal Highway Administration 2022a). Separately, modifications to the Alternative Fuel Refueling Property Tax Credit in IRA limit applicability to charging infrastructure installed in low-income or rural census tracts starting in 2023 (Public Law 117-169 2022). This can help residents in these communities install home charging and provide an incentive for businesses to site stations in these areas.

5.3.1.3.4 Other Public and Private Investments

States, utilities, auto manufacturers, charging network providers and others are also investing in and supporting PEV charging infrastructure deployment. California announced plans in 2021 to invest over $300 million in light-duty charging infrastructure and nearly $700 million in medium- and heavy-duty ZEV infrastructure (California Energy Commission 2021). Several states including New Jersey and Utah offer partial rebates for residential, workplace, or public charging while others such as Georgia and D.C. offer tax credits (U.S. Department of Energy, Alternative Fuels Data Center 2023c).[101] The NC Clean Energy Technology Center identified more than 200 actions taken across 38 states and D.C. related to providing financial incentives for electric vehicles and or charging infrastructure in 2022, a four-fold increase over the number of actions in 2017 (Apadula, et al. 2023).[102] The Edison Electric Institute estimates that electric

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[101] Details on eligibility, qualifying expenses, and rebate or tax credit amounts vary by state.

[102] Includes actions by states and investor-owned utilities.

companies have already invested nearly $3.7 billion (EEI 2023).[103] And over 60 electric companies and cooperatives serving customers in 48 states and the District of Columbia have joined together to advance fast charging through the National Electric Highway Coalition (EEI 2023).

Auto manufacturers are investing in charging infrastructure by offering consumers help with costs to install home charging or providing support for public charging. For example, GM will pay for a standard installation of a Level 2 (240 V) outlet for customers purchasing or leasing a new Bolt (Chevrolet 2023). GM is also partnering with charging provider EVgo to deploy over 2,700 DCFC ports and charging provider FLO to deploy as many as 40,000 L2 ports (GM 2021) (Joint Office of Energy and Transportation 2023). Volkswagen, Hyundai, and Kia all offer customers complimentary charging at Electrify America's public charging stations (subject to time limits or caps) in conjunction with the purchase of select new electric vehicle models (VW 2023) (Hyundai 2023) (Kia 2023). Ford has agreements with several charging providers to make it easier for their customers to charge and pay across different networks (Ford 2019) and plans to install publicly accessible DCFC ports at nearly 2,000 dealerships (Joint Office of Energy and Transportation 2023). Mercedes-Benz recently announced that it is planning to build 2,500 charging points in North America by 2027 (Reuters 2023). Tesla has its own network with over 17,000 DCFC ports and nearly 10,000 L2 ports in the United States (U.S. Department of Energy, Alternative Fuels Data Center 2023d). Tesla recently announced that by 2024, 7,500 or more existing and new ports (including 3,500 DCFC) would be open to all PEVs (The White House 2023).

Other charging networks are also expanding. Francis Energy, which has fewer than 1000 EVSE ports today (U.S. Department of Energy, Alternative Fuels Data Center 2023d), aims to deploy over 50,000 by the end of the decade (Joint Office of Energy and Transportation 2023). Electrify America plans to more than double its network size (U.S. Department of Energy, Alternative Fuels Data Center 2023d) to 10,000 fast charging ports across 1800 U.S. and Canadian stations by 2026. This is supported in part by a $450 million investment from Siemens and Volkswagen Group (Joint Office of Energy and Transportation 2023). Blink plans to invest over $60 million to grow its network over the next decade. Charging companies are also partnering with major retailers, restaurants, and other businesses to make charging available to customers and the public. For example, EVgo is deploying DCFC at certain Meijer locations, CBL properties, and Wawa. Volta is installing DCFC and L2 ports at select Giant Food, Kroger, and Stop and Shop stores, while ChargePoint and Volvo Cars are partnering with Starbucks to make charging available at select Starbucks locations (Joint Office of Energy and Transportation 2023). Other efforts will expand charging access along major highways at up to 500 Pilot and Flying J travel centers (through a partnership between Pilot, GM and EVgo) and 200 TravelCenters of America and Petro locations (through a partnership between TravelCenters of America and Electrify America). BP plans to invest $1 billion toward charging infrastructure by the end of the decade, including through a partnership to provide charging at various Hertz locations across the country that could support rental and ridesharing vehicles, taxis, and the public (Joint Office of Energy and Transportation 2023).

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[103] The $3.7 billion total includes infrastructure deployments and other customer programs to advance transportation electrification.

5.3.2 PEV Charging Infrastructure Cost Analysis

To assess the infrastructure needs and associated costs for this proposal, we start with estimates of PEV charging demand generated using the methodology described in Chapter 5.1. The share of demand we anticipate being met by different charging types (e.g., home L2 or public DCFC) is then used to project the number and mix of EVSE ports that may be needed each year in the proposal and no-action case. Finally, we assign costs for each EVSE port type intended to reflect upfront hardware and installation costs based on values in the literature.

We note that the no-action case referred to as part of the infrastructure cost analysis was based on earlier work with lower projected PEV penetration rates than the no-action case used for compliance modeling and described in Preamble Section IV.B. (See discussion in DRIA Chapter 5.3.2.6.)

5.3.2.1 Charging Demand Projections

Regionalized PEV charging demand under our proposal was simulated for select years from 2026–2055 under an Interagency Agreement between EPA and the U.S. Department of Energy, National Renewable Energy Laboratory (NREL). NREL's EVI-X modeling suite was used, including the EVI-Pro model to simulate charging demand from typical daily travel, EVI-RoadTrip to simulate demand from long-distance travel, and EVI-OnDemand to simulate demand from ride-hailing applications. Eight unique charging types and locations were considered: home L1, home L2, work L2, public L2, and public DCFC at 50 kW, 150 kW, 250 kW, and 350 kW power levels (DC-50, DC-150, DC-250, and DC-350). The following assumptions informed the respective charging shares for daily travel modeled with EVI-Pro:

- PEVs with access to residential charging are assumed to prefer home over either work or public charging when home charging is sufficient to support all travel needs.
- 75 percent of BEVs and 53 percent of PHEVs are assumed to use L2 for home charging with the remaining share using L1.[104]
- Workplace L2 is the next most preferred charging type after home charging.
- Remaining charging needs are met with public charging. DCFC is generally preferred for BEVs, and among DCFC, the highest power that a vehicle can accept (or "as fast as possible" charging) is preferred.
- Public L2 charging is used by PHEVs, which are assumed not to be DCFC-capable. It's also used by BEVs in certain long dwell time location types such as schools or medical facilities where it's assumed that DCFC is not available.

For road trips and travel by ride-hailing vehicles modeled in EVI-RoadTrip and EVI-OnDemand respectively, all public charging is assumed to be met with DCFC for BEVs.

[104] This in part reflects assumptions about the characteristics of PEVs modeled by OMEGA, including a percentage of low mileage PEVs for which L1 meets daily charging needs.

Additionally, BEVs able to accept higher-power charging (Gen 2) are assumed to be adopted more quickly for these applications than for daily travel needs modeled in EVI-Pro.[105]

As shown in Figure 5-14, the share of PEV charging demand by location and type is similar for the proposal and no-action case. The majority of PEV charging is home L2 across all years though the share under the proposal declines from over 70 percent in 2028 to just below 60 percent in 2055 as the share of workplace and public charging grow. DCFC has the next highest share of demand. Due to the modeling assumption that BEVs charge "as fast as possible" when using DCFC, 350 kW charging dominates. Since simulated BEV models are capable of higher-power charging, no DC-50 kW charging is found for either the proposal or no-action case.

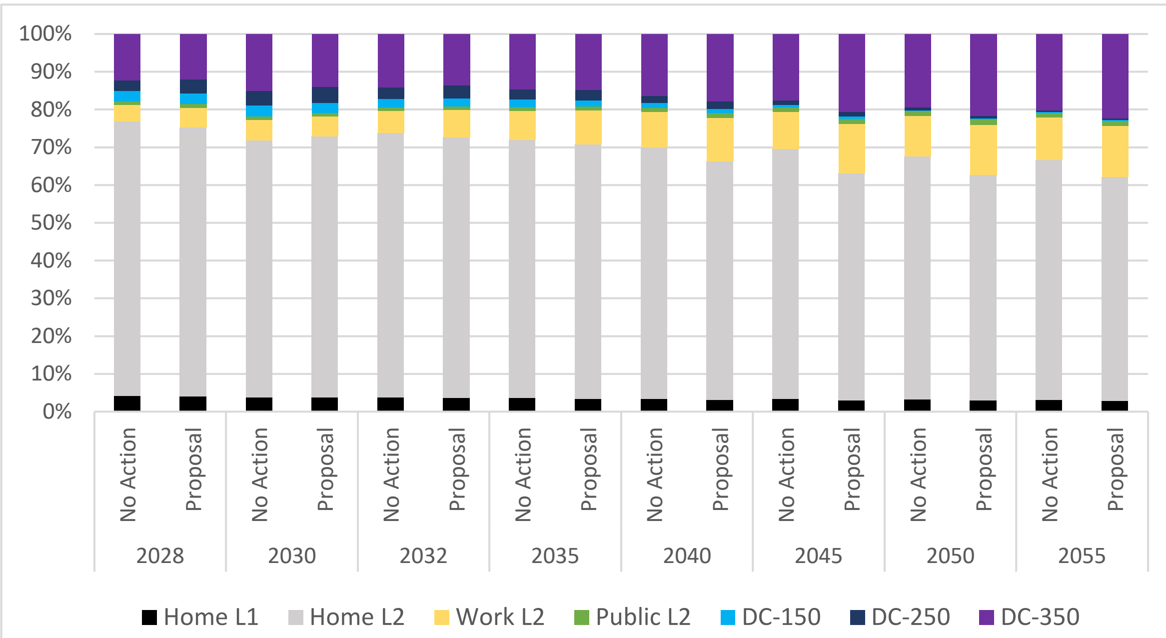

Figure 5-14: Share of charging demand by location and type for the no-action case (left side of each pair of bars) and proposal (right side of each pair of bars) for 2028─2055.

5.3.2.2 EVSE Port Counts

The number of EVSE ports needed to meet the level of PEV charging demand in our proposal and in the no-action case was estimated for all charging types described above. Home charging was further delineated into charging at single family houses (SFHs)—including both detached and attached houses (e.g., townhouses) — and non-SFHs which include apartments, condos, and mobile homes. Several additional assumptions informed this network sizing. For home charging, it was assumed that as PEV adoption increases, more home charging ports would be shared across vehicles. This could reflect SFHs with more than one PEV or residents of multi-unit dwellings that share L2 ports. Specifically, we assume that at 1 percent PEV adoption, 1 EVSE port is needed per PEV with home charging access. This declines to 0.6 EVSE ports per

[105] For max DC fast charging rates for different vehicle types modeled in this analysis, see Table 5-1.

PEV for SFHs and 0.5 EVSE ports per PEV for other home types when PEVs make up the entire light-duty fleet.

Network sizing for public and workplace charging is based on the regional charging load profiles described in Chapter 5.1. For each DCFC port type (DC-50, DC-150, DC-250, and DC-350), the total number of ports needed is scaled such that during the peak hour of usage 20 percent of ports in the region are fully utilized. For work and public L2 charging, 43 percent of ports are assumed to be fully utilized during the peak hour. These percentages are modeled after highly utilized stations today (Wood, Borlaug, et al. 2023). [106]

Figure 5-15 and Figure 5-16 show the growing charging network that may be needed to meet PEV charging demand in the proposal and no-action case respectively.[107] We anticipate that the highest number of ports will be needed at homes, growing from under 12 million in 2027 to over 75 million in 2055 under the proposal.[108] This is followed by workplace charging, estimated at about 400,000 EVSE ports in 2027 and over 12.7 million in 2055. Finally, public charging needs grow from just over 110,000 ports to more than 1.9 million in that timeframe. Notably, while DCFC at 350 kW constitutes a significant fraction of total electricity demand (Figure 13), the number of ports needed is relatively small compared to the scale shown. This is because far fewer 350 kW ports are needed to deliver the same amount of electricity as lower-powered options. Similar patterns are observed in the no-action case—though fewer total ports are needed than under the proposal due to the lower anticipated PEV demand.

[106] The same method and thresholds for sizing the non-residential charging network based on peak hour of usage was applied for all years in this analysis. If we instead assumed the percentage of L2 or DCFC ports that are fully utilized at peak grew as a function of time or PEV penetration, we would expect higher average utilizations per port and fewer total ports needed.

[107] Charging simulations were conducted for 2026, 2028, 2030, 2032, 2035, 2040, 2045, 2050, and 2055. Linear interpolations were used to estimate the network size in intermediate years. Estimates above do not include PEV charging demand for medium-duty or heavy-duty vehicles.

[108] The number of EVSE ports needed to meet a given level of electricity demand will vary based on the mix of charging ports, charging preferences, and other factors. Estimates shown reflect assumptions specific to this analysis, but actual needs could vary.

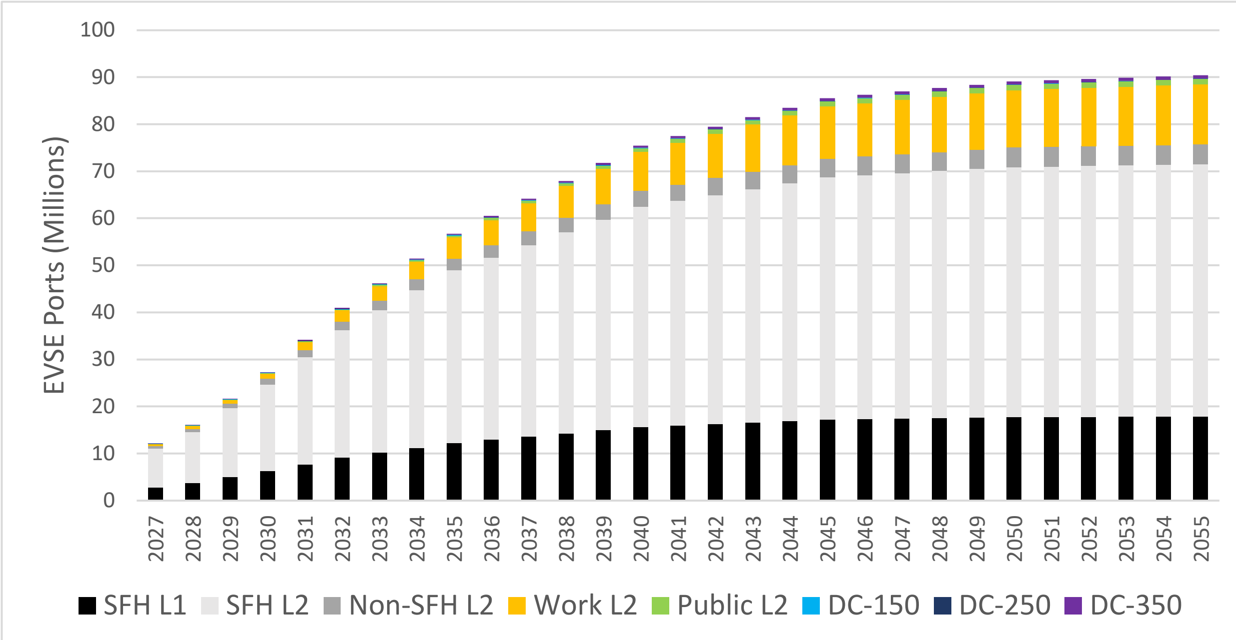

Figure 5-15: EVSE port counts by charging type for proposal 2027─2055.

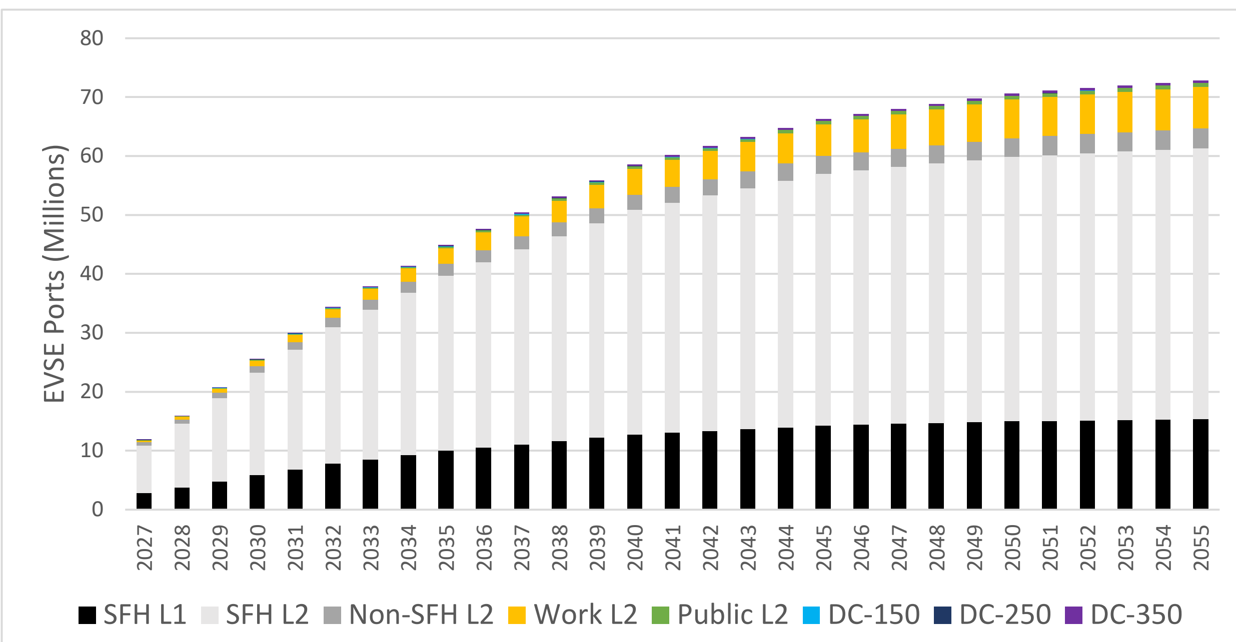

Figure 5-16: EVSE port counts by charging type for the no-action case 2027─2055.

In order to estimate the costs incurred each year, we calculate how many EVSE ports of each type would need to be procured and installed to achieve the charging network sizes shown in

Figure 5-15 and Figure 5-16. There is limited data on the expected lifespan and maintenance needs of PEV charging infrastructure. We make the simplifying assumption that all EVSE ports have a 15-year equipment lifetime (Borlaug, Salisbury, et al. 2020). 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. We do not attempt to estimate EVSE maintenance costs due to uncertainty but note that maintenance may be able to extend equipment lifetimes. Another simplifying assumption we make is that EVSE ports are operational and able to meet PEV charging demand the same year costs are incurred. The actual time to permit and install can vary widely by port type, power level, region, site conditions and other factors.

5.3.2.3 Hardware & Installation Costs

We assign costs to each of the above infrastructure types intended to reflect the upfront capital costs associated with procuring and installing the EVSE ports. There are many factors that can impact equipment costs, including whether ports are wall-mounted or on a pedestal as well as differences in equipment features and capabilities (Schey, Chu and Smart 2022). For example, an ICCT paper found that costs more than doubled between networked and non-networked L2 hardware (Nicholas, Estimating electric vehicle charging infrastructure costs across major U.S. metropolitan areas 2019). Among networked units with one or two ports per pedestal, about a 10 percent difference in per-port hardware costs was found (Nicholas, Estimating electric vehicle charging infrastructure costs across major U.S. metropolitan areas 2019). The power level of the EVSE is one of the most significant drivers of cost differences. While estimates for charging equipment vary across the literature, higher-power charging equipment is typically more expensive than lower-power units.

Installation costs may include labor, materials (e.g., wire or conduit), permitting, taxes, and upgrades or modifications to the on-site electrical service. These costs—particularly labor and permitting—can vary widely by region (Schey, Chu and Smart 2022). They also vary by site. For example, how much trenching is needed will depend on the distance from where the charging equipment will be located and the electrical panel. A recent study found that average L2 installation costs at condominiums and commercial locations increased by $16 or $20 for each extra foot of distance between the EVSE and power source respectively (Schey, Chu and Smart 2022). How many EVSE ports are installed also impacts cost. 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 (Nicholas, Estimating electric vehicle charging infrastructure costs across major U.S. metropolitan areas 2019). And, as with hardware costs, installation costs may rise with power levels.

To reflect the diversity of hardware and installation costs, we considered a range of costs for each charging type as shown in Table 5-10 and detailed below.[109]

Table 5-14: Cost (hardware and installation) per EVSE port[110]

	Home	Work	Public

[109] All costs shown above and used within the cost analysis are rounded to the nearest hundred.
[110] Costs shown are expressed in 2019 dollars, consistent with the original sources from the literature.

	L1	SFH L2	non-SFH L2	L2	L2	DC-50	DC-150	DC-250	DC-350
Low	$0	$800	$3,300	$5,100	$5,100	$30,000	$94,000	$124,000	$154,000
Mid	$0	$1,100	$3,700	$5,900	$5,900	$56,000	$121,000	$153,000	$185,000
High	$0	$1,500	$4,100	$7,300	$7,300	$82,000	$148,000	$182,000	$216,000

5.3.2.3.1 Home Charging Ports

PEVs typically come with a charging cord that can be used for L1 charging by plugging it into a standard 120 VAC[111] outlet, and, in some cases, for L2 charging by plugging into a 240 VAC outlet.[112] We include the cost for this cord as part of the vehicle costs described in Chapter 2, and therefore don't include it here. We make the simplifying assumption that PEV owners opting for L1 home charging already have access to a 120 VAC outlet and therefore do not incur installation costs.[113]

For L2 home charging, some PEV owners may opt to simply install or upgrade to a 240 VAC outlet for use with a provided cord while others may choose to purchase or install a wall-mounted or other L2 charging unit, which may have additional features and capabilities. In Table 5-10, the "Low" cost assumes outlet installations only, the "High" cost assumes the purchase and installation of L2 units, and the "Mid" cost assumes a 50%:50% split.

Costs vary by housing type with installation costs for SFHs typically lower than those for apartments, condos, or mobile homes (non-SFHs). We use costs by housing type from (Nicholas, Estimating electric vehicle charging infrastructure costs across major U.S. metropolitan areas 2019) for both outlet upgrades and L2 unit installations.[114] For SFH costs, we weight costs for detached and attached houses by 93 percent to 7 percent.[115] We use cost estimates for apartments to represent all non-SFH home types.

5.3.2.3.2 Work and Public Level 2 Charging Ports

We also source our assumed EVSE costs for work and public AC L2 ports from (Nicholas, Estimating electric vehicle charging infrastructure costs across major U.S. metropolitan areas 2019).[116] We select the lowest per port hardware and installation costs presented for networked EVSE as our "Low" value and the highest combination of hardware and installation costs presented as our "High" value. Specifically, we use the following combinations for the costs shown in Table 5-10:

[111] Volts, alternating current.

[112] Not all charging cords may be capable of Level 2 charging.

[113] (Ge, et al. 2021) found that while residential charging access is expected to decline as PEV adoption grows, the majority of PEVs are projected to have access to an outlet either where they regularly park or at another parking location at their home even if PEVs reach 100% of the light-duty fleet.

[114] We use costs from Table 5 of (Nicholas 2019), specifically "Level 2 outlet upgrade" for outlet only installations and "Level 2 charger upgrade" for hardware and installation costs associated with a Level 2 charging unit.

[115] Weighting reflects the relative share of light-duty vehicles owned by residents of detached versus attached houses, sourced from Figure 12 of (Ge, et al. 2021).

[116] While (Nicholas 2019) notes that it assumed lower installation costs for workplace charging ports than for public L2 ports, we make the simplifying assumption that both hardware and installation costs are the same.

- Low: hardware costs for units with two EVSE ports per pedestal, installation costs for sites with 6+ EVSE ports outside of California
- Mid: hardware costs for units with two networked EVSE ports per pedestal, installation costs for sites with 3–5 EVSE ports outside of California
- High: hardware costs for units with one EVSE per pedestal, installation costs for sites with one EVSE port in California

5.3.2.3.3 Public DC Fast Charging Ports

Cost estimates for DCFC ports are from a 2021 study that drew from various data and literature sources, including the ICCT report discussed above (Borlaug, Muratori, et al. 2021). We use the lower end of the ranges presented for procurement and installation costs as the "Low" costs for 50 kW, 150 kW, and 350 kW DCFCs in Table 5-10, and the upper end of the ranges for the "High" costs. Our "Mid" costs are the average of "Low" and "High". Since no estimate is provided for 250 kW DCFCs, we take the average of costs for 150 kW and 350 kW DCFCs.[117]

5.3.2.4 Will Costs Change Over Time?

The infrastructure costs shown above reflect present day costs (expressed in 2019 dollars). However, both hardware and installation costs 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 annual reduction in hardware costs (Nicholas, Estimating electric vehicle charging infrastructure costs across major U.S. metropolitan areas 2019) (Bauer, Hsu, et al., Charging Up America: Assessing the Growing Need for U.S. Charging Infrastructure Through 2030 2021). By contrast, installation costs could increase due to growth in labor or material costs. As noted above, installation costs also depend on site conditions, including whether sufficient electric capacity exists to add charging infrastructure and how much trenching is required between the EVSE port and electrical panel. If easier and, therefore, lower cost sites are selected first, then over time installation costs could rise as charging stations start to be installed in more challenging locations. (Bauer, Hsu, et al., Charging Up America: Assessing the Growing Need for U.S. Charging Infrastructure Through 2030 2021) 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, we have made the simplifying assumption for this analysis to keep combined hardware and installation costs per EVSE port constant.

5.3.2.5 Other Considerations

EPA acknowledges that there may be additional infrastructure needs and costs beyond those associated with charging equipment itself. While planning for additional electricity demand is a standard practice for utilities and not specific to PEV charging, the buildout of public and private charging stations (particularly those with multiple high-powered DC fast charging units) could in

[117] Costs may not scale linearly with power level. We take the average as a simplifying assumption but continue to monitor the literature for costs associated with this power level.

some cases require upgrades to local distribution systems. For example, a recent study found power needs as low as 200 kW could trigger the need to install a distribution transformer while a load of 5 MW or more could require upgrades to feeder circuits or the addition of a feeder breaker (Borlaug, Muratori, et al. 2021).

There are a variety of approaches that could reduce the need or scale of such upgrades—potentially saving both cost and deployment time. For example, distribution system capacity and interconnection could be factored into the site selection process, and when possible, utilities could work with station developers to evaluate multiple potential sites before a selection is made (Hernandez 2022). Another emerging best practice identified by the Interstate Renewable Energy Council is for utilities to provide hosting capacity maps (HCMs) that identify grid capacity constraints (Hernandez 2022). Such maps could help developers determine whether area feeders or substations have additional capacity for charging or other loads. By mid-2022, requirements for HCMs or related analyses were in place in ten states identified by Lawrence Berkeley National Laboratory (Schwartz 2022). More broadly, 25 states and the District of Columbia have ongoing efforts and requirements to support proactive distribution system planning and grid modernization (Schwartz 2022).

Managing the additional demand from PEV charging is another key strategy. 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—potentially reducing the need for upgrades at some sites (Nuvve and Enel X 2020) (BATRIES 2023). The use of onsite battery storage and renewables may also be able to reduce demand on the grid, and some station operators may opt for these technologies to mitigate demand charges associated with peak power (Alexander, et al. 2021). In addition, managed or smart charging can be used in some cases to reduce power or shift charging demand to times when it is easier to meet. Charging equipment funded under the NEVI Formula Program, or as part of publicly-accessible charging projects funded under Title 23, U.S.C., must be capable of smart charge management (88 FR 12724 2023).[118] Finally, we note that an adapter developed by Argonne National Laboratory to retrofit non-networked L2 EVSE to allow load management and other smart charging capabilities is in the process of being commercialized (EVmatch, Inc. 2023). (Also see the discussion of managed charging and vehicle-grid integration in Chapter 5.4 below.)

Innovative charging approaches may also reduce the need for upgrades in certain cases, or otherwise reduce infrastructure costs. Mobile charging units could be a solution for locations like parking garage decks in which it is challenging or costly to install EVSE ports (Alexander, et al. 2021), or be used as a temporary solution while stations are being built. These units are available in a variety of power levels (e.g., the dual-port Mobi EV charger by (FreeWire Technologies 2023) can provide up to 11 kW while the Lightning Mobile unit can be configured to have up to five 80 kW DCFC ports (Lightning eMotors 2023)), and can be recharged at times and locations in which there is sufficient electrical capacity. Standalone charging canopies with integrated

[118] The National Electric Vehicle Standards and Requirements Final Rule establishes requirements for standardized communication among vehicles, charging equipment, and networks to ensure interoperability. Specifically, the use of ISO 15118 is required for communication between vehicles and chargers, Open Charge Point Protocol for communication between chargers and networks, and Open Charge Point Interface for communication among charging networks. (See (88 FR 12724 2023) for details on applicable versions and the timing for these requirements.)

solar cells and battery storage that don't need to be connected to the grid (Alexander, et al. 2021) may be useful for remote locations or where construction is costly or difficult.

There is considerable uncertainty associated with future distribution upgrade needs as well as with the uptake of the technologies and approaches discussed above that could reduce upgrade costs, and we do not model them directly as part of our infrastructure cost analysis.[119]

5.3.2.6 PEV Charging Infrastructure Cost Summary

Table 5-11 shows the estimated annual PEV charging infrastructure costs for the indicated calendar years in the proposal relative to the no action case using the "Low", "Mid", and "High" per port cost estimates discussed above.[120] Annual costs range from $0.6 billion dollars under the low scenario to $10 billion under the high scenario. The table also shows the present value (PV) of these costs and the equivalent annualized value (EAV) for the calendar years 2027–2055 using both 3 percent and 7 percent discount rates. The "Mid" costs are included as social costs in the net benefits estimates for this proposal, presented in Chapter 10.6.

Table 5-15: EVSE costs for the proposal relative to no-action case (billions of 2020 dollars)

Calendar Year	Low	Mid	High
2027	1.0	1.3	1.6
2028	0.6	0.7	0.8
2029	0.9	1.1	1.4
2030	0.9	1.1	1.4
2031	6.8	8.3	10.0
2032	6.8	8.3	10.0
2035	5.5	6.7	8.1
2040	6.0	7.1	8.6
2045	6.1	7.3	8.8
2050	5.9	7.1	8.6
2055	6.0	7.1	8.5
PV3	96	120	140
PV7	57	68	83
EAV3	5.1	6.2	7.5
EAV7	4.7	5.6	6.8

As previously noted, the no-action case used throughout the PEV charging infrastructure cost analysis was based on earlier work with lower projected PEV penetration rates than the no-action case used for compliance modeling. As a result, the number of EVSE ports and associated costs for the no-action scenario discussed in this section are likely lower than they would be under the compliance no-action case. Since we estimate costs for the proposal relative to the no-action

[119] The per port EVSE costs shown in Table 5-10 may include some distribution system costs. For example, (Nicholas 2019) notes that public and workplace installation costs include "utility upgrades". We don't add to, or otherwise adjust, these values to account for transformer upgrades or other potential upstream distribution costs specific to the projected port counts in this analysis.

[120] See spreadsheet "PEV Charging Infrastructure Cost Analysis" in the docket.

case, the resulting EVSE costs shown in Table 5-11 are likely to be conservative, or higher, than if we had applied the same no-action case used for compliance modeling.

5.4 Grid Resiliency

How the additional electricity demand from PEVs will impact the grid will depend on many factors including the time-of-day that charging occurs, and the use of battery storage and vehicle-to-grid (V2G) or other Vehicle-Grid Integration (VGI) technology. For example, PEVs can be scheduled to charge at off-peak hours when the electricity demand is easier to meet. Onsite battery storage, if deployed at charging stations, could also reduce potential grid impacts by shifting when electricity is drawn from the grid while still providing power to vehicles when needed. Managed charging and battery storage could also enable increasing renewable use if charging load is shifted to times with excess solar or wind that might otherwise be curtailed. V2G technology, which allows electricity to be drawn from vehicles when not in use, could even allow PEVs to enhance grid reliability.

Electric power system reliability can be determined using a variety of statistical metrics. The generally accepted metrics by which electric utilities across the U.S. measure and report electric power system reliability is set by the Institute of Electrical and Electronics Engineers (IEEE) using the standard IEEE 1366-2022 (IEEE Guide for Electric Power Distribution Reliability Indices). The formulation of overall electric power system reliability metrics includes electric power outages associated with what is known as “loss of supply” events; these are events in which electric power generation and/or electric power transmission is the root cause for a power outage. As this discussion is limited to electric power distribution system reliability, an electric power system reliability metric that excludes electric power outages associated with the loss of supply events (i.e. loss of electric power generation and/or electric power transmission) is appropriate.

Using this approach, we observed that electric power utilities in 48 U.S. Census Division and State regions tracked by the U.S. Energy Information Administration (EIA) had overall trends in distribution grid reliability that were less than the national average for the years 2013 and 2021 (the most-recent years for which data is available) (EIA, 2022). Conversely, 13 U.S. Census Division and State regions had overall trends in distribution grid reliability for the same years that were greater than the national average for the years in question. According to the California Public Utilities Commission, "This data alone does not fully capture the current state of reliability of the U.S. electric power distribution system…" (Enis 2021). Given the massive size of the electric power distribution system – with its multitude of regional, climate, and density variations – interpreting distribution system reliability indices can be challenging to interpret. Moreover, such reliability statistics focus on outage duration and customer counts, which may obscure important regional variations. However, as the expected increase in electricity generation associated with the proposal relative to a no action case is relatively small – approximately 4.4 percent increase in 2050 – we do not expect the U.S. electric power distribution system to be adversely affected by the projected additional number of charging electric vehicles.

Grid reliability is not expected to be adversely affected by the modest increase in electricity demand associated with electric vehicle charging. As shown in Figure 5-8, we project the additional generation needed to meet the demand of PEVs in the proposal to be relatively modest compared to the no-action case, ranging from less than 0.4percent in 2030 to approximately

4.4percent in 2050. The California Public Utilities Commission (CPUC) (California Public Utilities Commission 2022) and the California Energy Commission (CEC) (Lipman, Harrington and Langton 2021) (Chhaya, et al. 2019) have been actively engaged in VGI[121] efforts for over a decade, along with the California Independent System Operator (CAISO) (California Independent System Operator 2014, California Energy Commission; California Public Utilities Commission; Governor's Office of Business and Economic Development 2021), large private and public electrical utilities (SCE, PG&E, SDG&E, etc.), several automakers (Ford, GM, FCA, BMW, Audi, Nissan, Toyota, Honda, and others), and EV charger companies, the Electric Power Research Institute (EPRI), and various other research organizations.

These efforts (Lipman, Harrington and Langton 2021) demonstrated the ability to shift up to 20 percent of electric vehicle charging loads in any given hour to other times of the day as well as the ability to add up to 30 percent of electric vehicle charging loads in a given hour (Lipman, Harrington and Langton 2021). We anticipate similar strategies could be used to shift PEV charging loads from peak times as needed to reduce grid impacts across different regions. As the expected increase in electric power demand resulting from PEV charging in this proposal will be well-under 20 percent, we do not anticipate it to pose grid reliability issues.

The increasing integration of electric vehicle charging into the electric power grid has also been found to increase grid reliability (Chhaya, et al. 2019) , as the ability to shift and curtail electric power loads improves grid operations and, therefore, grid reliability. Such integration has been found to create value for electric vehicle drivers, electric grid operators, and ratepayers. Management of PEV charging can reduce overall costs to utility ratepayers by delaying electric utility customer rate increases associated with equipment upgrades and may allow utilities to use electric vehicle charging as a resource to manage intermittent renewables or provide ancillary services.

The Electric Power Research Institute (EPRI)[122], is undertaking a three year-long research project to better-understand the scale of commitment and investment in the electric power grid that is required to meet the anticipated electric power loads. Thus far, the electric power sector and its regulators have focused on incremental EV load growth and charger utilization (Electric Power Research Institute 2022). The work of EPRI focuses on grid impacts and associated lead times required to better-prepare the grid (including transmission, substation, feeder, and transformer) for vehicle electrification. These efforts are, in part, based upon grid reliability research conducted by EPRI (Maitra 2013) (Electric Power Research Institute 2012), which identified grid and charging behavior characteristics associated with grid resiliency. We also consulted with FERC staff on distribution system reliability and related issues.

State government plays an important role in vehicle electrification (including aspects of grid resilience), as most electric utilities are regulated by state Public Service Commissions (PSC) and Public Utility Commissioners (PUC) and since Federal funding for vehicle electrification is largely distributed through state agencies. The National Association of Regulatory Utility Commissioners (NARUC), a national association representing the state public service commissioners who regulate essential utility services, including energy, telecommunications, and

[121] VGI is also sometimes referred to as Vehicle-to-Grid or VTG or V2G.

[122] EPRI is an independent, nonprofit, U.S.-based organization that conducts research and development related to the generation, delivery, and use of electricity [https://www.epri.com/].

water, produced a series of documents aimed at providing vehicle electrification-related guidance for state regulators (National Association of Regulatory Utility Commissioners 2022a), facilitating electric vehicle interoperability (National Association of Regulatory Utility Commisioners 2022b), and fostering vehicle electrification equity (National Association of Regulatory Utility Commissioners 2022c). NARUC, in conjunction with the National Association of State Energy Officials (NASEO) and the American Association of State Highway and Transportation Officials (AASHTO), also produced a guide for public utility commissions, state energy offices, and departments of transportation discussing the state-level roles and their interrelations vis-à-vis transportation electrification (National Council on Electricity Policy, National Association of Regulatory Utility Commissioners 2022).

We also note that DOE is engaged in multiple efforts to modernize the grid and improve resilience and reliability. For example, in November 2022, DOE announced $13 billion in funding opportunities under BIL to support transmission and distribution infrastructure. This includes $3 billion for smart grid grants with a focus on PEV integration among other topics (U.S. Department of Energy 2022).

Chapter 5 References

86 FR 74434. 2021.

88 FR 12724. 2023. https://www.federalregister.gov/documents/2023/02/28/2023-03500/national-electric-vehicle-infrastructure-standards-and-requirements.

Alexander, Matt, Noel Crisostomo, Wendell Krell, Jeffrey Lu, and Raja Ramesh. 2021. Assembly Bill 2127: Electric Vehicle Charging Infrastructure Assessment. California Energy Commission. https://www.energy.ca.gov/programs-and-topics/programs/electric-vehicle-charging-infrastructure-assessment-ab-2127.

Apadula, Emily, Rebekah de la Mora, Justin Lindemann, Brian Lips, Vincent Potter, Autumn Proudlove, and David Sarkisian. 2023. 50 States of Electric Vehicles Q4 2022 Quarterly Report & 2022 Annual Review Executive Summary. NC Clean Energy Technology Center. Accessed 3 5, 2023. https://nccleantech.ncsu.edu/wp-content/uploads/2023/02/Q4-22_EV_execsummary_Final.pdf.

BATRIES. 2023. "B. UL 1741 Certification Requirement Decision for Power Control Systems." Accessed March 27, 2023. https://energystorageinterconnection.org/viii-incorporating-updated-interconnection-standards-into-interconnection-procedures/b-ul-1741-certification-requirement-decision-for-power-control-systems/.

Bauer, Gordon, Chih-Wei Hsu, Mike Nicholas, and Nic Lutsey. 2021. Charging Up America: Assessing the Growing Need for U.S. Charging Infrastructure Through 2030. The International Council on Clean Transportation. Accessed 1 11, 2023. https://theicct.org/wp-content/uploads/2021/12/charging-up-america-jul2021.pdf.

BloombergNEF. 2023. "Next $100 Billion EV-Charger Spend to Be Super Fast." January 20. Accessed February 26, 2023. https://about.bnef.com/blog/next-100-billion-ev-charger-spend-to-be-super-fast/.

BloombergNEF. 2022. "Zero-Emission Vehicles Factbook A BloombergNEF special report prepared for COP27." Accessed March 5, 2023. https://www.bloomberg.com/professional/download/2022-zero-emissions-vehicle-factbook/.

Borlaug, Brennan, Matteo Muratori, Madeline Gilleran, David Woody, William Muston, Thomas Canada, Andrew Ingram, Hal Gresham, and Charlie McQueen. 2021. "Heavy-duty truck electrification and the impacts of depot charging on electricity distribution systems." Nature Energy 6: 673-682. Accessed 1 13, 2023. https://doi.org/10.1038/s41560-021-00855-0.

Borlaug, Brennan, Shawn Salisbury, Mindy Gerdes, and Matteo Muratori. 2020. "Levelized Cost of Charging Electric Vehicles in the United States." Joule 4 (7): 1470-1485. Accessed 1 11, 2023. doi:https://doi.org/10.1016/j.joule.2020.05.013.

Brown, Abby, Jeff Cappellucci, Emily White, Alexia Heinrich, and Emma Cost. 2022. Electric Vehicle Charging Infrastructure Trends from the Alternative Fueling Station Locator: Second Quarter 2022. Golden, CO: National Renewable Energy Laboratory. Accessed March 5, 2023. https://www.nrel.gov/docs/fy23osti/84263.pdf.

California Energy Commission. 2021. "CEC Approves $1.4 Billion Plan for Zero-Emission Transportation Infrastructure and Manufacturing." November 15. Accessed 1 11, 2023. https://www.energy.ca.gov/news/2021-11/cec-approves-14-billion-plan-zero-emission-transportation-infrastructure-and.

California Energy Commission; California Public Utilities Commission; Governor's Office of Business and Economic Development. 2021. "Joint Agency Workshop Agenda Accelerating Electric Vehicle Charging Infrastructure Deployment and Grid Integration;." October 12. Accessed December 13, 2022. https://efiling.energy.ca.gov/GetDocument.aspx?tn=239921.

California Independent System Operator. 2014. "California Vehicle-Grid Integration (VGI) Roadmap: Enabling vehicle-based grid services." February. Accessed March 15, 2023. https://efiling.energy.ca.gov/getdocument.aspx?tn=217997.

California Public Utilities Commission. 2022. "R18-12-006." July 20. Accessed December 13, 2022. http://www.caiso.com/Documents/Jul22-2022-OpeningComments-ElectricVehicleSubmeteringProtocols-CommunicationProtocols-R18-12-006.pdf.

CharIN e.V. 2022. "CharIN e.V. officially launches the Megawatt Charging System (MCS) at EVS35 in Oslo, Norway." June 14. Accessed March 8, 2023. https://www.charin.global/media/pages/news/charin-e-v-officially-launches-the-megawatt-charging-system-mcs-at-evs35-in-oslo-norway/2bca10e315-1655213569/press_release_mcs_charin_final.pdf.

Chevrolet. 2023. Installation Made Easy: Home Charging Installation on Us. Accessed 3 1, 2023. https://www.chevrolet.com/electric/living-electric/home-charging-installation.

Chhaya, S., V. Ananth, R. Ravikumar, G. Bellino, R. Scholer, E. Cutter, C. Botsford, et al. 2019. "Distribution System Constrained Vehicle-to-Grid Services for Improved Grid Stability and Reliability; Publication Number: CEC-500-2019-027; Chhaya, Sunil; McCollough, Norman; Ananth, Viswanath; Maitra, Arindam; Ravikumar, Ramakrishnan; Dunckley, et.al." Accessed December 13, 2022. https://www.energy.ca.gov/sites/default/files/2021-06/CEC-500-2019-027.pdf.

EEI. 2023. "Issues & Policy: National Electric Highway Coalition." Accessed 1 11, 2023. https://www.eei.org/issues-and-policy/national-electric-highway-coalition.

Electric Power Research Institute. 2022. "Supplemental Project Notice: EVs2Scale2030." Accessed December 14, 2022. https://www.epri.com/research/products/000000003002025622.

—. 2012. "Understanding the Grid Impacts of Plug-In Electric Vehicles (PEV): Phase 1 Study -- Distribution Impact Case Studies; Maitra, Arindam;1024101." December 31. Accessed December 13, 2022. https://www.epri.com/research/products/000000000001024101.

Enis, Julian. 2021. "Electric System Reliability (Presentation from the California Public Utilities Commission)." February 17. https://www.cpuc.ca.gov/-/media/cpuc-website/transparency/commissioner-committees/emerging-trends/2021/2021-02-17-electric-system-reliability-presentation---final.pdf.

EVmatch, Inc. 2023. "The EVmatch Adapter, A Handheld Device Patented by Argonne National Laboratory, Makes Level 2 EV Charging Stations Smart." Cision PR Newswire. February 6.

https://www.prnewswire.com/news-releases/the-evmatch-adapter-a-handheld-device-patented-by-argonne-national-laboratory-makes-level-2-ev-charging-stations-smart-301739075.html.

Ford. 2019. "Ford Introduces North America's Largest Electric Vehicle Charging Network, Helping Customers Confidently Switch to an All-Electric Lifestyle." October 17. Accessed January 11, 2023. https://media.ford.com/content/fordmedia/fna/us/en/news/2019/10/17/ford-introduces-north-americas-largest-electric-vehicle-charting-network.html.

FreeWire Technologies. 2023. "Mobi EV Charger Data Sheet." Accessed March 26, 2023. https://freewiretech.com/products/mobi-ev/.

Ge, Y., C. Simeone, A. Duvall, and E. Wood. 2021. There's No Place Like Home: Residential Parking, Electrical Access, and Implications for the Future of Electric Vehicle Charging Infrastructure. Technical Report No. NREL/TP-5400-81065, National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy22osti/81065.pdf.

GM. 2021. "To Put 'Everybody In' an Electric Vehicle, GM introduces Ultium Charge 360." Accessed 1 11, 2023. https://media.gm.com/media/us/en/gm/home.detail.html/content/Pages/news/us/en/2021/apr/0428-ultium-charge-360.html.

Hampleton. 2023. "Autotech & Mobility M&A market report 1H2023." Accessed March 5, 2023. https://www.hampletonpartners.com/fileadmin/user_upload/Report_PDFs/Hampleton-Partners-Autotech-Mobility-Report-1H2023-FINAL.pdf.

Hernandez, Mari. 2022. Paving the Way Emerging Best Practices for Electric Vehicle Charger Interconnection. IREC. Accessed March 26, 2023. https://irecusa.org/wp-content/uploads/2022/06/EV-Paper-3-Charger-Interconnection_compressed.pdf.

Hyundai. 2023. Stay powered for your drive. Accessed 1 11, 2023. https://www.hyundaiusa.com/us/en/electrified/charging.

ICF. 2019. "Documentation of the Retail Price Model." ICF Contract Report to the U.S. EPA. https://www.epa.gov/sites/default/files/2019-06/documents/rpm_documentation_june2019.pdf.

Joint Committee on Taxation. 2022. "Estimated Budget Effects of the Revenue Provisions of Title I - Committee on Finance, of an Amendment in the Nature of a Substitute to H.R. 5376, "An Act to Provide for Reconciliation Pursuant to Title II of S. Con Res. 14," ..." August 9. https://www.jct.gov/publications/2022/jcx-18-22/.

Joint Office of Energy and Transportation. 2023. "Private Sector Continues to Play Key Part in Accelerating Buildout of EV Charging Networks." February 15. https://driveelectric.gov/news/#private-investment.

Joint Office of Energy and Transportation. 2023b. “Biden-Harris Admin Opens First Round Applications for $2.5 Billion Program to Build EV Charging in U.S. Communities.” May 14. https://driveelectric.gov/news/#charging-fueling-infrastructure.

Kempower. 2023. "Kempower establishes an EV charging station production facility in North Carolina, United States." February 7. Accessed March 27, 2023. https://kempower.com/news/kempower-establishes-production-facility-in-north-carolina/.

Kia. 2023. Enroll Now in the Electrify America Kia Charge Pass Program. Accessed 3 1, 2023. https://owners.kia.com/content/owners/en/kia-electrify.html.

Lightning eMotors. 2023. "Go anywhere power for a go anywhere world." Accessed March 26, 2023. https://lightningemotors.com/wp-content/uploads/2023/01/LE_Lightning_Mobile_sheet_Jan2023_v1_online.pdf.

Lipman, Timothy, Alissa Harrington, and Adam Langton. 2021. Total Charge Management of Electric Vehicles, Publication Number: CEC-500-2021- 055. California Energy Commission. Accessed December 13, 2022. https://www.energy.ca.gov/sites/default/files/2021-12/CEC-500-2021-055.pdf.

Maitra, Arindam. 2013. "Analysis of Projected Impact of Plug-in Electric Vehicles on the Distribution Grid." In Frontiers of Engineering: Reports on Leading-Edge Engineering from the 2012 Symposium. The National Academies Press. Accessed December 13, 2022. doi:10.17226/18185.

McDonald, J. 2023. "PEV Regionalized Charge Demand - Memo to the Docket."

McKenzie, Lucy, and Nick Nigro. 2021. "U.S. Passenger Vehicle Electrification Infrastructure Assessment ." Atlast Public Policy, April 28. Accessed March 5, 2023. https://atlaspolicy.com/wp-content/uploads/2021/04/2021-04-21_US_Electrification_Infrastructure_Assessment.pdf.

National Association of Regulatory Utility Commisioners. 2022b. "Electric Vehicle Interoperability Considerations for Public Utility Regulators - An addendum to the NARUC report, Electric Vehicles: Key Trends, Issues, and Considerations for State Regulators (2019); Villarreal, Christopher;." Accessed December 15, 2022. https://pubs.naruc.org/pub/D548E5DA-1866-DAAC-99FB-70957246AEBE.

National Association of Regulatory Utility Commissioners. 2022a. "Electric Vehicles: Key Trends, Issues, and Considerations for State Regulators; Harper, Charles; McAndrews, Gregory; Sass Byrnett, Danielle;." Accessed December 15, 2022. https://pubs.naruc.org/pub/32857459-0005-B8C5-95C6-1920829CABFE.

—. 2022c. "Models for Incorporating Equity in Transportation Electrification Considerations for Public Utility Regulators - An addendum to the NARUC report, Electric Vehicles: Key Trends, Issues, and Considerations for State Regulators (2019); McAdams, Jasmine;." Accessed December 15, 2022. https://pubs.naruc.org/pub/D4E4DD39-1866-DAAC-99FB-4CE60044ACA7.

National Council on Electricity Policy, National Association of Regulatory Utility Commissioners. 2022. "Mini Guide on Transportation Electrification: State-Level Roles and Collaboration among Public Utility Commissions, State Energy Offices, and Departments of Transportation; Dixon, Delaney; Powers, Cassie; McAdams, Jasmine; Stephens, Sam; Sass Byrnett, Dan." Accessed December 15, 2022. https://pubs.naruc.org/pub/131FFF33-1866-DAAC-99FB-D86EE13B1709.

Nicholas, Michael. 2019. Estimating electric vehicle charging infrastructure costs across major U.S. metropolitan areas. The International Council on Clean Transportation. Accessed January

11, 2023.
https://theicct.org/sites/default/files/publications/ICCT_EV_Charging_Cost_20190813.pdf.

Nuvve and Enel X. 2020. "Brief - Automated Load Management for EVSE Interconnection." Accessed March 27, 2023.
https://docs.cpuc.ca.gov/PublishedDocs/Efile/G000/M354/K191/354191323.PDF.

Public Law 117-169. 2022. (August 16). https://www.congress.gov/117/plaws/publ169/PLAW-117publ169.pdf.

Public Law 117-58. 2021. (November 15). https://www.govinfo.gov/content/pkg/PLAW-117publ58/pdf/PLAW-117publ58.pdf.

Reuters. 2023. "Mercedes to launch vehicle-charging network, starting in North America." January 6. Accessed January 10, 2023. https://www.reuters.com/business/autos-transportation/mercedes-launch-vehicle-charging-network-starting-north-america-2023-01-05/.

Schey, Stephen, Kang-Ching Chu, and John Smart. 2022. Breakdown of Electric Vehicle Supply Equipment Installation Costs. Idaho National Laboratory. Accessed March 8, 2023.
https://inldigitallibrary.inl.gov/sites/sti/sti/Sort_63124.pdf.

Schwartz, Lisa. 2022. "State Regulatory Approaches for Distribution Planning." National Association of State Utility Consumer Advocates 2022 Mid-Year Meeting, June 14. Accessed March 26, 2023. https://www.nasuca.org/wp-content/uploads/2021/10/NASUCA-Schwartz-distribution-planning-20220610.pdf.

St. John, Alexa, and Nora Naughton. 2022. "Automakers need way more plug-in stations to make their EV plans work. That has sparked a buyer frenzy as big charging players gobble up smaller ones." Insider, November 24. Accessed March 5, 2023.
https://www.businessinsider.com/ev-charging-industry-merger-acquisition-meet-electric-vehicle-demand-2022-11.

The White House. 2023. "Fact Sheet: Biden-Harris Administration Announces New Standards and Major Progress for a Made-in-America National Network of EV Chargers." February 15. Accessed February 27, 2023. https://www.whitehouse.gov/briefing-room/statements-releases/2023/02/15/fact-sheet-biden-harris-administration-announces-new-standards-and-major-progress-for-a-made-in-america-national-network-of-electric-vehicle-chargers/.

U.S. Department of Energy. 2022. Biden-Harris Administration Announces $13 Billion to Modernize and Expand America's Power Grid. November 18. Accessed January 11, 2023.
https://www.energy.gov/articles/biden-harris-administration-announces-13-billion-modernize-and-expand-americas-power-grid.

—. 2021. FOTW #1210, November 1, 2021: Sixty Percent of Electric Vehicle DC Fast Charging Ports Had Power Levels Greater Than 50 kW in the First Quarter of 2021. November 1. Accessed March 8, 2023. https://www.energy.gov/eere/vehicles/articles/fotw-1210-november-1-2021-sixty-percent-electric-vehicle-dc-fast-charging.

U.S. Department of Energy, Alternative Fuels Data Center. 2023a. Developing Infrastructure to Charge Electric Vehicles. Accessed February 27, 2023.
https://afdc.energy.gov/fuels/electricity_infrastructure.html.

—. 2023b. Electric Vehicle Charging Infrastructure Trends. Accessed January 10, 2023. https://afdc.energy.gov/fuels/electricity_infrastructure_trends.html.

—. 2023d. "Electric Vehicle Charging Station Locations." Accessed 2 28, 2023. https://afdc.energy.gov/fuels/electricity_locations.html#/analyze?country=US&fuel=ELEC&ev_networks=Tesla&ev_networks=Tesla%20Destination&ev_levels=dc_fast; https://afdc.energy.gov/fuels/electricity_locations.html#/analyze?country=US&fuel=ELEC&ev_networks=.

—. 2023c. "State Laws and Incentives." Accessed 1 11, 2023. https://afdc.energy.gov/laws/state; https://afdc.energy.gov/laws/12832; https://afdc.energy.gov/laws/12320; https://afdc.energy.gov/laws/5182; https://afdc.energy.gov/laws/11493.

U.S. Department of Transportation, Federal Highway Administration. 2022b. "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. Accessed January 10, 2023. https://highways.dot.gov/newsroom/historic-step-all-fifty-states-plus-dc-and-puerto-rico-greenlit-move-ev-charging-networks.

—. 2022a. "The National Electric Vehicle Infrastructure (NEVI) Formula Program Guidance." February 10. Accessed January 10, 2023. https://www.fhwa.dot.gov/environment/alternative_fuel_corridors/nominations/90d_nevi_formula_program_guidance.pdf.

U.S. Energy Information Administraton. 2019. "The National Energy Modeling System: An Overview 2018." Independent Statistics and Analysis. https://www.eia.gov/outlooks/aeo/nems/overview/pdf/0581(2018).pdf.

U.S. EPA. 2021. "Flat File Generation Methodology - Version: Summer 2021, Reference Case Using EPA Platform v6." https://www.epa.gov/system/files/documents/2021-09/flat-file-methodology-epa-platform-v6-summer-2021-reference-case.pdf.

U.S. EPA. 2022a. "GHG Emissions Factors Hub, Table 1 - Stationary Combustion." https://www.epa.gov/climateleadership/ghg-emission-factors-hub.

—. 2023. " Post-IRA 2022 Reference Case - EPA's Power Sector Modeling Platform Using IPM." https://www.epa.gov/power-sector-modeling/post-ira-2022-reference-case.

U.S. EPA. 2022b. "Regulatory Impact Analysis for Proposed Federal Implementation Plan Addressing Regional Ozone Transport for the 2015 Ozone National Ambient Air Quality Standard, EPA Docket No. EPA-HQ-OAR-2021-0668-0151." https://www.regulations.gov/document/EPA-HQ-OAR-2021-0668-0151.

VW. 2023. ID.4. Accessed 1 11, 2023. https://www.vw.com/en/models/id-4.html.

Wood, E., B. Borlaug, M. Moniot, D.Y. Lee, Y. Ge, F. Yang, and Z. Liu. 2023. National Electric Vehicle Infrastructure Needs Assessment: Estimating U.S. Charging Needs Towards 50% Light-Duty EV Sales by 2030. (forthcoming). Golden, CO USA: National Renewable Energy Laboratory.

Wood, E., C. Rames, M. Muratori, and S. and Young, S. Raghavan. 2018. Charging Electric Vehicles in Smart Cities: An EVI-Pro Analysis of Columbus, Ohio. Golden, CO: National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy18osti/70367.pdf.

Wood, Eric, Clement Rames, Matteo. Muratori, Sesha. Raghavan, and Marc Melaina. 2017. National Plug-In Electric Vehicle Infrastructure Analysis. U.S. Department of Energy Office of Energy Efficiency & Renewable Energy. Accessed March 8, 2023. https://www.nrel.gov/docs/fy17osti/69031.pdf.

Zayer, Eric, Lucas Martin, Trent Murphey, Mary Stroncek, and Ingo Stein. 2022. EV Charging Shifts into High Gear. Bain & Company. Accessed March 5, 2023. https://www.bain.com/insights/electric-vehicle-charging-shifts-into-high-gear/.

Chapter 6: [RESERVED]

The content from the previous version of this chapter has been streamlined and incorporated into other chapters in the DRIA.

Chapter 7: Health and welfare impacts

The proposed rule will impact emissions of GHGs, criteria pollutants, and air toxic pollutants. There are health and welfare impacts associated with ambient concentrations of GHGs, criteria pollutants and air toxics which are described in this chapter.

7.1 Climate Change Impacts from GHG Emissions

Elevated concentrations of GHGs have been warming the planet, leading to changes in the Earth's climate including changes in the frequency and intensity of heat waves, precipitation, and extreme weather events, rising seas, and retreating snow and ice. The changes taking place in the atmosphere as a result of the well-documented buildup of GHGs due to human activities are changing the climate 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 some scientific background on climate change to offer additional context for this rulemaking and to increase the public's understanding of the environmental impacts of GHGs.

Extensive additional 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 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 in the U.S. (42 USC § 7602 (h) 2021)[123] with resulting economic costs, 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 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 (81 FR 54422 2016). 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. These updated observations and projections document the rapid rate of current and future climate change both globally and in the U.S. (Reidmiller, et al. 2018, Roy, et al. 2019, NASEM 2019, NOAA 2021).

7.2 Health Effects Associated with Exposure to Criteria and Air Toxics Pollutants

Emissions sources impacted by this proposal, including vehicles and power plants, emit pollutants that contribute to ambient concentrations of ozone, PM, NO_2, SO_2, CO, and air toxics. This section of the RIA discusses the health effects associated with exposure to these pollutants.

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 do, and consequently may be exposed to relatively higher amounts of air pollution. (US EPA 2009) Children also 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. (US EPA 2019) (Foos, et al. 2008) Furthermore, air pollutants may pose health

[123] 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 USC § 7602 (h) 2021).

risks specific to children because children's bodies are still developing (US EPA 2021).[124] For example, during periods of rapid growth such as fetal development, infancy and puberty, their developing systems and organs may be more easily harmed. (US EPA 2006, US EPA 2005) 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. (US EPA 2022)

7.2.1 Ozone

7.2.1.1 Background on Ozone

Ground-level ozone pollution forms in areas with high concentrations of ambient nitrogen oxides (NO_X) and volatile organic compounds (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, with natural sources, such as soil, vegetation, and lightning, serving as smaller sources. Vegetation is the dominant source of VOCs in the U.S. 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 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 actually increase local ozone under certain circumstances, but overall ozone production (considering downwind formation) decreases. 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 to become NO_X-limited.

[124] Children's environmental health includes conception, infancy, early childhood and through adolescence until 21 years of age as described in an EPA Memorandum (US EPA 2021).

7.2.1.2 Health Effects Associated with Exposure to Ozone

This section provides a summary of the health effects associated with exposure to ambient concentrations of ozone.[125] The information in this section is based on the information and conclusions in the April 2020 Integrated Science Assessment for Ozone (Ozone ISA). (US EPA 2020) 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.[126] 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. The evidence is also suggestive of a causal relationship between short-term exposure to ozone and cardiovascular effects, central nervous system effects and total mortality.

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 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. Children also have a higher asthma prevalence compared to

[125] Human exposure to ozone varies over time due to changes in ambient ozone concentration and because people move between locations which have notably different ozone concentrations. Also, the amount of ozone delivered to the lung is influenced not only by the ambient concentrations but also by the breathing route and rate.

[126] 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.

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 among 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 in Section IX.G of the Preamble.

7.2.2 Particulate Matter

7.2.2.1 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. (US EPA 2020) 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 greater than 2.5 μm and less than or equal to 10 μm). EPA currently has NAAQS for $PM_{2.5}$ and PM_{10} (Title 40 CFR Part 50 2023, Title 40 CFR Part 53 2023, Title 40 CFR Part 58 2023).[127]

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. (US EPA 2019) 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, 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.

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

[127] 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., $PM_{10-2.5}$).

atmospheric chemical reactions of gaseous precursors (e.g., sulfur oxides (SO_X), NO_X and VOCs).

7.2.2.2 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 (PM ISA). (US EPA 2019) In addition, there is 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). (US EPA 2022) 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. (US EPA 2019) 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. (US EPA 2022)

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. (US EPA 2009) 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 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. (US EPA 2019) (US EPA 2022) 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, particularly ischemic events and heart failure, and to a lesser degree for respiratory 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 (US EPA 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 of 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 come 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 copollutants, 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. In addition, experimental and epidemiologic studies of genotoxicity, epigenetic effects, carcinogenic potential, and that $PM_{2.5}$ exhibits several characteristics of carcinogens, 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 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.” (US EPA 2019)

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 persists with respect to the method used to estimate $PM_{10-2.5}$ concentrations in epidemiologic studies. 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 <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 U.S., 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" (US EPA 2019). 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. 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 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. (US EPA 2022)

7.2.3 Nitrogen Oxides

7.2.3.1 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. The health effects of PM and ozone are discussed in Sections 7.2.1 and 7.2.2 respectively.

7.2.3.2 Heath 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 (ISA for Oxides of Nitrogen). (US EPA 2016) 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 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 copollutant 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.

7.2.4 Sulfur Oxides

7.2.4.1 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.

7.2.4.2 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). (US EPA 2017) 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 copollutant 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.

7.2.5 Carbon Monoxide

7.2.5.1 Background on Carbon Monoxide

Carbon monoxide (CO) is a colorless, odorless gas emitted from combustion processes. Nationally, particularly in urban areas, the majority of CO emissions to ambient air come from mobile sources.

7.2.5.2 Health Effects Associated with Exposure to 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). (US EPA 2010) The CO ISA presents conclusions regarding the presence of causal relationships between CO exposure and categories of adverse health effects.[128] This section provides a summary of the health effects associated with exposure to ambient concentrations of CO, along with the CO ISA conclusions.[129]

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 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 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

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[128] 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.

[129] 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.

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 copollutants 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 that was often observed in copollutant 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.

7.2.6 Diesel Exhaust

7.2.6.1 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 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 (< 2.5 µm), of which a significant fraction is ultrafine particles (< 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 days.

7.2.6.2 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. (US EPA 1999, US EPA 2002) 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 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 $\mu g/m^3$.[130] 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 is designed to provide protection from the noncancer health effects and premature mortality 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

[130] See Chapter 8.1 for discussion of the current $PM_{2.5}$ NAAQS standard.

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 that 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. (Garshick 2012, Silverman 2012, Olsson 2011) 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 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." (IARC, Diesel and gasoline engine exhausts and some nitroarenes 2013) This designation was an update from its 1988 evaluation that considered the evidence to be indicative of a "probable human carcinogen."

7.2.7 Air Toxics

Light- and medium-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, acrolein, benzene, 1,3-butadiene, ethylbenzene, formaldehyde, naphthalene and polycyclic organic matter. These compounds were identified as national or regional cancer risk drivers or contributors in the 2018 AirToxScreen Assessment. (US EPA 2022, US EPA 2022)

7.2.7.1 Health Effects Associated with Exposure to 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 and increased proliferation of bone marrow cells in mice. (US EPA 2000, IARC 1982, Irons, et al. 1992) 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/m3 as the unit risk estimate (URE) for benzene.[131] (US EPA 2000) The 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. (IARC 2018, NTP, Report on Carcinogens, Fourteenth Edition 2016)

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. (Aksoy 1989, Goldstein 1988) The most sensitive noncancer effect observed in humans, based on current data, is the depression of the absolute lymphocyte count in blood. (Rothman 1996, US EPA 2002) EPA's inhalation reference concentration (RfC) for benzene is 30 µg/m3. 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 benzene exposure than previously known. (O. Qu, et al. 2003, Q. Qu, et al. 2002, Lan, et al. 2004, Turtletaub and Mani 2003) 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 exposure to benzene is 29 µg/m3 for 1-14 days exposure.[132] (ATSDR, Toxicological profile for benzene 2007)

There is limited information from two studies regarding an increased risk of adverse effects to children whose parents have been occupationally exposed to benzene. (Corti and Snyder 1996, P.A., et al. 1991) Data from animal studies have shown benzene exposures result in damage to the hematopoietic (blood cell formation) system during development. (Keller and Snyder 1986, Keller and Snyder 1988, Corti and Snyder 1996) Also, key changes related to the development of childhood leukemia occur in the developing fetus. (US EPA 2002) 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. (Ford, et al. 1997)

7.2.7.2 Health Effects Associated with Exposure to 1,3-Butadiene

EPA has characterized 1,3-butadiene as carcinogenic to humans by inhalation. (US EPA 2002), (US EPA 2002) The IARC has determined that 1,3-butadiene is a human carcinogen and the U.S. DHHS has characterized 1,3-butadiene as a known human carcinogen. (IARC 1999) (IARC 2008) (NTP 2016) (IARC 2012) 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/m3. (US EPA 2002) 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

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[131] A unit risk estimate is defined as the increase in the lifetime risk of cancer of an individual who is exposed for a lifetime to 1 µg/m3 benzene in air.

[132] 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.

effect was ovarian atrophy observed in a lifetime bioassay of female mice. (Bevan, Stadler and al 1996) 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).

7.2.7.3 Health Effects Associated with Exposure to 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. (US EPA 1990) 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. (NTP, Report on Carcinogens, Fourteenth Edition 2016, IARC 2006, IARC 2012)

The conclusions by IARC and NTP reflect the results of epidemiologic research published since 1991 in combination with previous 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 to formaldehyde. (Hauptmann, Lubin, et al. 2003, Hauptmann, Lubin, et al. 2004, Beane Freeman, et al. 2009) 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. (Pinkerton 2004) 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. (Coggon, et al. 2003) Finally, a study of embalmers reported formaldehyde exposures to be associated with an increased risk of myeloid leukemia but not brain cancer. (Hauptmann, et al. 2009)

Health effects of formaldehyde in addition to cancer were reviewed by the ATSDR in 1999, supplemented in 2010, and by the World Health Organization. (ATSDR 1999, ATSDR 2010, IPCS 2002) 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 were 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. (US EPA 2010) 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. (NRC, Review of the Environmental Protection Agency's Draft IRIS Assessment of Formaldehyde 2011) EPA's draft assessment, which addresses NRC recommendations, was suspended in 2018 and unsuspended in March 2021. An external review draft was released in April 2022 and is currently review by the National Academy of Sciences, Engineering, and Medicine. (US EPA 2021)

7.2.7.4 Health Effects Associated with Exposure to 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. (US EPA 1991) The URE in IRIS for acetaldehyde is 2.2 × 10-6 per µg/m^3. (US EPA 1991) 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. (NTP, Report on Carcinogens, Fourteenth Edition 2016) (IARC 1999)

The primary noncancer effects of exposure to acetaldehyde vapors include irritation of the eyes, skin, and respiratory tract. (US EPA 1991) In short-term (4 week) rat studies, degeneration of olfactory epithelium was observed at various concentration levels of acetaldehyde exposure. (Appleman, Woutersen and Feron 1982) Data from these studies were used by EPA to develop an inhalation reference concentration of 9 µg/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. (Myou, et al. 1993) 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. (OEHHA 2014)

7.2.7.5 Health Effects Associated with Exposure to 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. (US EPA 1998) Chronic (long term) exposure of workers and rodents to naphthalene has been reported to cause cataracts and retinal damage. (US EPA 1998) 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). (US EPA 1998) EPA released an external review draft of a reassessment of the inhalation carcinogenicity of naphthalene based on a number of recent animal carcinogenicity studies. (US EPA 1998) The draft reassessment completed external peer review. (Oak Ridge Institute for Science and Education 2004) 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 (US EPA 2023). The external review draft does not 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. (NTP, Report on Carcinogens, Fourteenth Edition 2016) 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. (IARC 2002)

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. (US EPA 1998) 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/m^3.

(US EPA 1998) 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. (ATSDR 2005) 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. (ATSDR 2014) 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. (US EPA 2022) 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.

7.2.7.6 Health Effects Associated with Exposure to Acrolein

EPA most recently evaluated the toxicological and health effects literature related to acrolein in 2003 and concluded that the human carcinogenic potential of acrolein could not be determined because the available data were inadequate. No information was available on the carcinogenic effects of acrolein in humans and the animal data provided inadequate evidence of carcinogenicity. (US EPA 2003) In 2021, the IARC classified acrolein as probably carcinogenic to humans. (IARC 2021)

Lesions to the lungs and upper respiratory tract of rats, rabbits, and hamsters have been observed after subchronic exposure to acrolein. (US EPA 2003) The agency has developed an RfC for acrolein of 0.02 µg/m^3 and an RfD of 0.5 µg/kg-day. (US EPA 2003)

Acrolein is extremely acrid and irritating to humans when inhaled, with acute exposure resulting in upper respiratory tract irritation, mucus hypersecretion and congestion. The intense irritancy of this carbonyl has been demonstrated during controlled tests in human subjects, who suffer intolerable eye and nasal mucosal sensory reactions within minutes of exposure. (US EPA 2003) These data and additional studies regarding acute effects of human exposure to acrolein are summarized in EPA's 2003 IRIS Human Health Assessment for acrolein. (US EPA 2003) Studies in humans indicate that levels as low as 0.09 ppm (0.21 mg/m^3) for five minutes may elicit subjective complaints of eye irritation with increasing concentrations leading to more extensive eye, nose and respiratory symptoms. Acute exposures in animal studies report bronchial hyper-responsiveness. Based on animal data (more pronounced respiratory irritancy in mice with allergic airway disease in comparison to non-diseased mice (Morris JB, et al. 2003)) and demonstration of similar effects in humans (e.g., reduction in respiratory rate), individuals with compromised respiratory function (e.g., emphysema, asthma) are expected to be at increased risk of developing adverse responses to strong respiratory irritants such as acrolein. EPA does not currently have an acute reference concentration for acrolein. The available health effect reference values for acrolein have been summarized by EPA and include an ATSDR MRL for acute exposure to acrolein of 7 µg/m^3 for 1-14 days exposure; and Reference Exposure Level (REL) values from the California Office of Environmental Health Hazard Assessment (OEHHA) for one-hour and 8-hour exposures of 2.5 µg/m^3 and 0.7 µg/m^3, respectively. (US EPA 2009)

7.2.7.7 Health Effects Associated with Exposure to Ethylbenzene

EPA's inhalation RfC for ethylbenzene is 1 mg/m^3. This conclusion on a weight of evidence determination and RfC are contained in the 1991 IRIS file for ethylbenzene. (US EPA 1991) The RfC is based on developmental effects. A study in rabbits found reductions in live rabbit kits per litter at 1000 ppm. In addition, a study on rats found an increased incidence of supernumerary and rudimentary ribs at 1000 ppm, and elevated incidence of extra ribs at 100 ppm. In 1988, EPA concluded that data were inadequate to give a weight of evidence characterization for carcinogenic effects. EPA released an IRIS Assessment Plan for Ethylbenzene in 2017 (US EPA 2017) and EPA will be releasing the Systematic Review Protocol for ethylbenzene in 2023. (US EPA 2022)

California EPA completed a cancer risk assessment for ethylbenzene in 2007 and developed an inhalation unit risk estimate of 2.5×10^{-6}. (California OEHHA 2007) This value was based on incidence of kidney cancer in male rats. California EPA also developed a chronic inhalation noncancer reference exposure level (REL) of 2000 $\mu g/m^3$, based on nephrotoxicity and body weight reduction in rats, liver cellular alterations, necrosis in mice, and hyperplasia of the pituitary gland in mice. (California OEHHA 2008)

ATSDR developed chronic Minimal Risk Levels (MRLs) for ethylbenzene of 0.06 ppm based on renal effects, and an acute MRL of 5 ppm based on auditory effects. (ATSDR 2010)

7.2.7.8 Health Effects Associated with Exposure to PAHs/POM

The term polycyclic organic matter (POM) defines a broad class of compounds that includes the polycyclic aromatic hydrocarbon compounds (PAHs). One of these compounds, naphthalene, is discussed separately below. POM compounds are formed primarily from combustion and are present in the atmosphere in gas and particulate form as well as in some fried and grilled foods. Epidemiologic studies have reported an increase in lung cancer in humans exposed to diesel exhaust, coke oven emissions, roofing tar emissions, and cigarette smoke; all of these mixtures contain POM compounds. (ATSDR 1995) (US EPA 2002) In 1991 EPA classified seven PAHs (benzo[a]pyrene, benz[a]anthracene, chrysene, benzo[b]fluoranthene, benzo[k]fluoranthene, dibenz[a,h]anthracene, and indeno[1,2,3-cd]pyrene) as Group B2, probable human carcinogens based on the 1986 EPA Guidelines for Carcinogen Risk Assessment. (US EPA 1991) Studies in multiple animal species demonstrate that benzo[a]pyrene is carcinogenic at multiple tumor sites (alimentary tract, liver, kidney, respiratory tract, pharynx, and skin) by all routes of exposure. An increasing number of occupational studies demonstrate a positive exposure-response relationship with cumulative benzo[a]pyrene exposure and lung cancer. The inhalation URE in IRIS for benzo[a]pyrene is 6×10^{-4} per $\mu g/m^3$ and the oral slope factor for cancer is 1 per mg/kg-day. (US EPA 2017)

Animal studies demonstrate that exposure to benzo[a]pyrene is also associated with developmental (including developmental neurotoxicity), reproductive, and immunological effects. In addition, epidemiology studies involving exposure to PAH mixtures have reported associations between internal biomarkers of exposure to benzo[a]pyrene (benzo[a]pyrene diol epoxide-DNA adducts) and adverse birth outcomes (including reduced birth weight, postnatal body weight, and head circumference), neurobehavioral effects, and decreased fertility. The inhalation RfC for benzo[a]pyrene is 2×10^{-6} mg/m^3 and the RfD for oral exposure is 3×10^{-4} mg/kg-day. (US EPA 2017)

7.2.8 Exposure and Health Effects Associated with Traffic

Locations in close proximity to 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, PM, 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 at locations within 50 meters (about 165 feet) of the edge of a roadway's traffic lanes.

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, UFPs, metals, elemental carbon (EC), NO, NO_X, and several VOCs. (Karner, Eisinger and Niemeier 2014) 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., (2014) reported that results varied based on the method of statistical analysis used to determine the gradient in pollutant concentration. More recent studies continue to show significant concentration gradients of traffic-related air pollution around major roads. (McDonald, et al. 2014, Kimbrough, Baldauf, et al. 2013, Kimbrough, Palma and Baldauf 2014, Kimbrough, Owen, et al. 2017, Hilker, et al. 2019, Grivas, et al. 2019, Apte, et al. 2017, Dabek-Zlotorzynska, et al. 2019) There is evidence that EPA's regulations for vehicles have lowered the near-road concentrations and gradients. (Sarnat, et al. 2018) 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 $PM_{2.5}$ (in addition to those existing monitors located in neighborhoods and other locations farther away from pollution sources). The monitoring data for NO_2 indicate that in urban areas, monitors near roadways often report the highest concentrations of NO_2. (Gantt, Owen and Watkins 2021) More recent studies of traffic-related air pollutants continue to report sharp gradients around roadways, particularly within several hundred meters. (Apte, et al. 2017, Gu, et al. 2018)

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 as a result 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. (Liu, et al. 2006, Cahill, Charles and Seaman 2010) 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.[133] 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. (Laden,

[133] 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.

et al. 2007, Peters, et al. 2004, Zanobetti, et al. 2009, Adar, et al. 2007) The health outcomes with the strongest evidence linking them with traffic-associated air pollutants are respiratory effects, particularly in asthmatic children, and cardiovascular effects.

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. (HEI 2022)[134] 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, circulatory, and ischemic heart disease mortality. (Boogaard, et al. 2022) 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. 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'. (Boothe and Shendell 2008, Salam, Islam and Gilliland 2008, Sun, Zhang and Ma 2014, Raaschou-Nielsen and Reynolds 2006) 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. (Boothe, et al. 2014) The U.S. Department of Health and Human Services' National Toxicology Program (NTP) published a monograph including a systematic review of traffic-related air pollution and its impacts on hypertensive disorders of pregnancy. The NTP concluded that exposure to traffic-related air pollution is "presumed to be a hazard to pregnant women" for developing hypertensive disorders of pregnancy. (NTP 2019)

Health outcomes with few publications suggest the possibility of other effects still lacking sufficient evidence to draw definitive conclusions. Among these outcomes with a small number of positive studies are neurological impacts (e.g., autism and reduced cognitive function) and reproductive outcomes (e.g., preterm birth, low birth weight). (Volk, et al. 2011, Franco-Suglia, et al. 2007, Power, et al. 2011, Wu, et al. 2011, Stenson, et al. 2021)

In addition to health outcomes, particularly cardiopulmonary effects, conclusions of numerous studies suggest mechanisms by which traffic-related air pollution affects health. For example, numerous studies indicate that near-roadway exposures may increase systemic inflammation, affecting organ systems, including blood vessels and lungs. (Riediker, Cardiovascular effects of fine particulate matter components in highway patrol officers 2007, Alexeef, et al. 2011, S.P., et al. 2011, Zhang, et al. 2009) Additionally, long-term exposures in near-road environments have been associated with inflammation-associated conditions, such as atherosclerosis and asthma. (Adar, Klein, et al. 2010, Kan, et al. 2008, McConnell, et al. 2010)

The risks associated with residence, workplace, or schools 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 were within 300 feet of an "airport, railroad, or highway with four or more

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[134] This more recent review focused on health outcomes related to birth effects, respiratory effects, cardiometabolic effects, and mortality.

lanes."[135] The 2013 survey reports that 17.3 million housing units, or 13 percent of all housing units in the U.S., 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 within 300 feet of high-traffic roadways or other transportation sources. According to the Central Intelligence Agency's World Factbook, based on data collected between 2012-2014, the United States had 6,586,610 km of roadways, 293,564 km of railways, and 13,513 airports. As such, highways represent the overwhelming majority of transportation facilities described by this factor in the AHS.

Scientific literature suggests that some factors may increase susceptibility to the effects of traffic-associated air pollution. Several studies have found stronger adverse health associations in children experiencing chronic social stress, such as in violent neighborhoods or in homes with low incomes or high family stress. (Islam, et al. 2011, Clougherty, et al. 2007, Chen, et al. 2008, Long, Lewis and Langpap 2021) Similarly, two studies found some evidence that children exposed to higher levels of traffic-related air pollution show poorer academic performance than those exposed to lower levels of traffic-related air pollution. (Stenson, et al. 2021, Gartland, et al. 2022) However, this evidence was judged to be weak due to limitations in the assessment methods.

EPA 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 medium-duty vehicles operate. (US EPA 2021) 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 (US DOT 2023).[136,137] This analysis includes the population living within twice the distance of major roads compared with the analysis of housing units near major roads described above in this section. The larger distance and other methodological differences explain the difference in the two estimates for populations living near major roads.

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.[138] To determine school proximities to major roadways, we used a geographic information system (GIS) to map each school and roadways based on the U.S. Census's TIGER roadway file. (Pedde and Bailey 2011) Ten million students attend public schools within 200 meters of major roads, about 20 percent of the total number of public school

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[135] The variable was known as "ETRANS" in the questions about the neighborhood.

[136] 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 (US DOT 2023).

[137] The same analysis estimated the population living within 100 meters of a FAF4 truck route is 41 million.

138 This information is available at: http://nces.ed.gov/ccd/.

students in the U.S., and about 800,000 students attend public schools within 200 meters of primary roads. [139]

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. (Riediker, Cascio, et al. 2004, Peters, et al. 2004, Adar, Gold and Coull 2007) 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. (Sabin, et al. 2005, Li, N and Ryan 2009, Austin, Heutel and Kreisman 2019, Adar, D.Souza and Sheppard 2015)

In addition, 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. (US EPA 2016) 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. (Riediker, Cascio, et al. 2004, Peters, et al. 2004, Adar, Gold and Coull 2007)

7.3 Welfare Effects Associated with Exposure to Criteria and Air Toxics Pollutants

This section discusses the environmental effects associated with non-GHG pollutants affected by this rule, specifically PM, ozone, NO_X, SO_X, and air toxics.

7.3.1 Visibility Degradation

Visibility can be defined as the degree to which the atmosphere is transparent to visible light. (NRC 1993) 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. Fine particles with significant light-extinction efficiencies include sulfates, nitrates, organic carbon, elemental carbon, sea salt, and soil. (J. e. Hand 2011, Sisler 1996) 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. (US EPA 2019)

The extent to which any amount of light extinction affects a person's ability to view a scene depends on both scene and light characteristics. For example, the appearance of a nearby object (e.g., a building) is generally less sensitive to a change in light extinction than the appearance of a similar object at a greater distance. See Figure 7-1 for an illustration of the important factors affecting visibility. (Malm 2016)

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[139] 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."

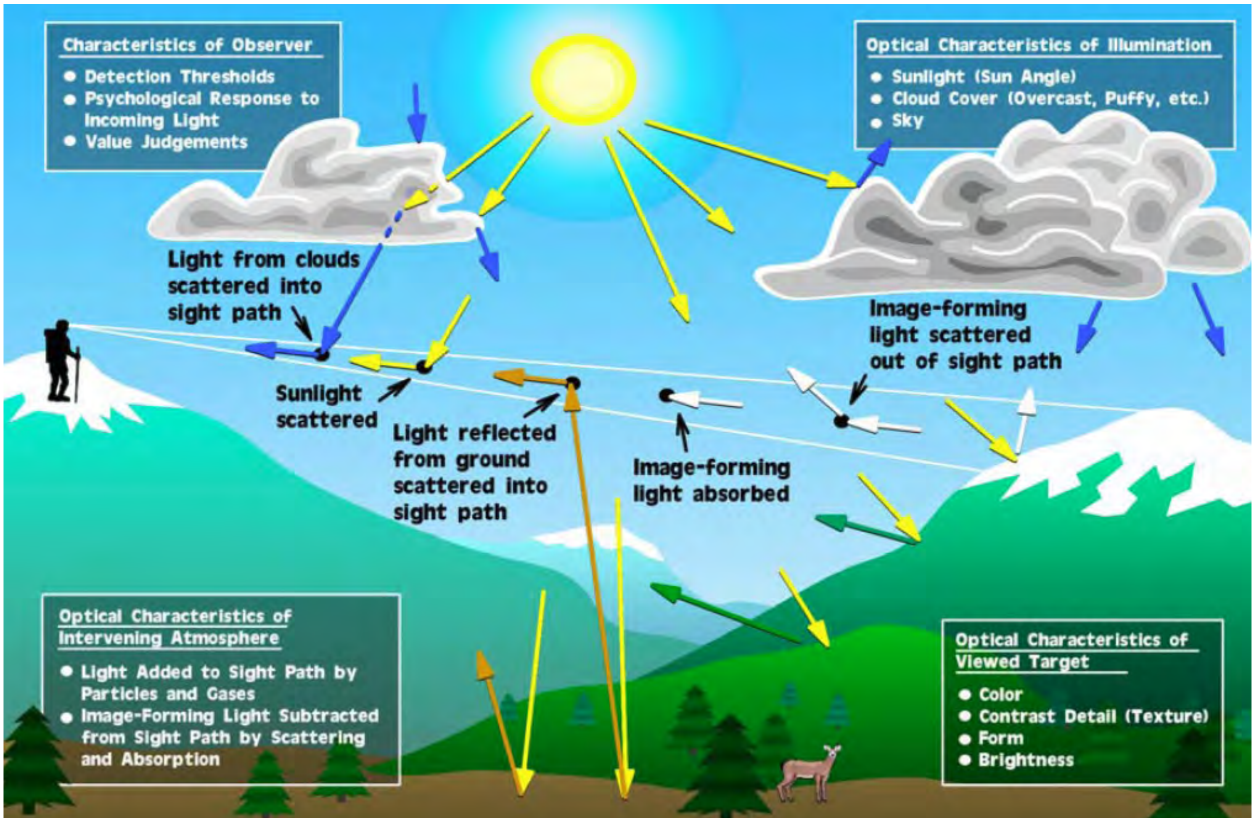

Figure 7-1 Important Factors Involved in Seeing a Scenic Vista (Malm, 2016)

EPA is working to address visibility impairment. Reductions in air pollution from implementation of various programs called for in the Clean Air Act Amendments of 1990 (CAAA) 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 emissions 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. (US EPA 2019) 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. (Hand, et al. 2020)

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 (42 USC §7491 (a) 2013). In 1999, EPA finalized the regional haze program (64 FR 35714) to protect the visibility in Mandatory Class I Federal areas. There are 156 national parks, forests and wilderness areas categorized as Mandatory Class I Federal areas (62 FR 38680-38681, July 18, 1997). 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 that were in existence on August 7, 1977. Figure 7-2 shows the location of the 156 Mandatory Class I Federal areas.

Figure 7-2: Mandatory Class I Federal Areas in the U.S.

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.

7.3.1.1 Visibility Monitoring

In conjunction with the U.S. National Park Service, the U.S. Forest Service, other Federal land managers, and State organizations in the U.S., EPA has supported visibility monitoring in national parks and wilderness areas since 1988. The monitoring network was originally established at 20 sites, but it has now been expanded to 152 sites that represent all but one of the 156 Mandatory Federal Class I areas across the country (see Figure 7-2). This long-term visibility monitoring network is known as IMPROVE (Interagency Monitoring of Protected Visual Environments).

IMPROVE provides direct measurement of particles that contribute to visibility impairment. The IMPROVE network employs aerosol measurements at all sites, and optical and scene measurements at some of the sites. Aerosol measurements are taken for PM_{10} and $PM_{2.5}$ mass, and for key constituents of $PM_{2.5}$, such as sulfate, nitrate, organic and elemental carbon (OC and EC), and other elements that can be used to estimate soil dust and sea salt contributions. Measurements for specific aerosol constituents are used to calculate "reconstructed" aerosol light extinction by multiplying the mass for each constituent by its empirically-derived scattering and/or absorption efficiency, with adjustment for the relative humidity. The IMPROVE program utilizes both an “original” and a “revised” reconstruction formula for this purpose, with the latter explicitly accounting for sea salt concentrations. Knowledge of the main constituents of a site's light extinction "budget" is critical for source apportionment and control strategy development. In addition to this indirect method of assessing light extinction, there are optical measurements which directly measure light extinction or its components. Such measurements are made principally with a nephelometer to measure light scattering; some sites also include an aethalometer for light absorption; and a few sites use a transmissometer, which measures total light extinction. Scene characteristics are typically recorded using digital or video photography and are used to determine the quality of visibility conditions (such as effects on color and contrast) associated with specific levels of light extinction as measured under both direct and aerosol-related methods. Directly measured light extinction is used under the IMPROVE protocol to cross check that total light extinction calculated from the IMPROVE reconstruction formula are consistent with directly measured extinction. Aerosol-derived light extinction from the IMPROVE equation is used to document spatial and temporal trends and to determine how changes in atmospheric constituents would affect future visibility conditions.

Annual average visibility conditions (reflecting light extinction due to both anthropogenic and non-anthropogenic sources) vary regionally across the U.S. Figures 13-1 through 13-14 in the PM ISA detail the percent contributions to particulate light extinction for ammonium nitrate and sulfate, EC and OC, and coarse mass and fine soil, by month. (US EPA 2019)

7.3.2 Plant and Ecosystem Effects of Ozone

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. When ozone effects that begin at small spatial scales, such as the leaf of an individual plant, occur at sufficient magnitudes (or to a sufficient degree), they can result in effects being propagated along a continuum 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 (73 FR 16486 2008). In those sensitive species[140,] 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. (US EPA 2020)[141] 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 (73 FR 16492 2008). These latter impacts include increased susceptibility of plants to insect attack, disease, harsh weather, interspecies competition, and overall decreased plant vigor.

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[140] 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.
[141] 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.

The adverse effects of ozone on areas with sensitive species could potentially lead to species shifts and loss from the affected ecosystems[142], resulting in a loss or reduction in associated ecosystem goods and services (73 FR 16493-16494 2008). 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 (73 FR 16490-16497 2008). In addition to ozone effects on vegetation, newer evidence 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 Ozone ISA presents more detailed information on how ozone affects vegetation and ecosystems (US EPA 2020). 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.[143] 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.

7.3.3 Deposition

Deposited airborne pollutants contribute to adverse effects on ecosystems, and to soiling and materials damage. These welfare effects result mainly from exposure to excess amounts of specific chemical species, regardless of their source or predominant form (particle, gas or liquid). Nitrogen and sulfur tend to comprise a large portion of PM in many locations; however, gas-phase forms of oxidized nitrogen and sulfur also cause adverse ecological effects. The following characterizations of the nature of these environmental effects are based on information contained in the 2019 PM ISA, and the 2020 Integrated Science Assessment for Oxides of Nitrogen, Oxides of Sulfur, and Particulate Matter - Ecological Criteria. (US EPA 2020, US EPA 2019)

7.3.3.1 Deposition of Nitrogen and Sulfur

Nitrogen and sulfur interactions in the environment are highly complex, as shown in Figure 7-3. (US EPA 2020) Both nitrogen and sulfur are essential, and sometimes limiting, nutrients needed for growth and productivity of ecosystem components (e.g., algae, plants). In terrestrial and aquatic ecosystems, excesses of nitrogen or sulfur can lead to acidification and nutrient enrichment. (US EPA 2020) In addition, in aquatic ecosystems, sulfur deposition can increase mercury methylation.

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[142] Per footnote above, ozone impacts could be occurring in areas where plant species sensitive to ozone have not yet been studied or identified.

[143] 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.

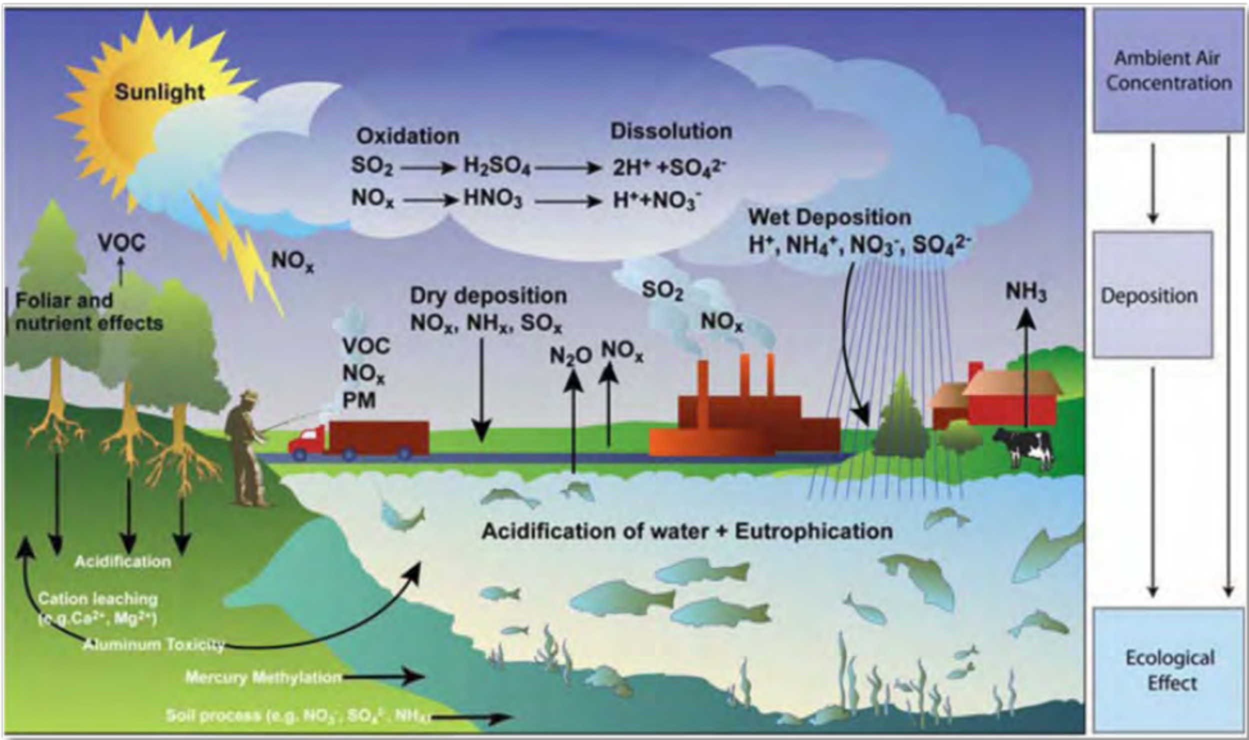

Figure 7-3: Nitrogen and Sulfur Cycling, and Interactions in the Environment

7.3.3.1.1 Ecological Effects of Acidification

Deposition of nitrogen and sulfur can cause acidification, which alters biogeochemistry and affects animal and plant life in terrestrial and aquatic ecosystems across the U.S. Soil acidification is a natural process, but is often accelerated by acidifying deposition, which can decrease concentrations of exchangeable base cations in soils. (US EPA 2020) Biological effects of acidification in terrestrial ecosystems are generally linked to aluminum toxicity and decreased ability of plant roots to take up base cations. (US EPA 2020) Decreases in the acid neutralizing capacity and increases in inorganic aluminum concentration contribute to declines in zooplankton, macro invertebrates, and fish species richness in aquatic ecosystems. (US EPA 2020)

Geology (particularly surficial geology) is the principal factor governing the sensitivity of terrestrial and aquatic ecosystems to acidification from nitrogen and sulfur deposition. (US EPA 2020) Geologic formations having low base cation supply generally underlie the watersheds of acid-sensitive lakes and streams. Other factors contribute to the sensitivity of soils and surface waters to acidifying deposition, including topography, soil chemistry, land use, and hydrologic flow path. (US EPA 2020).

7.3.3.1.1.1 Aquatic Acidification

Aquatic effects of acidification have been well studied in the U.S. and elsewhere at various trophic levels. These studies indicate that aquatic biota have been affected by acidification at virtually all levels of the food web in acid sensitive aquatic ecosystems. Effects have been most clearly documented for fish, aquatic insects, other invertebrates, and algae. Biological effects are primarily attributable to a combination of low pH and high inorganic aluminum concentrations. Such conditions occur more frequently during rainfall and snowmelt that cause high flows of water, and less commonly during low-flow conditions, except where chronic acidity conditions are severe. Biological effects of episodes include reduced fish condition factor, changes in species composition and declines in aquatic species richness across multiple taxa, ecosystems and regions.

Because acidification primarily affects the diversity and abundance of aquatic biota, it also affects the ecosystem services, e.g., recreational and subsistence fishing, that are derived from the fish and other aquatic life found in these surface waters. For example, in the northeastern United States, the surface waters affected by acidification are a source of food for some recreational and subsistence fishermen and for other consumers with particularly high rates of self-caught fish consumption, such as the Hmong and Chippewa ethnic groups. (Hutchison 1994, Peterson, et al. 1994)

7.3.3.1.1.2 Terrestrial Acidification

Acidifying deposition has altered major biogeochemical processes in the U.S. by increasing the nitrogen and sulfur content of soils, accelerating nitrate and sulfate leaching from soil to drainage waters, depleting base cations (especially calcium and magnesium) from soils, and increasing the mobility of aluminum. Inorganic aluminum is toxic to some tree roots. Plants affected by high levels of aluminum from the soil often have reduced root growth, which restricts the ability of the plant to take up water and nutrients, especially calcium. (US EPA 2020) These direct effects can, in turn, influence the response of these plants to climatic stresses such as droughts and cold temperatures. They can also influence the sensitivity of plants to other stresses, including insect pests and disease leading to increased mortality of canopy trees. (Joslin 1992) In the U.S., terrestrial effects of acidification are best described for forested ecosystems (especially red spruce and sugar maple ecosystems) with additional information on other plant communities, including shrubs and lichen. (US EPA 2020)

Both coniferous and deciduous forests throughout the eastern U.S. are experiencing gradual losses of base cation nutrients from the soil due to accelerated leaching from acidifying deposition. This change in nutrient availability may reduce the quality of forest nutrition over the long term. Evidence suggests that red spruce and sugar maple in some areas in the eastern U.S. have experienced declining health because of this deposition. For red spruce (Picea rubens), dieback or decline has been observed across high elevation landscapes of the northeastern U.S. and, to a lesser extent, the southeastern U.S., and acidifying deposition has been implicated as a causal factor. (DeHayes, et al. 1999)

7.3.3.1.2 Ecological Effects from Nitrogen Enrichment

7.3.3.1.2.1 Aquatic Enrichment

Eutrophication in estuaries is associated with a range of adverse ecological effects including low dissolved oxygen (DO), harmful algal blooms (HABs), loss of submerged aquatic vegetation (SAV), and low water clarity. Low DO disrupts aquatic habitats, causing stress to fish and shellfish, which, in the short-term, can lead to episodic fish kills and, in the long-term, can damage overall growth in fish and shellfish populations. Low DO also degrades the aesthetic qualities of surface water. In addition to often being toxic to fish and shellfish and leading to fish kills and aesthetic impairments of estuaries, HABs can, in some instances, also be harmful to human health. SAV provides critical habitat for many aquatic species in estuaries and, in some instances, can also protect shorelines by reducing wave strength; therefore, declines in SAV due to nutrient enrichment are an important source of concern. Low water clarity is in part the result of accumulations of both algae and sediments in estuarine waters. In addition to contributing to declines in SAV, high levels of turbidity also degrade the aesthetic qualities of the estuarine environment.

An assessment of estuaries nationwide by the National Oceanic and Atmospheric Administration (NOAA) concluded that 64 estuaries (out of 99 with available data) suffered from moderate or high levels of eutrophication due to excessive inputs of both nitrogen (N) and phosphorus. (Bricker, et al. 2007) For estuaries in the Mid-Atlantic region, the contribution of atmospheric deposition to total N loads is estimated to range between 10 percent and 58 percent. (Valigura, et al. 2001) Estuaries in the eastern United States are an important source of food production, in particular for fish and shellfish production. The estuaries are capable of supporting large stocks of resident commercial species, and they serve as the breeding grounds and interim habitat for several migratory species. Eutrophication in estuaries may also affect the demand for seafood (after well-publicized toxic blooms), water-based recreation, and erosion protection provided by SAV.

7.3.3.1.2.2 Terrestrial Enrichment

Terrestrial enrichment occurs when terrestrial ecosystems receive N loadings in excess of natural background levels, through either atmospheric deposition or direct application. Atmospheric N deposition is associated with changes in the types and number of species and biodiversity in terrestrial systems. Nitrogen enrichment occurs over a long time period; as a result, it may take as many as 50 years or more to see changes in ecosystem conditions and indicators. One of the main provisioning services potentially affected by N deposition is grazing opportunities offered by grasslands for livestock production in the Central U.S. Although N deposition on these grasslands can offer supplementary nutritive value and promote overall grass production, there are concerns that fertilization may favor invasive grasses and shift the species composition away from native grasses. This process may ultimately reduce the productivity of grasslands for livestock production.

Terrestrial enrichment also affects habitats, for example the Coastal Sage Scrub (CSS) and Mixed Conifer Forest (MCF) habitats which are an integral part of the California landscape. Together the ranges of these habitats include the densely populated and valuable coastline and the mountain areas. Numerous threatened and endangered species at both the state and federal levels reside in CSS and MCF. Nutrient enrichment of the CSS and MCF also affects the regulating service of fire, by encouraging the growth of more flammable grasses and thus increasing fuel loads and altering the fire cycle.

7.3.3.1.3 Vegetation Effects Associated with Gaseous Sulfur Dioxide, Nitric Oxide, Nitrogen Dioxide, Peroxyacetyl Nitrate, and Nitric Acid

Uptake of gaseous pollutants in a plant canopy is a complex process involving adsorption to surfaces (leaves, stems, and soil) and absorption into leaves. These pollutants penetrate into leaves through the stomata, although there is evidence for limited pathways via the cuticle. (US EPA 2020) Pollutants must be transported from the bulk air to the leaf boundary layer in order to reach the stomata. When the stomata are closed, as occurs under dark or drought conditions, resistance to gas uptake is very high and the plant has a very low degree of susceptibility to injury. In contrast, mosses and lichens do not have a protective cuticle barrier to gaseous pollutants or stomates and are generally more sensitive to gaseous sulfur and nitrogen than vascular plants. (US EPA 2020)

Acute foliar injury from SO_2 usually happens within hours of exposure, involves a rapid absorption of a toxic dose, and involves collapse or necrosis of plant tissues. Another type of visible injury is termed chronic injury and is usually a result of variable SO_2 exposures over the growing season. Besides foliar injury, chronic exposure to low SO_2 concentrations can result in reduced photosynthesis, growth, and yield of plants. (US EPA 2022) These effects are cumulative over the season and are often not associated with visible foliar injury. As with foliar injury, these effects vary among species and growing environment. SO_2 is also considered the primary factor causing the death of lichens in many urban and industrial areas. (Hutchinson, Maynard and Geiser 1996)

Similarly, in sufficient concentrations, nitric oxide (NO), nitrogen dioxide (NO_2), peroxyacetyl nitrate (PAN), and nitric acid (HNO_3) can have phytotoxic effects on plants such as decreasing photosynthesis and inducing visible foliar injury. It is also known that these gases can alter the N cycle in some ecosystems, especially in the western U.S., and contribute to N saturation. Further, there are several lines of evidence that past and current HNO_3 concentrations may be contributing to the decline in lichen species in the Los Angeles basin. (Riddell, Nash and Padgett 2008)

7.3.3.1.4 Mercury Methylation

Mercury is a persistent, bioaccumulative toxic metal that is emitted in three forms: gaseous elemental Hg (Hg0), oxidized Hg compounds (Hg+2), and particle-bound Hg (HgP). Methylmercury (MeHg) is formed by microbial action in the top layers of sediment and soils after Hg has precipitated from the air and deposited into waterbodies or land. Once formed, MeHg is taken up by aquatic organisms and bioaccumulates up the aquatic food web. Larger predatory fish may have MeHg concentrations many times higher, typically on the order of one million times, than the concentrations in the freshwater body in which they live. The NO_X SO_X ISA—Ecological Criteria concluded that evidence is sufficient to infer a causal relationship between sulfur deposition and increased mercury methylation in wetlands and aquatic environments. (US EPA 2020) Specifically, there appears to be a relationship between SO_4^{2-} deposition and mercury methylation; however, the rate of mercury methylation varies according to several spatial and biogeochemical factors whose influence has not been fully quantified. Therefore, the correlation between SO_4^{2-} deposition and MeHg cannot yet be quantified for the purpose of interpolating the association across waterbodies or regions. Nevertheless, because changes in MeHg in ecosystems represent changes in significant human and ecological health risks, the association between sulfur and mercury cannot be neglected. (US EPA 2020)

7.3.3.2 Deposition of Metallic and Organic Constituents of PM

Several significant ecological effects are associated with the deposition of chemical constituents of ambient PM such as metals and organics. (US EPA 2020) The trace metal constituents of PM include cadmium, copper, chromium, mercury, nickel, zinc, and lead. The organics include persistent organic pollutants (POPs), polyaromatic hydrocarbons (PAHs) and polybrominated diphenyl ethers (PBDEs). Direct effect exposures to PM occur via deposition (e.g., wet, dry or occult) to vegetation surfaces, while indirect effects occur via deposition to ecosystem soils or surface waters where the deposited constituents of PM then interact with biological organisms. While both fine and coarse-mode particles may affect plants and other organisms, more often the chemical constituents drive the ecosystem response to PM. (Grantz, Garner and Johnson 2003) Ecological effects of PM include direct effects to metabolic processes of plant foliage; contribution to total metal loading resulting in alteration of soil biogeochemistry and microbiology, plant and animal growth and reproduction; and contribution to total organics loading resulting in bioaccumulation and biomagnification.

Particulate matter can adversely impact plants and ecosystem services provided by plants by deposition to vegetative surfaces. (US EPA 2020) Particulates deposited on the surfaces of leaves and needles can block light, altering the radiation received by the plant. PM deposition near sources of heavy deposition can obstruct stomata (limiting gas exchange), damage leaf cuticles and increase plant temperatures. (US EPA 2020) Plants growing on roadsides exhibit impact damage from near-road PM deposition, having higher levels of organics and heavy metals, and accumulating salt from road de-icing during winter months. (US EPA 2020) In addition, atmospheric PM can convert direct solar radiation to diffuse radiation, which is more uniformly distributed in a tree canopy, allowing radiation to reach lower leaves. (US EPA 2020) Decreases in crop yields (a provisioning service) due to reductions in solar radiation have been attributed to regional scale air pollution in counties with especially severe regional haze. (Chameides, et al. 1999)

In addition to damage to plant surfaces, deposited PM can be taken up by plants from soil or foliage. Copper, zinc, and nickel have been shown to be directly toxic to vegetation under field conditions. (US EPA 2020) The ability of vegetation to take up heavy metals is dependent upon the amount, solubility and chemical composition of the deposited PM. Uptake of PM by plants from soils and vegetative surfaces can disrupt photosynthesis, alter pigments and mineral content, reduce plant vigor, decrease frost hardiness and impair root development.

Particulate matter can also contain organic air toxic pollutants, including PAHs, which are a class of polycyclic organic matter (POM). PAHs can accumulate in sediments and bioaccumulate in freshwater, flora and fauna. The uptake of organic air toxic pollutants depends on the plant species, site of deposition, physical and chemical properties of the organic compound and prevailing environmental conditions. (US EPA 2020) Different species can have different uptake rates of PAHs. PAHs can accumulate to high enough concentrations in some coastal environments to pose an environmental health threat that includes cancer in fish populations, toxicity to organisms living in the sediment and risks to those (e.g., migratory birds) that consume these organisms. (Simcik, S.J. and Lioy 1999, Simcik, et al. 1996) Atmospheric deposition of particles is thought to be the major source of PAHs in the sediments of Lake Michigan, Chesapeake Bay, Tampa Bay and other coastal areas of the U.S. (Arzavus, Dickhut and Canuel 2001)

Contamination of plant leaves by heavy metals can lead to elevated concentrations in the soil. Trace metals absorbed into the plant, frequently by binding to the leaf tissue, and then are shed when the leaf drops. As the fallen leaves decompose, the heavy metals are transferred into the soil. (Cotrufo, et al. 1995, Niklinska, Laskowski and Maryanski 1998) Many of the major indirect plant responses to PM deposition are chiefly soil-mediated and depend on the chemical composition of individual components of deposited PM. Upon entering the soil environment, PM pollutants can alter ecological processes of energy flow and nutrient cycling, inhibit nutrient uptake to plants, change microbial community structure, and affect biodiversity. Accumulation of heavy metals in soils depends on factors such as local soil characteristics, geologic origin of parent soils, and metal bioavailability. Heavy metals such as zinc, copper, and cadmium, and some pesticides can interfere with microorganisms that are responsible for decomposition of soil litter, an important regulating ecosystem service that serves as a source of soil nutrients. (US EPA 2020) Surface litter decomposition is reduced in soils having high metal concentrations. Soil communities have associated bacteria, fungi, and invertebrates that are essential to soil nutrient cycling processes. Changes to the relative species abundance and community composition are associated with deposited PM to soil biota. (US EPA 2020)

Atmospheric deposition can be the primary source of some organics and metals to watersheds. Deposition of PM to surfaces in urban settings increases the metal and organic component of storm water runoff. (US EPA 2020) This atmospherically-associated pollutant burden can then be toxic to aquatic biota. The contribution of atmospherically deposited PAHs to aquatic food webs was demonstrated in high elevation mountain lakes with no other anthropogenic contaminant sources. (US EPA 2020) Metals associated with PM deposition limit phytoplankton growth, affecting aquatic trophic structure. Long-range atmospheric transport of 47 pesticides and degradation products to the snowpack in seven national parks in the Western U.S. was recently quantified indicating PM-associated contaminant inputs in receiving waters during spring snowmelt. The recently completed Western Airborne Contaminants Assessment Project (WACAP) is the most comprehensive database on contaminant transport and PM depositional effects on sensitive ecosystems in the Western U.S. (Landers, et al. 2008) In this project, the transport, fate, and ecological impacts of anthropogenic contaminants from atmospheric sources were assessed from 2002 to 2007 in seven ecosystem components (air, snow, water, sediment, lichen, conifer needles and fish) in eight core national parks. The study concluded that bioaccumulation of semi-volatile organic compounds occurred throughout park ecosystems, an elevational gradient in PM deposition exists with greater accumulation in higher altitude areas, and contaminants accumulate in proximity to individual agriculture and industry sources, which is counter to the original working hypothesis that most of the contaminants would originate from Eastern Europe and Asia.

7.3.3.3 Materials Damage and Soiling

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, degrading paints and deteriorating building materials such as stone, concrete and marble. (US EPA 2020) The effects of PM are exacerbated by the presence of acidic gases and can be additive or synergistic depending on 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 (such as monuments and building facings), and surface coatings (paints). (Irving 1991) 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 becoming an important consideration for impacts of air pollutants on materials.

7.3.4 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. VOCs, some of which are considered air toxics, have long been suspected to play a role in vegetation damage. (US EPA 1991) In laboratory experiments, a wide range of tolerance to VOCs has been observed. (Cape, et al. 2003) 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. (Cape, et al. 2003)

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 NO_X. (Viskari 2000, Ugrekhelidze, Korte and Kvesitadze 1997, Kammerbauer, et al. 1987) 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.

7.4 Criteria Pollutant Human Health Benefits

The light-duty passenger cars and light trucks and medium-duty vehicles subject to the proposed standards are significant sources of mobile source air pollution, including directly-emitted $PM_{2.5}$ as well as NO_X and VOC emissions (both precursors to ozone formation and secondarily-formed $PM_{2.5}$). The proposed program would reduce exhaust emissions of these pollutants from the regulated vehicles, which would in turn reduce ambient concentrations of ozone and $PM_{2.5}$. Emissions from upstream sources would likely increase in some cases (e.g., power plants) and decrease in others (e.g., refineries). We project that in total, the proposed standards would result in substantial net reductions of emissions of pollutants like $PM_{2.5}$, NO_X and VOCs and a net increase in emissions of SO_2. Emissions changes attributable to the proposed standards are presented in Section VII of this preamble. Exposures to ambient pollutants such as $PM_{2.5}$ and ozone are linked to adverse environmental and human health impacts, such as premature deaths and non-fatal illnesses (as explained in Section II.C of this preamble). Reducing human exposure to these pollutants results in significant and measurable health benefits.

This section discusses the economic benefits from reductions in adverse health and environmental impacts resulting from criteria pollutant emission reductions that can be expected to occur as a result of the proposed emission standards. 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.

EPA conducted an illustrative air quality modeling analysis of a regulatory scenario involving light- and medium-duty vehicle emission reductions and corresponding changes in “upstream” emission sources like EGU (electric generating unit) emissions and refinery emissions (see DRIA Chapter 8). Decisions about the emissions and other elements used in the air quality modeling were made early in the analytical process for the proposed rulemaking. Accordingly, the air quality analysis does not represent the proposal's regulatory scenario, nor does it reflect the expected impacts of the Inflation Reduction Act (IRA). Based on updated power sector modeling that incorporated expected generation mix impacts of the IRA, we are projecting the IRA will lead to a significantly cleaner power grid. Because the air quality analysis does not account for these impacts on EGU emissions, we instead used the OMEGA-based emissions analysis (see DRIA Chapter 9) and benefit-per-ton (BPT) values to estimate the criteria pollutant ($PM_{2.5}$) health benefits of the proposed and alternative standards.

The BPT approach estimates the monetized economic value of $PM_{2.5}$-related emission reductions or increases (such as direct PM, NO_X and SO_2) due to implementation of the proposed program. Similar to the SC-GHG approach for monetizing reductions in GHGs, the BPT approach monetizes health benefits of avoiding one ton of $PM_{2.5}$-related emissions from a particular onroad mobile or upstream source. The value of health benefits from reductions (or increases) in $PM_{2.5}$ emissions associated with this proposal were estimated by multiplying $PM_{2.5}$-related BPT 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 proposal would be larger if we were able to monetize these unquantified benefits at this time.

Using the BPT approach, we estimate the present value of $PM_{2.5}$-related benefits of the proposed program to be $97 to $200 billion at a 3% discount rate and $42 to $89 billion at a 7% discount rate. Benefits are reported in year 2020 dollars and reflect the $PM_{2.5}$-related benefits associated with reductions in NO_X, SO_2, and direct $PM_{2.5}$ emissions. Because premature mortality typically constitutes the vast majority of monetized benefits in a $PM_{2.5}$ benefits assessment, we present a range of 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. Tables of the monetized $PM_{2.5}$-related benefits of the proposed standards can be found in draft RIA Chapter 10.

7.4.1 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 proposal. We use a BPT approach that is conceptually consistent with EPA’s use of BPT estimates in its regulatory analyses (US EPA 2018) (US EPA 2023). 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 NO_X, SO_2 or directly-emitted $PM_{2.5}$.

The mobile sector BPT estimates used in this proposal were published in 2019, but were recently updated using the suite of premature mortality and morbidity studies in use by EPA for the 2023 PM NAAQS Reconsideration Proposal (Wolfe, et al. 2019) (US EPA 2022). The upstream Refinery and EGU BPT estimates used in this proposal were also recently updated (US EPA 2023). The health benefits Technical Support Document (Benefits TSD) that accompanied the 2023 PM NAAQS Proposal details the approach used to estimate the $PM_{2.5}$-related benefits reflected in these BPTs (US EPA 2023). We multiply these BPT values by national reductions in annual emissions in tons to estimate the total monetized human health benefits associated with the proposal.

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, Refineries, and Electricity Generating Units), 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) (US EPA 2023).[144] 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 7-1. Table 7-3 in Chapter 7.4.6 lists the ozone, $PM_{2.5}$, SO_2 and NO_X health and welfare categories that are not quantified and monetized by the BPT approach and are therefore not included in the estimated benefits analysis for this proposal.

[144] 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.

Table 7-1 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 7-1, 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 (US EPA 2019) (US EPA 2022).[145] 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).

[145] 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.

We anticipate the proposed 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. The 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 7-3 in Section 7.4.6 of this Chapter.

We also do not provide estimated monetized benefits due to reductions in mobile source air toxics. This is primarily 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.

7.4.2 Estimating $PM_{2.5}$-attributable Adult Premature Death

Of the $PM_{2.5}$-related health endpoints listed in Table 7-1, 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 (US EPA 2019) (US EPA 2022). This body of literature reflects thousands of epidemiology, toxicology, and clinical studies. The PM ISA, completed as part of the review of the recently proposed PM standards and reviewed by the Clean Air Scientific Advisory Committee (CASAC) (Sheppard 2022), 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 that accompanied the 2023 PM NAAQS Proposal.

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) chohort study (Pope III et al. 2019) and an extended analysis of the Medicare cohort (Wu et al. 2020). 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 2016) (Di 2017) respectively. 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, 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 2023 PM NAAQS proposal, reviewed available studies that examined the potential for a population-level threshold to exist in 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." Consistent with this evidence, the Agency historically has estimated health impacts above and below the prevailing NAAQS.

7.4.3 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 that accompanied the 2023 PM NAAQS Proposal. 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 (US EPA-SAB 2000). 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 (US EPA 2016). This VSL value is the mean of the values reported in 26 labor market and contingent valuation studies published between 1974 and 1991. 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 2020 dollars after adjusting for income growth is $9.5 million for 2020.[146]

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 (US EPA 2017). EPA is taking the SAB's formal recommendations under advisement.

7.4.4 Dollar Value per Ton of Directly-Emitted $PM_{2.5}$ and $PM_{2.5}$ Precursors

The value of health benefits from reductions in $PM_{2.5}$ emissions associated with this proposal 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 in 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 7-2 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 a "cessation" lag between the change in PM exposures and the total realization of changes in mortality effects. The source sectors include: onroad light-duty gasoline cars, onroad light-duty gasoline trucks, onroad light-duty diesel cars/trucks, electricity generating units, and refineries. We note that reductions in medium-duty vehicle emissions are monetized using light-duty BPT values.

Detailed tables of the monetized $PM_{2.5}$-related benefits of the proposed standards can be found in draft RIA Chapter 10.

[146] In 1990$, when the study was conducted, the base VSL was $4.8 million.

Table 7-2 $PM_{2.5}$-related Benefit Per Ton values (2020$) associated with the reduction of NO_X, SO_2 and directly emitted $PM_{2.5}$ emissions for (A) Onroad light-duty gasoline cars, (B) Onroad light-duty gasoline trucks, (C) Onroad light-duty diesel cars/trucks, (D) Electricity Generating Units, and (E) Refineries.

A. Onroad Light-Duty Gasoline Cars												
	NOX				SO2				Direct PM			
	3% Discount Rate		7% Discount Rate		3% Discount Rate		7% Discount Rate		3% Discount Rate		7% Discount Rate	
2020$	Wu	Pope	Wu	Pope	Wu	Pope	Wu	Pope	Wu	Pope	Wu	Pope
2025	$7,230	$15,400	$6,490	$13,800	$128,000	$274,000	$115,000	$246,000	$709,000	$1,520,000	$637,000	$1,360,000
2030	$8,160	$16,800	$7,330	$15,100	$147,000	$303,000	$132,000	$273,000	$814,000	$1,680,000	$731,000	$1,510,000
2035	$9,200	$18,500	$8,260	$16,600	$169,000	$341,000	$152,000	$307,000	$939,000	$1,890,000	$843,000	$1,700,000
2040	$10,100	$19,900	$9,050	$17,900	$191,000	$378,000	$172,000	$340,000	$1,060,000	$2,100,000	$953,000	$1,890,000
2045	$10,700	$21,000	$9,640	$18,900	$211,000	$413,000	$190,000	$371,000	$1,170,000	$2,290,000	$1,050,000	$2,060,000
2050	$11,200	$21,600	$10,000	$19,500	$229,000	$443,000	$206,000	$398,000	$1,270,000	$2,450,000	$1,140,000	$2,200,000
2055	$11,700	$22,500	$10,500	$20,300	$249,000	$477,000	$224,000	$429,000	$1,370,000	$2,630,000	$1,240,000	$2,360,000
B. Onroad Light-Duty Gasoline Trucks												
	NOX				SO2				Direct PM			
	3% Discount Rate		7% Discount Rate		3% Discount Rate		7% Discount Rate		3% Discount Rate		7% Discount Rate	
2020$	Wu	Pope	Wu	Pope	Wu	Pope	Wu	Pope	Wu	Pope	Wu	Pope
2025	$6,550	$13,900	$5,880	$12,500	$102,000	$219,000	$91,700	$197,000	$597,000	$1,280,000	$536,000	$1,150,000
2030	$7,400	$15,200	$6,640	$13,700	$117,000	$243,000	$105,000	$218,000	$685,000	$1,420,000	$615,000	$1,270,000
2035	$8,360	$16,800	$7,510	$15,100	$135,000	$272,000	$121,000	$245,000	$789,000	$1,590,000	$708,000	$1,430,000
2040	$9,190	$18,200	$8,250	$16,400	$152,000	$302,000	$137,000	$271,000	$889,000	$1,760,000	$798,000	$1,580,000
2045	$9,820	$19,200	$8,820	$17,300	$168,000	$329,000	$151,000	$296,000	$979,000	$1,910,000	$880,000	$1,720,000
2050	$10,300	$19,900	$9,220	$17,900	$182,000	$352,000	$163,000	$316,000	$1,060,000	$2,040,000	$950,000	$1,840,000
2055	$10,800	$20,800	$9,700	$18,700	$197,000	$378,000	$177,000	$340,000	$1,140,000	$2,190,000	$1,030,000	$1,970,000
C. Onroad Light-Duty Diesel Cars/Trucks												
	NOX				SO2				Direct PM			
	3% Discount Rate		7% Discount Rate		3% Discount Rate		7% Discount Rate		3% Discount Rate		7% Discount Rate	
2020$	Wu	Pope	Wu	Pope	Wu	Pope	Wu	Pope	Wu	Pope	Wu	Pope
2025	$5,790	$12,300	$5,200	$11,100	$305,000	$655,000	$274,000	$589,000	$489,000	$1,050,000	$439,000	$942,000
2030	$6,550	$13,500	$5,880	$12,100	$349,000	$725,000	$314,000	$652,000	$560,000	$1,160,000	$503,000	$1,040,000
2035	$7,400	$14,900	$6,640	$13,400	$402,000	$813,000	$361,000	$731,000	$646,000	$1,300,000	$580,000	$1,170,000
2040	$8,130	$16,100	$7,310	$14,500	$453,000	$900,000	$407,000	$810,000	$728,000	$1,440,000	$654,000	$1,300,000
2045	$8,700	$17,000	$7,820	$15,300	$500,000	$980,000	$449,000	$882,000	$803,000	$1,570,000	$721,000	$1,410,000
2050	$9,100	$17,700	$8,180	$15,900	$541,000	$1,050,000	$486,000	$944,000	$868,000	$1,680,000	$780,000	$1,510,000
2055	$9,570	$18,400	$8,600	$16,600	$587,000	$1,130,000	$528,000	$1,010,000	$939,000	$1,800,000	$844,000	$1,620,000
D. Electricity Generating Units												
	NOX				SO2				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	$7,470	$15,800	$6,710	$14,200	$55,200	$118,000	$49,700	$106,000	$110,000	$235,000	$98,400	$211,000
2030	$8,370	$17,100	$7,530	$15,400	$62,300	$129,000	$56,000	$116,000	$125,000	$258,000	$112,000	$232,000
2035	$9,370	$18,700	$8,420	$16,900	$69,900	$141,000	$62,900	$127,000	$142,000	$287,000	$128,000	$258,000
2040	$10,200	$20,000	$9,130	$18,000	$76,400	$152,000	$68,700	$136,000	$158,000	$314,000	$142,000	$283,000
E. Refineries												
	NOX				SO2				Direct PM			
	3% Discount Rate		7% Discount Rate		3% Discount Rate		7% Discount Rate		3% Discount Rate		7% Discount Rate	
2020$	Wu	Pope	Wu	Pope	Wu	Pope	Wu	Pope	Wu	Pope	Wu	Pope
2025	$22,500	$48,300	$20,200	$43,400	$49,600	$107,000	$44,500	$96,400	$358,000	$776,000	$322,000	$698,000
2030	$24,800	$51,500	$22,300	$46,300	$54,800	$114,000	$49,200	$103,000	$395,000	$826,000	$355,000	$743,000
2035	$28,500	$57,500	$25,600	$51,800	$62,700	$127,000	$56,400	$115,000	$453,000	$923,000	$407,000	$831,000
2040	$31,900	$63,300	$28,700	$56,900	$70,100	$140,000	$63,000	$126,000	$509,000	$1,020,000	$458,000	$915,000

Notes: All estimates are rounded to three significant figures. The benefit-per-ton 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. Benefit-per-ton values were estimated for 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 hold values constant for intervening years (e.g., the 2025 values are assumed to apply to years 2021-2024, and so on). We hold 2040 values constant out to 2055 for EGUs and Refineries.

7.4.5 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 that accompanied the 2023 PM NAAQS Proposal 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. When the uncertainties from each stage of the analysis are compounded, even small uncertainties can have large effects on the total quantified benefits.

The BPT approach is a simplified approach that relies on additional assumptions and has its own limitations, some of which are described in Chapter 7.4.6. Additional uncertainties related to key assumptions underlying the estimates for $PM_{2.5}$-related premature mortality described in Section 7.4.2 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." (US EPA 2019)

- 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." (US EPA 2019)

- 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 (US EPA-SAB 2005). Similarly, we assume there is a cessation lag between the change in PM exposures and both the development and diagnosis of lung cancer.

7.4.6 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 7-3 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 7-3: Unquantified Health and Welfare Benefits Categories

Category	Unquantified Effect	More Information
Improved Human Health		
Nonfatal morbidity 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]
	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[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]

Reduced effects from acid deposition	Recreational fishing	NOX SOX ISA[a]
	Tree mortality and decline	NOX SOX ISA[b]
	Commercial fishing and forestry effects	NOX SOX ISA[b]
	Recreational demand in terrestrial and aquatic ecosystems	NOX SOX ISA[b]
	Other non-use effects	NOX SOX ISA[b]
	Ecosystem functions (e.g., biogeochemical cycles)	NOX SOX ISA[b]
Reduced effects from nutrient enrichment	Species composition and biodiversity in terrestrial and estuarine ecosystems	NOX SOX ISA[b]
	Coastal eutrophication	NOX SOX ISA[b]
	Recreational demand in terrestrial and estuarine ecosystems	NOX SOX ISA[b]
	Other non-use effects	NOX SOX ISA[b]
	Ecosystem functions (e.g., biogeochemical cycles, fire regulation)	NOX SOX ISA[b]
Reduced vegetation effects from ambient exposure to SO_2 and NO_X	Injury to vegetation from SO_2 exposure	NOX SOX ISA[b]
	Injury to vegetation from NO_X exposure	NOX SOX ISA[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 would result from the program (see draft RIA Chapter 7.2.7) but that the $PM_{2.5}$-related BPT approach 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 would 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 proposed standards. For this reason, the PM-related health benefits reported here may be larger, or smaller, than those that would be realized through this proposal.

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. 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 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 (US EPA 2019). We note that the BPT values used to monetize the benefits of the proposed program were not part of the Project, though we believe they are our best estimate of benefits absent air quality modeling and we have confidence in the BPT approach and the appropriateness of relying on BPT health estimates for this rulemaking. EPA continues to research and develop reduced-form approaches for estimating $PM_{2.5}$ benefits.

Chapter 7 References

42 USC § 7602 (h). 2021. https://www.govinfo.gov/content/pkg/USCODE-2021-title42/pdf/USCODE-2021-title42-chap85-subchapIII-sec7602.pdf.

42 USC §7491 (a). 2013. https://www.govinfo.gov/content/pkg/USCODE-2013-title42/html/USCODE-2013-title42-chap85-subchapI-partC-subpartii-sec7491.htm.

73 FR 16486 . 2008.

73 FR 16490-16497. 2008.

73 FR 16492 . 2008.

73 FR 16493-16494 . 2008.

81 FR 54422. 2016.

Adar, S., G. Adamkiewicz, D.R. Gold, J. Schwartz, B.A. Coull, and H. Suh. 2007. "Ambient and microenvironmental particles and exhaled nitric oxide before and after a group bus trip." Environ Health Perspect 115: 507-512.

Adar, S.D., D.R. Gold, and B.A. Coull. 2007. "Focused exposure to airborne traffic particles and heart rate variability in the elderly." Epidemiology 18: 95-103.

Adar, S.D., J. D.Souza, and L. Sheppard. 2015. "Adopting clean fuels and technologies on school buses. Pollution and health impacts in children." Am J Respir Crit Care Med 191 (12): 1413-1421.

Adar, S.D., R. Klein, E.K. Klein, and 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.

Aksoy, M. 1989. "Hematotoxicity and carcinogenicity of benzene." Environ. Health Perspect 82: 193-197.

Alexeef, S.E., B.A. Coull, A. Gryparis, and et al. 2011. "Medium-term exposure to traffic-related air pollution and markers of inflammation and endothelial function." Environ Health Perspect 119: 481-486.

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.

Apte, J.S., K.P. Messier, S. Gani, M. Brauer, T.W. Kirchstetter, M.M. Lunden, J.D. Marshall, C.J. Portier, R.C.H. Vermeulen, and S.P. Hamburg. 2017. "High-Resolution Air Pollution Mapping with Google Street View Cars: Exploiting Big Data." Environ Sci Technol 51: 6999-7008.

Arzavus, K.M., R.M. Dickhut, and E.A. Canuel. 2001. "Fate of Atmospherically Deposited Polycyclic Aromatic Hydrocarbons (PAHs) in Chesapeake Bay." Environmental Science & Technology 35: 2178-2183.

ATSDR. 2010. Addendum to the Toxicological Profile for Formaldehyde. Washington, DC: U.S. Department of Health and Human Services (HHS).

ATSDR. 2014. Letter Health Consultation, Radiac Abrasives, Inc. Chicago, Illinois: CDC. https://www.atsdr.cdc.gov/HAC/pha/RadiacAbrasives/Radiac%20Abrasives,%20Inc.%20_%20LHC%20(Final)%20_%2003-24-2014%20(2)_508.pdf.

ATSDR. 2007. Toxicological profile for benzene. Atlanta: U.S. Agency for Toxic Substances and Disease Registry (ATSDR), U.S. Department of Health and Human Services, Public Health Service. http://www.atsdr.cdc.gov/ToxProfiles/tp3.pdf.

ATSDR. 2010. Toxicological Profile for Ethylbenzene. Washington, D.C.: U.S. Department of Health and Human Services, Public Health Service, Agency for Toxic Substances and Disease Registry. https://www.atsdr.cdc.gov/ToxProfiles/tp110.pdf.

ATSDR. 1999. Toxicological Profile for Formaldehyde. Washington, DC: U.S. Department of Health and Human Services.

ATSDR. 2005. Toxicological Profile for Naphthalene, 1-Methylnaphthalene, and 2-Methylnaphthalene. CDC. https://www.atsdr.cdc.gov/ToxProfiles/tp67-p.pdf.

ATSDR. 1995. Toxicological profile for Polycyclic Aromatic Hydrocarbons (PAHs). Atlanta, GA: Agency for Toxic Substances and Disease Registry, U.S. Department of Health and Human Services, Public Health Service. http://www.atsdr.cdc.gov/ToxProfiles/TP.asp?id=122&tid=25.

Austin, W., G. Heutel, and D. Kreisman. 2019. "School bus emissions, student health and academic performance." Econ Edu Rev 70: 108-112.

Beane Freeman, L. E., A. Blair, J. H. Lubin, P. A. Stewart, R. B. Hayes, R. N. Hoover, and M. Hauptmann. 2009. "Mortality from lymphohematopoietic malignancies among workers in formaldehyde industries: The National Cancer Institute cohort." J. National Cancer Inst. 101: 751-761.

Bevan, C, J.C. Stadler, and et al. 1996. "Subchronic toxicity of 4-vinylcyclohexene in rats and mice by inhalation." Fundamentals of Applied Toxicology 1-10.

Boogaard, H., Patton. A.P., R.W. Atkinson, J.R. Brook, H.H. Chang, D.L. Crouse, J.C. Fussell, et al. 2022. "Long-term exposure to traffic-related air pollution and selected health outcomes: a systematic review and meta-analysis." Environ Intl 164: 107262.

Boothe, V.L., and D.G. Shendell. 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.

Boothe, VL., T.K. Boehmer, A.M. Wendel, and F.Y. Yip. 2014. "Residential traffic exposure and childhood leukemia: a systematic review and meta-analysis." Am J Prev Med 46: 413-422.

Bricker, S., B. Longstaff, W. Dennison, A. Jones, K. Boicourt, C. Wicks, and J. Woerner. 2007. Effects of Nutrient Enrichment In the Nation’s Estuaries: A Decade of Change. Silver Spring, MD: NOAA Coastal Ocean Program Decision Analysis Series No. 26. National Centers for Coastal Ocean Science.

Cahill, T.M., M.J. Charles, and V.Y. Seaman. 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. https://www.healtheffects.org/system/files/Cahill149.pdf.

California OEHHA. 2007. "Adoption of a Unit Risk Value for Ethylbenzene." https://oehha.ca.gov/air/report-hot-spots/adoption-unit-risk-value-ethylbenzene.

California OEHHA. 2008. "Technical Supporting Document for Noncancer RELs, Appendix D3." https://oehha.ca.gov/media/downloads/crnr/appendixd3final.pdf.

Cape, JN, ID Leith, J Binnie, J Content, M Donkin, M Skewes, DN Price, AR Brown, and AD Sharpe. 2003. "Effects of VOCs on herbaceous plants in an open-top chamber experiment." Environ. Pollut 124: 341-343.

Chameides, W.L., H. Yu, S.C. Liu, M. Bergin, X. Zhou, L. Mearns, G. Wang, et al. 1999. "Case study of the effects of atmospheric aerosols and regional haze on agriculture: an opportunity to enhance crop yields in China through emission controls?" PNAS 96: 13626-13633.

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.

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.

Coggon, D, EC Harris, J Poole, and KT Palmer. 2003. "Extended follow-up of a cohort of British chemical workers exposed to formaldehyde." J National Cancer Inst. 95: 1608-1615.

Corti, M., and C.A. Snyder. 1996. "Influences of gender, development, pregnancy and ethanol consumption on the hematotoxicity of inhaled 10 ppm benzene." Arch Toxicol 70: 209-217.

Cotrufo, M.F., De Santo A.V., Alfani A., Bartoli G., and De Cristofaro A. 1995. "Effects of urban heavy metal pollution on organic matter decomposition in Quercus ilex L. Woods." Environmental Pollution 89 (1): 81-87.

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.

DeHayes, D.H., P.G. Schaberg, G.J. Hawley, and G.R. Strimbeck. 1999. "Acid rain impacts on calcium nutrition and forest health." Bioscience 49 (10): 789–800.

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.

Foos, B., M. Marty, J. Schwartz, W. Bennet, J. Moya, A.M. Jarabek, and A.G. Salmon. 2008. "Focusing on children's inhalation dosimetry and health effects for risk assessment: An introduction." J Toxicol Environ Health (71A): 149-165.

Ford, AM, MS Pombo-de-Oliveira, KP McCarthy, JM MacLean, KC Carrico, RF Vincent, and M. Greaves. 1997. "Monoclonal origin of concordant T-cell malignancy in identical twins." Blood 89: 281-285.

Franco-Suglia, S., A. Gryparis, R.O. Wright, and 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.

Gantt, B, R.C. Owen, and N. Watkins. 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.

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.

Gartland, N, H.E. Aljofi, K. Dienes, L.A. Munford, A.L. Theakston, and M. van Tongeren. 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 10: 749.

Goldstein, B.D. 1988. "Benzene toxicity." Occupational Medicine - State of the Art Reviews 3: 541-554.

Grantz, DA, JHB Garner, and DW Johnson. 2003. "Ecological effects of particulate matter." Environ Int 29: 213-239.

Grivas, G., I. Stavroulas, E. Liakakou, D.G. Kaskaoutis, A. Bougiatioti, D. Paraskevopoulou, E. Gerasopoulos, and N. Mihalopoulos. 2019. "Measuring the spatial variability of black carbon in Athens during wintertime." Air Quality, Atmosphere & Health 12: 1405–1417.

Gu, P., H.Z. Li, Q. Ye, and et al. 2018. "Intercity variability of particulate matter is driven by carbonaceous sources and correlated with land-use variables." Environ Sci Technol 52: 11545-11554.

Hand, J.L. et al. 2011. Spatial and Temporal Variability of Haze and its Constituents in the United States. IMPROVE Report 0737-5352 (HERO #3121721). http://vista.cira.colostate.edu/improve/wp-content/uploads/2016/08/IMPROVE_V_FullReport.pdf.

Hand, JL, AJ Prenni, S Copeland, BA Schichtel, and WC Malm. 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.

Hauptmann, M,, Stewart P. A., Lubin J. H., L. E. Beane Freeman, R. W. Hornung, R. F. Herrick, R. N. Hoover, J. F. Fraumeni, and R. B. Hayes. 2009. "Mortality from lymphohematopoietic malignancies and brain cancer among embalmers exposed to formaldehyde." Journal of the National Cancer Institute 101: 1696-1708.

Hauptmann, M., J. H. Lubin, P. A. Stewart, R. B. Hayes, and A. Blair. 2003. "Mortality from lymphohematopoetic malignancies among workers in formaldehyde industries." Journal of the National Cancer Institute 95: 1615-1623.

Hauptmann, M., J. H. Lubin, P. A. Stewart, R. B. Hayes, and A. Blair. 2004. "Mortality from solid cancers among workers in formaldehyde industries." American Journal of Epidemiology 159: 1117-1130.

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.

Hilker, N., J.W. Wang, C-H. Jong, R.M. Healy, U. Sofowote, J. Debosz, Y. Su, et al. 2019. "Traffic-related air pollution near roadways: discerning local impacts from background." Atmos. Meas. Tech 12: 5247–5261.

Hutchinson, J, D Maynard, and L Geiser. 1996. Air quality and lichens - a literature review emphasizing the Pacific Northwest, USA. Pacific Northwest Region Air Resource Management Program; U.S. Forest Service; U.S. Department of Agriculture (USDA).

Hutchison, R., and C.E. Kraft. 1994. "Hmong Fishing Activity and Fish Consumption." Journal of Great Lakes Research 20 (2): 471-487.

IARC. 2013. "Diesel and gasoline engine exhausts and some nitroarenes." IARC Monographs 105. http://monographs.iarc.fr/ENG/Monographs/vol105/index.php.

IARC. 1982. IARC monographs on the evaluation of carcinogenic risk of chemicals to humans. Lyons, France: International Agency for Research on Cancer, World Health Organization.

IARC. 2008. "Monographs on the evaluation of carcinogenic risk of chemicals to humans, 1,3-butadiene, ethylene oxide, and vinyl halides, Vol 97."

IARC. 2018. Monographs on the evaluation of carcinogenic risks to humans. Lyons, France: International Agency for Research on Cancer, World Health Organization. http://publications.iarc.fr/Book-And-Report-Series/Iarc-Monographs-On-The-Identification-Of-Carcinogenic-Hazards-To-Humans/Benzene-2018.

IARC. 2012. Monographs on the Evaluation of Carcinogenic Risks to Humans, Volume 100F: Formaldehyde. International Agency for Research on Cancer.

IARC. 2006. Monographs on the Evaluation of Carcinogenic Risks to Humans, Volume 88: Formaldehyde, 2-Butoxyethanol and 1-tert-Butoxypropan-2-ol. International Agency for Research on Cancer.

IARC. 2002. Monographs on the Evaluation of the Carcinogenic Risk of Chemicals for Humans. Lyons, France: International Agency for Research on Cancer .

IARC. 2021. Monographs on the Identification of Carcinogenic Hazards to humans, Volume 128. Acrolein, Crotonaldehyde, and Arecoline. Lyons, France: International Agency for Research on Cancer, World Health Organization.

IARC. 1999. Re-evaluation of some organic chemicals, hydrazine, and hydrogen peroxide. Lyon, France: IARC Monographs on the Evaluation of Carcinogenic Risk of Chemical to Humans Vol. 71.

IPCS. 2002. Concise International Chemical Assessment Document 40. Formaldehyde. World Health Organization.

Irons, R.D., W.S. Stillman, D.B. Colagiovanni, and V.A. Henry. 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.

Irving, P.M. 1991. Acidic deposition: State of science and technology. Vols I-IV. Washington, DC: The U.S. National Acid Precipitation Assessment Program, 24-76.

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.

Joslin, J.D., Kelly, J.M., and van Miegroet, H. 1992. "Soil chemistry and nutrition of North American spruce-fir stands: evidence for recent change." Journal of Environmental Quality 21: 12-30.

Kammerbauer, H., H. Selinger, R. Rommelt, A. Ziegler-Jons, D. Knoppik, and B. Hock. 1987. "Toxic components of motor vehicle emissions for the spruce Picea abies." Environ. Pollut. 48: 235-243.

Kan, H., G. Heiss, K.M. Rose, and 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.

Karner, A.A., D.S. Eisinger, and D.A. Niemeier. 2014. "Near-roadway air quality: synthesizing the findings from real-world data." Environ Sci Technol 44: 5334-5344.

Keller, KA, and CA. Snyder. 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.

Keller, KA, and CA. Snyder. 1986. "Mice exposed in utero to low concentrations of benzene exhibit enduring changes in their colony forming hematopoietic cells." Toxicology 42: 171-181.

Kimbrough, S., R.C. Owen, M. Snyder, and J. Richmond-Bryant. 2017. "NO to NO2 Conversion Rate Analysis and Implications for Dispersion Model Chemistry Methods using Las Vegas, Nevada Near-Road Field Measurements." Atmos Environ 165: 23-24.

Kimbrough, S., R.W. Baldauf, G.S.W. Hagler, R.C. Shores, W. Mitchell, D.A. Whitaker, C.W. Croghan, and D.A. Vallero. 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.

Kimbrough, S., T. Palma, and R.W. Baldauf. 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.

Laden, F., J.E. Hart, T.J. Smith, M.E. Davis, and E. Garshick. 2007. "Cause-specific mortality in the unionized U.S. trucking industry." Environmental Health Perspect 115: 1192-1196.

Lan, Qing, L. Zhang, G. Li, and R., et al. Vermeulen. 2004. "Hematotoxically in Workers Exposed to Low Levels of Benzene." Science 306: 1774-1776.

Landers, DH, SL Simonich, DA Jaffe, LH Geiser, DH Campbell, AR Schwindt, CB Schreck, et al. 2008. The Fate, Transport and Ecological Impacts of Airborne Contaminants in Western National Parks (USA). EPA/600/R-07/138. Corvallis, Oregon: U.S. Environmental Protection Agency, Office of Research and Development, NHEERL, Western Ecology Division.

Li, C., Q. N, and P.H. Ryan. 2009. "School bus pollution and changes in the air quality at schools: a case study." J Environ Monit 11: 1037-1042.

Liu, W., J. Zhang, J.l Kwon, and et al. 2006. "Concentrations and source characteristics of airborne carbonyl compounds measured outside urban residences." J Air Waste Manage Assoc 56: 1196-1204.

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.

Malm, William. 2016. Visibility – The Seeing of Near and Distant Landscape Features. Elsevier.

McConnell, R., T. Islam, K. Shankardass, and et al. 2010. "Childhood incident asthma and traffic-related air pollution at home and school." Environ Health Perspect 1021-1026.

McDonald, B.C., Z.C. McBride, E.W. Martin, and R.A. Harley. 2014. "High-resolution mapping of motor vehicle carbon dioxide emissions." J. Geophys. Res.Atmos 119: 5283–5298. doi:10.1002/2013JD021219.

Morris JB, Symanowicz PT, Olsen JE, and et al. 2003. "Immediate sensory nerve-mediated respiratory responses to irritants in healthy and allergic airway-diseased mice." J Appl Physiol 94 (4): 1563-1571.

Myou, S., M. Fujimura, Nishi K., T. Ohka, and T. and Matsuda. 1993. "Aerosolized acetaldehyde induces histamine-mediated bronchoconstriction in asthmatics." Am. Rev. Respir. Dis 148 (4 Pt 1): 940-943.

NASEM. 2019. Climate Change and Ecosystems. Washington, DC: National Academy of Sciences, The National Academies Press. https://nap.nationalacademies.org/catalog/25504/climate-change-and-ecosystems.

Niklinska, M, R Laskowski, and M. Maryanski. 1998. "Effect of heavy metals and storage time on two types of forest litter: basal respiration rate and exchangeable metals." Ecotoxicological Environmental Safety 41: 41.

NOAA. 2021. State of the Climate: Global Climate Report for Annual 2020. National Centers for Environmental Information, National Oceanic and Atmospheric Administration. https://www.ncdc.noaa.gov/sotc/global/202013.

NRC. 1993. Protecting Visibility in National Parks and Wilderness Areas. Washington, DC: National Research Council, National Academy of Sciences Committee on Haze in National Parks and Wilderness Areas. https://nap.nationalacademies.org/initiative/committee-on-haze-in-national-parks-and-wilderness-areas.

NRC. 2011. Review of the Environmental Protection Agency’s Draft IRIS Assessment of Formaldehyde. Washington, DC: National Research Council, National Academies Press. http://books.nap.edu/openbook.php?record_id=13142.

NTP. 2019. NTP Monograph on the Systematic Review of Traffic-related Air Pollution and Hypertensive Disorders of Pregnancy. National Toxicology Program Monograph 7. https://ntp.niehs.nih.gov/ntp/ohat/trap/mgraph/trap_final_508.pdf.

NTP. 2016. Report on Carcinogens, Fourteenth Edition. Washington, DC: National Toxicology Program, U.S. Department of Health and Human Services, Public Health Service. https://ntp.niehs.nih.gov/go/roc14.

Oak Ridge Institute for Science and Education. 2004. "External Peer Review for the IRIS Reassessment of the Inhalation Carcinogenicity of Naphthalene." http://cfpub.epa.gov/ncea/cfm/recordisplay.cfm?deid=84403.

OEHHA, California. 2014. "TSD for Noncancer RELs: Appendix D. Individual, Acute, 8-Hour, and Chronic Reference Exposure Level Summaries." https://oehha.ca.gov/media/downloads/crnr/appendixd1final.pdf.

Olsson, Ann C., et al. 2011. "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): 941-948.

P.A., McKinney, F.E. Alexander, R.A. Cartwright, and et al. 1991. "Parental occupations of children with leukemia in west Cumbria, north Humberside, and Gateshead." Br. Med. J 302: 681-686.

Pedde, M., and C. Bailey. 2011. Identification of Schools within 200 Meters of U.S. Primary and Secondary Roads. Memorandum to the docket, U.S. Environmental Protection Agency.

Peters, A., S. von Klot, M. Heier, I. Trentinaglia, A. Hörmann, H.E. Wichmann, and H. Löwel. 2004. "Exposure to traffic and the onset of myocardial infarction." New England J Med 351: 1721-1730.

Peterson, D.E., M.S. Kanarek, M.A. Kuykendall, J.M. Diedrich, H.A. Anderson, P.L. Remington, and T.B. Sheffy. 1994. "Fish Consumption Patterns and Blood Mercury Levels in Wisconsin Chippewa Indians." Archives of Environmental Health 49 (1): 53–58.

Pinkerton, L. E. 2004. "Mortality among a cohort of garment workers exposed to formaldehyde: an update." Occup. Environ. Med. 61: 193-200.

Pope III et al., 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.

Power, M.C., M.G. Weisskopf, S.E. Alexeef, and et al. 2011. "Traffic-related air pollution and cognitive function in a cohort of older men." Environ Health Perspect 682-687.

Qu, O., R. Shore, G. Li, X. Jin, C.L. Chen, B. Cohen, A. Melikian, et al. 2003. Validation & Evaluation of Biomarkers in Workers Exposed to Benzene in China HEI Report 115. Health Effects Institute .

Qu, Q., R. Shore, G. Li, X. Jin, L.C. Chen, and et al. B. Cohen. 2002. "Hematological changes among Chinese workers with a broad range of benzene exposures." American Journal of Industrial Medicine 42: 275-285.

Raaschou-Nielsen, O., and P Reynolds. 2006. "Air pollution and childhood cancer: a review of the epidemiological literature." Int J Cancer 118: 2920-2929.

Reidmiller, D.R., C.W. Avery, D.R. Eastering, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart. 2018. Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II. Washington, DC: U.S. Global Change Research Program. https://nca2018.globalchange.gov.

Riddell, J., T.H. Nash, and P. Padgett. 2008. "The effect of HNO3 gas on the lichen Ramalina menziesii." Flora - Morphology, Distribution, Functional Ecology of Plants 203 (1): 47-54.

Riediker, M. 2007. "Cardiovascular effects of fine particulate matter components in highway patrol officers." Inhal Toxicol 19: 99-105.

Riediker, M., W.E. Cascio, T.R. Griggs, and et al. 2004. "Particulate matter exposure in cars is associated with cardiovascular effects in healthy young men." Am J Respir Crit Care Med 169.

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." American Journal of Industrial Medicine 29: 236-246.

Roy, J., P. Tschakert, H. Waisman, S. Abdul Halim, P. Antwi-Agyei, P. Dasgupta, B. Hayward, et al. 2019. 2018: Sustainable Development, Poverty Eradication and Reducing Inequalities. In: 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. Cambridge, UK and New York, NY: Intergovernmental Panel on Climate Change, Cambridge University Press.

S.P., Eckel., K. Berhane, M.T. Salam, and 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.

Sabin, L., E. Behrentz, A.M. Winer, and et al. 2005. "Characterizing the range of children's air pollutant exposure during school bus commutes." J Expo Anal Environ Epidemiol 15: 377-387.

Salam, M.T., T. Islam, and F.D. Gilliland. 2008. "Recent evidence for adverse effects of residential proximity to traffic sources on asthma." Curr Opin Pulm Med 14: 3-8.

Sarnat, J.A., A. Russell, D. Liang, J.L Moutinho, R. Golan, R. Weber, D. Gao, et al. 2018. Developing Multipollutant Exposure Indicators of Traffic Pollution: The Dorm Room Inhalation to Vehicle Emissions (DRIVE) Study. Health Effects Institute Research Report Number 196. https://www.healtheffects.org/publication/developing-multipollutant-exposure-indicators-traffic-pollution-dorm-room-inhalation.

Sheppard, EL (2022). 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). EPA-CASAC-22-001, March 18.

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.

Simcik, M.F, Eisenreich S.J., and P.J. Lioy. 1999. "Source apportionment and source/sink relationship of PAHs in the coastal atmosphere of Chicago and Lake Michigan." Atmospheric Environment 33: 5071-5079.

Simcik, M.F., S.J. Eisenreich, Golden K.A., S. Liu, E. Lipiatou, D.L. Swackhamer, and D.T.Environ. Sci. Technol. Long. 1996. "Atmospheric Loading of Polycyclic Aromatic Hydrocarbons to Lake Michigan as Recorded in the Sediments." Environ. Sci. Technol. 30 (10): 3039-3046.

Sisler, J.F. 1996. Spatial and seasonal patterns and long-term variability of the composition of the haze in the United States: an analysis of data from the IMPROVE network. CIRA Report, ISSN 0737-5352-32, Colorado State University.

Stenson, C., A.J. Wheeler, A. Carver, and et al. 2021. "The impact of traffic-related air pollution on child and adolescent academic performance: a systematic review." Environ Intl 155: 106696.

Sun, X., S. Zhang, and X. Ma. 2014. "No association between traffic density and risk of childhood leukemia: a meta-analysis." Asia Pac J Cancer Prev 15: 5229-5232.

Title 40 CFR Part 50. 2023. https://www.ecfr.gov/current/title-40/chapter-I/subchapter-C/part-50.

Title 40 CFR Part 53. 2023. https://www.ecfr.gov/current/title-40/chapter-I/subchapter-C/part-53.

Title 40 CFR Part 58. 2023. https://www.ecfr.gov/current/title-40/chapter-I/subchapter-C/part-58.

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). 2016. "Long-term ozone exposure and mortality in a large prospective study." American Journal of Respiratory and Critical Care Medicine 193 (10): 1134-1142.

Turtletaub, K.W., and C. Mani. 2003. Benzene metabolism in rodents at doses relevant to human exposure from Urban Air. HEI Report 113. Health Effects Institutue.

Ugrekhelidze, D., F, Korte, and G. Kvesitadze. 1997. "Uptake and transformation of benzene and toluene by plant leaves." Ecotox. Environ. Safety 37: 24-29.

US DOT. 2023. Freight Analysis Framework. https://ops.fhwa.dot.gov/freight/freight_analysis/faf/.

US EPA. 2002. 1,3-Butadiene IRIS page. https://cfpub.epa.gov/ncea/iris2/chemicalLanding.cfm?substance_nmbr=139.

US EPA. 2022. 2018 AirToxScreen Risk Drivers. Washington, DC: U.S. Environmental Protection Agency. https://www.epa.gov/system/files/documents/2022-08/AirToxScreen%20Risk%20Drivers.pdf.

—. 2021. "2021 Policy on Children's Health." October 5. https://www.epa.gov/system/files/documents/2021-10/2021-policy-on-childrens-health.pdf.

US EPA. 2022. "2023 PM NAAQS Reconsideration Proposal RIA." EPA-HQ-OAR-2019-0587.

US EPA. 2006. "A Framework for Assessing Health Risks of Environmental Exposures to Children. EPA/600/R-05/093F." Washinton, DC.

—. 2022. America's Children and the Environment. May 16. Accessed March 7, 2023. https://www.epa.gov/americaschildrenenvironment.

—. 2023. BenMAP-CE. Accessed March 10, 2023. https://github.com/BenMAPCE/BenMAP-CE.

US EPA. 2022. Derivation of an acute reference concentration for inhalation exposure to naphthalene. EPA/600/R-21/292. Washington, D.C.: U.S. Environmental Protection Agency. https://cfpub.epa.gov/ncea/risk/recordisplay.cfm?deid=355035.

US EPA. 1991. Drinking Water Criteria Document for Polycyclic Aromatic Hydrocarbons (PAHS). ECAO-CIN-0010. EPA Research and Development.

US EPA. 1991. Effects of organic chemicals in the atmosphere on terrestrial plants. EPA/600/3-91/001. Washington, DC: U.S. Environmental Protection Agency.

US EPA. 2023. "Estimating PM2.5- and Ozone-Attributable Health Benefits. Technical Support Document (TSD) for the 2023 PM NAAQS Reconsideration Proposal." EPA-HQ-OAR-2019-0587.

US EPA. 2021. "Estimating the Benefit per Ton of Reducing Directly-Emitted PM2.5, PM2.5 Precursors and Ozone Precursors from 21 Sectors." https://www.epa.gov/system/files/documents/2021-10/source-apportionment-tsd-oct-2021_0.pdf.

US EPA. 2018. "Estimating the Benefit per Ton of reducing PM2.5 Precursors from 17 Sectors." https://www.epa.gov/sites/default/files/2018-02/documents/sourceapportionmentbpttsd_2018.pdf.

US EPA. 2021. Estimation of Population Size and Demographic Characteristics among People Living Near Truck Routes in the Conterminous United States. Memorandum to the Docket, U.S. Environmental Protection Agency.

US EPA. 2016. Exposure Factors Handbook: 2011 Edition. Chapter 16. U.S. Environmental Protection Agency. https://www.epa.gov/sites/production/files/2015-09/documents/efh-Chapter16.pdf.

US EPA. 1990. Formaldehyde (CASRN 50-00-0) Chemical Assessment Summary. Washington, DC: U.S. Environmental Protection Agency, Integrated Risk Information Systems (IRIS). https://cfpub.epa.gov/ncea/iris2/chemicalLanding.cfm?substance_nmbr=419.

US EPA. 2009. Graphical Arrays of Chemical-Specific Health Effect Reference Values for Inhalation Exposures (Final Report) EPA/600/R-09/061. Washington, DC: U.S. Environmental Protection Agency. http://cfpub.epa.gov/ncea/cfm/recordisplay.cfm?deid=211003.

US EPA. 1999. Guidelines for Carcinogen Risk Assessment (Review Draft) NCEA-F-0644. Washinton, DC: U.S. Environmental Protection Agency. Accessed January 11, 2023. https://cfpub.epa.gov/ncea/risk/recordisplay.cfm?deid=54932.

US EPA. 2016. "Guidelines for Preparing Economic Analyses." Accessed March 10, 2023. https://www.epa.gov/sites/default/files/2017-08/documents/ee-0568-50.pdf.

US EPA. 2002. Health Assessment Document for Diesel Engine Exhaust. EPA/600/8-90/057F. Washington. DC: U.S. Environmental Protection Agency.

US EPA. 2002. "Health Assessment of 1,3-Butadiene." EPA 600-P-98-001F.

US EPA. 2000. Integrated Risk Information System File for Benzene. Washington, DC: U.S. Environmental Protection Agency. https://cfpub.epa.gov/ncea/iris2/chemicalLanding.cfm?substance_nmbr=276.

US EPA. 1991. Integrated Risk Information System File for Ethylbenzene. Washington, D.C.: U.S. Environmental Protection Agency. https://iris.epa.gov/ChemicalLanding/&substance_nmbr=51.

US EPA. 1991. Integrated Risk Information System File of Acetaldehyde. Washington, D.C.: Research and Development, National Center for Environmental Assessment, U.S. Environmental Protection Agency. https://cfpub.epa.gov/ncea/iris2/chemicalLanding.cfm?substance_nmbr=290.

US EPA. 2003. Integrated Risk Information System File of Acrolein. Washinton, D.C.: Research and Development, National Center for Environmental Assessment, U.S. Environmental Protection Agency. http://www.epa.gov/iris/subst/0364.htm.

US EPA. 2010. Integrated Science Assessment (ISA) for Carbon Monoxide (Final Report) EPA/600/R-09/019F. Washington, DC: U.S. Environmental Protection Agency.

US EPA. 2020. Integrated Science Assessment (ISA) for Oxides of Nitrogen, Oxides of Sulfur and Particulate Matter Ecological Criteria (Final Report) EPA/600/R-20/278. Washington, D.C.: U.S. Environmental Protection Agency.

US EPA. 2020. Integrated Science Assessment (ISA) for Ozone and Related Photochemical Oxidants (Final Report) EPA/600/R-20/012. Washington, DC: US Environmental Protection Agency.

US EPA. 2019. "Integrated Science Assessment (ISA) for Particulate Matter (Final Report)." Office of Research and Development, Center for Public Health and Environmental Assessment EPA-HQ-OAR-2020-0272.

US EPA. 2017. Integrated Science Assessment (ISA) for Sulfur Oxides - Health Criteria (Final Report) EPA/600/R-17/451. Washington, DC: U.S. Environmental Protection Agency.

—. 2016. "Integrated Science Assessment for Oxides of Nitrogen - Health Criteria (Final Report)." National Center for Environmental Assessment, Research Triangle Park, NC. July. https://cfpub.epa.gov/ncea/isa/recordisplay.cfm?deid=310879.

US EPA. 2019. "Integrated Science Assessment for Particulate Matter (Final Report) EPA/600/R-06/129F." Washington, DC, Ch 4 "Overall Conclusions" p. 4-1.

US EPA. 2009. Integrated Science Assessment for Particulate Matter (Final Report) EPA/600/R-08/139F. Washinton, D.C.: U.S. Environmental Protection Agency.

—. 2023. IRIS - Naphthalene CASRN 91-20-3. https://cfpub.epa.gov/ncea/iris_drafts/recordisplay.cfm?deid=340791.

US EPA. 2017. IRIS Assessment Plan for Ethylbenzene. EPA/635/R-17/332. Washington, D.C.: U.S. Environmental Protection Agency. https://cfpub.epa.gov/ncea/iris_drafts/recordisplay.cfm?deid=337468.

US EPA. 2022. IRIS Program Outlook. Washington, D.C.: U.S. Environmental Protection Agency. https://www.epa.gov/system/files/documents/2022-06/IRIS%20Program%20Outlook_June22.pdf.

US EPA. 2021. IRIS Toxicological Review of Formaldehyde-Inhalation (Interagency Science Consultation Draft, 2021) EPA/635/R-21/286. Washington, DC: U.S. Environmental Protection Agency.

US EPA. 2009. Metabolically-derived ventilation rates: A revised approach based upon oxygen consumption rates EPA/600/R-06/129F. Washington, DC: Office of Research and Development. http://cfpub.epa.gov/ncea/cfm/recordisplay.cfm?deid=202543.

US EPA. 2022. Policy Assessment (PA) for the Reconsideration of the National Ambient Air Quality Standards for Particulate Matter (Final Report) EPA/452/R-22-004. Washington, D.C.: U.S. Environmental Protection Agency.

US EPA. 2020. Policy Assessment (PA) for the Review of the National Ambient Air Quality Standards for Particulate Matter (Final Report) EPA/452/R-20/002. Washington DC: US EPA.

—. 2019. "Reduced Form Evaluation Project Report." https://www.epa.gov/benmap/reduced-form-evaluation-project-report.

—. 2017. "SAB Review of EPA’s Proposed Methodology for Updating Mortality Risk Valuation Estimates for Policy Analysis." https://nepis.epa.gov/Exe/ZyPDF.cgi/P100ROQR.PDF?Dockey=P100ROQR.PDF.

US EPA. 2022. "Supplement to the 2019 Integrated Science Assessment for Particulate Matter (Final Report)." Office of Research and Development, Center for Public Health and Environmental Assessment EPA-600-R-19-188.

US EPA. 2005. Supplemental guidance for assessing susceptibility from early-life exposure to carcinogens. EPA/630/R-03/003F. Washington, DC: Risk Assessment Forum. https://www3.epa.gov/airtoxics/childrens_supplement_final.pdf.

US EPA. 2022. Technical Support Document (TSD) EPA Air Toxics Screening Assessment (2017AirToxScreen). Washington, D.C.: U.S. Environmental Protection Agency. https://www.epa.gov/system/files/documents/2022-03/airtoxscreen_2017tsd.pdf.

US EPA. 2023. "Technical Support Document: Estimating the Benefit per Ton of Reducing Directly-Emitted PM2.5, PM2.5 Precursors and Ozone Precursors from 21 Sectors."

US EPA. 2003. Toxicological review of acrolein in support of summary information on Integrated Risk Information System (IRIS) National Center for Environmental Assessment EPA/635/R-03/003. Washington, D.C.: National Center for Environmental Assessment, U.S. Environmental Protection Agency. http://www.epa.gov/ncea/iris/toxreviews/0364tr.pdf.

US EPA. 2002. Toxicological Review of Benzene (Noncancer Effects) EPA/635/R-02/001F. Washington, DC: U.S. Environmental Protection Agency, Integrated Risk Information System (IRIS), National Center for Environmental Assessment.

US EPA. 2017. Toxicological Review of Benzo[a]pyrene. Washington, DC: U.S. Environmental Protection Agency. https://cfpub.epa.gov/ncea/iris/iris_documents/documents/toxreviews/0136tr.pdf.

US EPA. 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. Washington, DC: U.S. Environmental Protection Agency. http://cfpub.epa.gov/ncea/iris_drafts/recordisplay.cfm?deid=223614.

US EPA. 1998. Toxicological Review of Naphthalene (Reassessment of the Inhalation Cancer Risk). Washington, D.C.: Environmental Protection Agency, Integrated Risk Information System, Research and Development, National Center for Environmental Assessment. https://cfpub.epa.gov/ncea/iris_drafts/recordisplay.cfm?deid=56434.

US EPA-SAB. 2005. "Advisory Council on Clean Air Compliance Analysis Response to Agency Request on Cessation Lag." EPA-COUNCIL-LTR-05-001. December. https://council.epa.gov/ords/sab/f?p=104:12:968651521971.

—. 2000. "An SAB Report on EPA's White Paper Valuing the Benefits of Fatal Cancer Risk Reduction." https://www.epa.gov/system/files/documents/2022-03/86189901_0.pdf.

Valigura, R.A, R.B. Alexande, M.S. Castro, T.P. Meyers, H.W. Paerl, P.E. Stacy, and R.E. Turner. 2001. Nitrogen Loading in Coastal Water Bodies: An Atmospheric Perspective. Washington, DC: American Geophysical Union.

Viskari, E.L. 2000. "Epicuticular wax of Norway spruce needles as indicator of traffic pollutant deposition." Water, Air, and Soil Pollut. 121: 327-337.

Volk, H.E., I. Hertz-Picciotto, L. Delwiche, and et al. 2011. "Residential proximity to freeways and autism in the CHARGE study." Environ Health Perspect 119: 873-877.

Wolfe, P., K. Davidson, C. Fulcher, N. Fann, M. Zawacki, and K. R. Baker. 2019. "Monetized Health Benefits Attributable to Mobile Source Emission Reductions across the United States in 2025." Science of the Total Environment (650): 2490-2498. doi:https://doi.org/10.1016/J.SCITOTENV.2018.09.273.

Wu et al., 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.

Wu, J., M. Wilhelm, J. Chung, and et al. 2011. "Comparing exposure assessment methods for traffic-related air pollution in and adverse pregnancy outcome study." Environ Res 111: 6685-6692.

Zanobetti, A., P.H. Stone, F.E. Spelzer, J.D. Schwartz, B.A. Coull, H.H. Suh, B.D. Nearling, M.A. Mittleman, R.L. Verrier, and D.R. Gold. 2009. "T-wave alternans, air pollution and traffic in high-risk subjects." Am J Cardiol 104: 665-670.

Zhang, J., J.E. McCreanor, P. Cullinan, and et al. 2009. "Health effects of real-world exposure diesel exhaust in persons with asthma." Res Rep Health Effects Inst 138.

Chapter 8: Illustrative Analysis of Air Quality Impacts of a Light- and Medium-Duty Vehicles Regulatory Scenario

EPA conducted an illustrative air quality modeling analysis of a regulatory scenario involving light- and medium-duty "onroad" vehicle emission reductions and corresponding changes in “upstream” emission sources like EGU (electric generating unit) emissions and refinery emissions. Decisions about the emissions and other elements used in the air quality modeling were made early in the analytical process for the proposed rulemaking. Accordingly, the air quality analysis does not represent the proposal's regulatory scenario, nor does it reflect the expected impacts of the Inflation Reduction Act (IRA). Based on updated power sector modeling that incorporated expected generation mix impacts of the IRA (presented in Chapter 5), we are projecting the IRA will lead to a significantly cleaner power grid; because the air quality analysis presented here does not account for these impacts on EGU emissions, the location and magnitude of the changes in pollutant concentrations should be considered illustrative and not viewed as Agency projections of what we expect will be the total impact of the proposed standards. Nevertheless, the analysis provides some insights into potential air quality impacts associated with emissions increases and decreases from these multiple sectors.

This chapter presents a discussion of current air quality in Chapter 8.1, information about the inventory used in the illustrative air quality modeling analysis in Chapter 8.2, details related to the methodology used for the illustrative air quality modeling analysis in Chapter 8.3, results of the illustrative air quality modeling analysis in Chapter 8.4 and quantified and monetized benefits of the illustrative analysis in Chapter 8.5.

8.1 Current Air Quality

In this section we present information related to current air pollutant concentrations and deposition amounts. This provides context for the modeled projections of pollutants in the illustrative air quality analysis.

8.1.1 $PM_{2.5}$ Concentrations

As described in Chapter 7 of this DRIA, PM causes adverse health effects, and EPA has set NAAQS to protect against those health effects. There are two primary NAAQS for $PM_{2.5}$: an annual standard (12.0 micrograms per cubic meter ($\mu g/m^3$)) and a 24-hour standard (35 $\mu g/m^3$), and there are two secondary NAAQS for $PM_{2.5}$: an annual standard (15.0 $\mu g/ m^3$) and a 24-hour standard (35 $\mu g/m^3$). The initial $PM_{2.5}$ standards were set in 1997 and revisions to the standards were finalized in 2006 and in December 2012, and then retained in 2020. On January 6, 2023, EPA announced its proposed decision to revise the PM NAAQS. (US EPA 2023)

There are many areas of the country that are currently in nonattainment for the annual and 24-hour primary $PM_{2.5}$ NAAQS. As of December 31, 2022, more than 19 million people lived in the 4 areas that are designated as nonattainment for the 1997 annual $PM_{2.5}$ NAAQS. (US EPA 2022) Also, as of December 31, 2022, more than 31 million people lived in the 11 areas that are designated as nonattainment for the 2006 24-hour $PM_{2.5}$ NAAQS, and more than 20 million people lived in the 5 areas designated as nonattainment for the 2012 annual $PM_{2.5}$ NAAQS. (US EPA 2022) (US EPA 2022) In total, there are currently 13 $PM_{2.5}$ nonattainment areas with a population of more than 31 million people. (US EPA 2022)[147] Nonattainment areas for the $PM_{2.5}$ NAAQS are pictured in Figure 8-1.

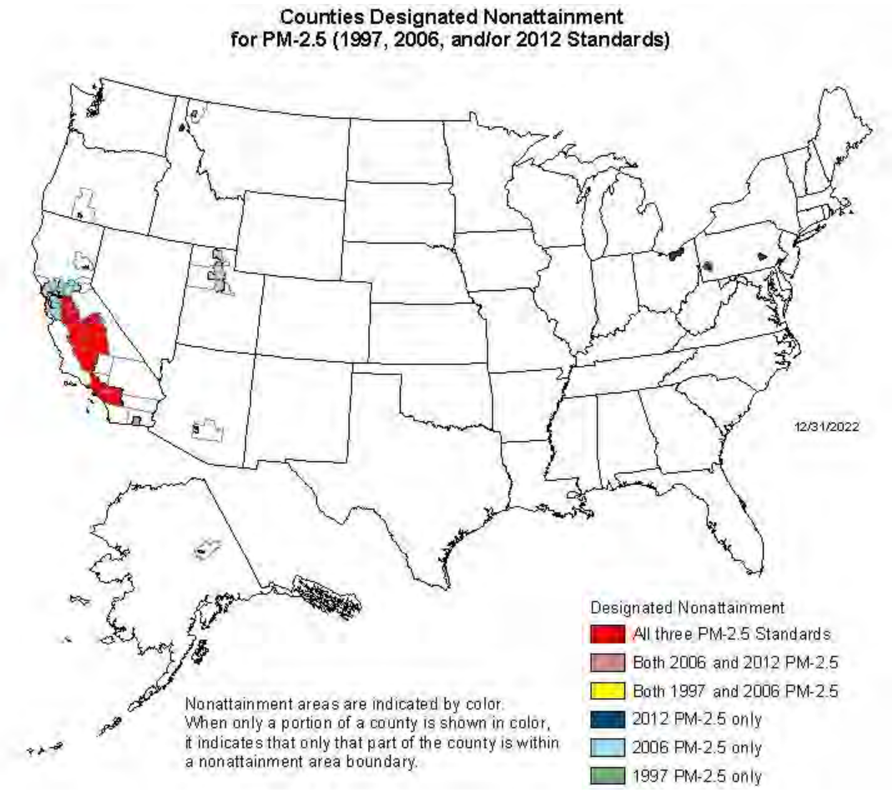

Figure 8-1: Counties designated nonattainment for $PM_{2.5}$ (1997, 2006, and/or 2012 standards).

8.1.2 <u>Ozone Concentrations</u>

As described in Chapter 7 of this DRIA, ozone causes adverse health effects, and EPA has set national ambient air quality standards (NAAQS) to protect against those health effects. The primary NAAQS for ozone, established in 2015 and retained in 2020, is an 8-hour standard with a level of 0.07 ppm. (US EPA 2020) EPA recently announced that it will reconsider the decision to retain the ozone NAAQS. (US EPA 2022) EPA is also implementing the previous 8-hour ozone primary standard, set in 2008 at a level of 0.075 ppm. As of December 31, 2022, there were 34 ozone nonattainment areas for the 2008 primary ozone NAAQS, composed of 133 full or partial counties, with a population of more than 90 million (see Figure 8-2); there were 49 ozone nonattainment areas for the 2015 primary ozone NAAQS, composed of 203 full or partial counties, with a population of more than 125 million (see Figure 8-3). (US EPA 2022) (US EPA

[147] The population total is calculated by summing, without double counting, the 1997, 2006 and 2012 PM2.5 nonattainment populations contained in the Criteria Pollutant Nonattainment Summary report (https://www.epa.gov/green-book/green-book-data-download).

2022) In total, there were, as of December 31, 2022, 56 ozone nonattainment areas with a population of more than 122 million people. (US EPA 2022).[148]

Figure 8-2: 8-Hour ozone nonattainment areas (2008 Standard).

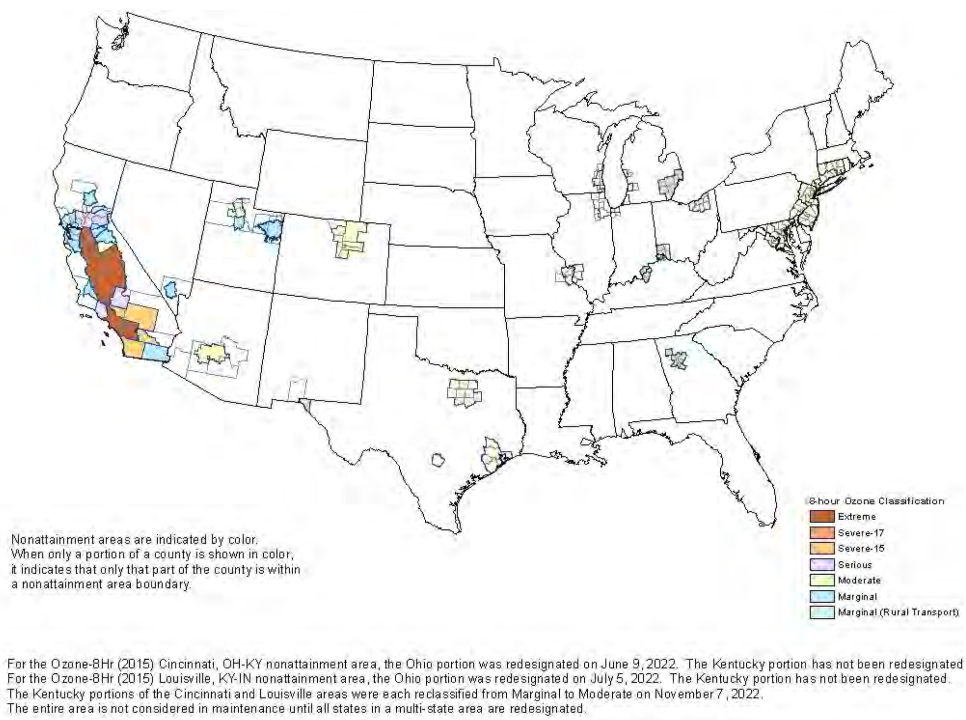

Figure 8-3: 8-Hour ozone nonattainment areas (2015 Standard).

[148] The total population is calculated by summing, without double counting, the 2008 and 2015 ozone nonattainment populations contained in the Criteria Pollutant Nonattainment Summary report (https://www.epa.gov/green-book/green-book-data-download).

8.1.3 NO_2 Concentrations

There are two primary NAAQS for NO_2: an annual standard (53 ppb) and a 1-hour standard (100 ppb).[149] In 2010, EPA established requirements for monitoring NO_2 near roadways expected to have the highest concentrations of NO_2 within large cities. Monitoring within this near-roadway network began in 2014, with additional sites deployed in the following years. At present, there are no nonattainment areas for NO_2.

8.1.4 SO_2 Concentrations

The primary NAAQS for SO_2 is a 1-hour standard (95 ppb).[150] As of Dec 31, 2022, there are 40 counties that make up 30 SO_2 nonattainment areas, with a population of over 2 million people. (US EPA 2022).

Figure 8-4: counties designated nonattainment for SO_2 (2010 standard).

8.1.5 CO Concentrations

There are two primary NAAQS for CO: an 8-hour standard (9 ppm) and a 1-hour standard (35 ppm). There are currently no CO nonattainment areas; as of September 27, 2010, all CO nonattainment areas had been redesignated to attainment.

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[149] The statistical form of the 1-hour NAAQS for NO2 is the 3-year average of the yearly distribution of 1-hour daily maximum concentrations.

[150] The statistical form of the 1-hour NAAQS for SO_2 is the 3-year average of the 99th percentile of 1-hour daily maximum concentrations.

8.1.6 Air Toxics Concentrations

The most recent available data indicate that millions of Americans live in areas where air toxics pose potential health concerns. (US EPA 2022) 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. (US EPA 2007) According to EPA's Air Toxics Screening Assessment (AirToxScreen) for 2018, mobile sources were responsible for 40 percent of outdoor anthropogenic toxic emissions and were the largest contributor to national average cancer and noncancer risk from directly emitted pollutants. (US EPA 2018)[151] Mobile sources are also significant contributors to precursor emissions which react to form air toxics. (Cook, et al. 2020) Formaldehyde is the largest contributor to cancer risk of all 71 pollutants quantitatively assessed in the 2018 AirToxScreen. Mobile sources were responsible for 26 percent of primary anthropogenic emissions of this pollutant in 2018 and are significant contributors to formaldehyde precursor emissions. Benzene is also a large contributor to cancer risk, and mobile sources account for about 60 percent of average exposure to ambient concentrations.

8.1.7 Deposition

Over the past two decades, the EPA has undertaken numerous efforts to reduce nitrogen and sulfur deposition across the U.S. Analyses of monitoring data for the U.S. show that deposition of nitrogen and sulfur compounds has decreased over the last 25 years. At 34 long-term monitoring sites in the eastern U.S., where data are most abundant, average total nitrogen deposition decreased by 43 percent between 1989-1991 and 2014-2016. (US EPA 2022) Although total nitrogen deposition has decreased over time, many areas continue to be negatively impacted by deposition.

8.2 Emissions Modeling for Illustrative Air Quality Analysis

Air pollution emission inventories are an important input to air quality modeling (AQM). This section describes the modeled changes to onroad emissions from light- and medium-duty vehicles, as well as modeled emission changes from "upstream" sectors like electricity generating units (EGUs) and refineries. Emission inventories for unchanging sectors are detailed in the air quality modeling technical support document (AQM TSD). (US EPA 2023)

For this analysis, air quality modeling was performed for a 2016 base case, a 2055 reference case, and a 2055 light- and medium duty vehicle (LMDV) regulatory case. The "reference" scenario represents projected 2055 emissions and air quality without any additional LMDV controls. The proposal scenario had not been determined at the time of the inventory modeling for the air quality analysis, so the "LMDV regulatory case" is illustrative and does not represent the specifics of the proposed rule. The illustrative LMDV regulatory case assumes a light- and medium-duty fleet that phased-in to reach 50 percent of new vehicle sales as BEVs in 2030 and remained constant at about 50 percent BEVs sales for model years 2030-2055, for a total national light duty vehicle population of 48% BEVs in 2055. The regulatory case also assumes a phase-in

[151] 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.

of gasoline particulate filters for gasoline vehicles beginning in model year 2027. The emissions used for the 2055 LMDV regulatory case were the same as those in the 2055 reference scenario for all emissions sectors except for onroad mobile source emissions, EGU emissions, and petroleum sector emissions (specifically refineries, crude oil production well sites and natural gas production well sites). The net changes in emissions for these sectors is summarized in Table 8-12 below. Air quality modeling was done for the future year 2055 when the LMDV regulatory scenario would be fully implemented and when most of the regulated fleet would have turned over.

The CMAQ air quality model requires hourly emissions of specific gas and particle species for the horizontal and vertical grid cells contained within the modeled region (i.e., modeling domain). Additional information on projecting air quality model-ready emissions is included in the AQM TSD.

8.2.1 Onroad Vehicle Emission Estimates with MOVES

8.2.1.1 Overview

EPA's MOtor Vehicle Emission Simulator (MOVES) is a state-of-the-science emissions modeling system that estimates air pollution emissions for criteria air pollutants, greenhouse gases and air toxics. MOVES covers light, medium and heavy-duty onroad vehicles such as cars, trucks, and buses, and other mobile sources. MOVES accounts for the phase-in of federal emissions standards, vehicle and equipment activity, fuels, temperatures, humidity, and emission control activities such as inspection and maintenance (I/M) programs (US EPA 2020). Unlike the OMEGA model described elsewhere in the DRIA, MOVES can be used to estimate emissions for specific counties as done here to capture geographical and temporal variation in onroad vehicle emissions.

8.2.1.2 MOVES version used for air quality modeling

To generate the onroad emission inventories used for this illustrative air quality modeling analysis, we updated the public MOVES3.0 model to create MOVES3.R1, an internal regulatory version which incorporates the latest vehicle activity data, newer emission rules, and changes that reflect improvements in our understanding of vehicle emissions and adds features to better model electric vehicles. In particular, we updated light-duty energy consumption and light- and heavy-duty national average electric vehicle fractions to reflect EPA's Revised 2023 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions Standards, (86 FR 74434 2021) and CARB's Advanced Clean Trucks regulation. (Advanced Clean Trucks 2021) We did not consider implications of the Inflation Reduction Act since our analysis was completed before the Act was passed.

The changes to MOVES code and defaults from MOVES3 to MOVES3.R1 are detailed in a docket memo. (Beardsley 2023) MOVES3.R1 updates were peer reviewed under EPA's peer review policy. (US EPA 2015) (US EPA 2023) Developing onroad inventories for the LMDV regulatory case required additional revised inputs as described in Section 8.2.1.3.

County-specific age distributions and fuel mix inputs were derived to preserve current differences between counties, such that counties with newer-than-average vehicle fleets and more light-duty electric vehicles than average in calendar year 2020 also have newer fleets and more electric vehicles in calendar year 2055. Additional detail is provided in the AQM TSD.

8.2.1.3 Modeling the Regulatory Case with MOVES

The regulatory case was modeled with a light- and medium-duty fleet that phased-in new vehicle BEV sales to reach 50 percent in 2030 and remain constant at about 50 percent sales for model years 2030-2055. We assumed no net improvement in average CO_2 emissions for light-duty vehicles; for HC and NO_x emissions, we modeled an ICEV emission cap at model year 2026 levels. For PM, we modeled reduced LD gasoline vehicle organic carbon and elemental carbon rates consistent with predicted impact of gasoline particulate filters based on OTAQ literature review and testing as described in 8.2.1.3.4.1. More details on each of these changes are provided below.

8.2.1.3.1 EV sales and stock

The regulatory case EV penetrations (fraction of new sales) for light-duty passenger cars and light-duty trucks were modeled in MOVES based on OMEGA EV outputs for a pre-IRA scenario. These penetrations are fleet wide BEV penetration by model years separately for light-duty passenger cars and light-duty trucks. The passenger cars assume a constant BEV penetration of 48.45% for model year 2030 and beyond, whereas light-trucks have a constant BEV new sales penetration of 50.28% for model year 2030 and beyond.

For medium-duty class 2b and 3, the regulatory case was modeled assuming 55% of new sales are BEVs or FCEVs for model year 2035 and beyond.

The distribution of EV sales among counties was similar to the reference case and is discussed in detail in the AQM TSD.

Note that the impact of EV sales on vehicle age distributions was not modeled using MOVES.

8.2.1.3.2 ICEV Energy Consumption

For the regulatory case modeling, the ICEV energy rates (MY2027-MY2060) were adjusted to match rates from OMEGA modeling of a scenario where EV sales were mandated as described above, and ICEV rates were limited by light-duty fleet-wide averages that assume zero tailpipe CO2 g/mi for BEVs and allow averaging, banking, and trading between ICEVs and electric vehicles. This meant that average light-duty ICEV fuel efficiency decreased from the reference to the regulatory case. Energy consumption for medium-duty class 2b and 3 was modeled the same as in the reference case.

8.2.1.3.3 ICEV NMOG and NOx rates

The regulatory case cap on HC and NOx emissions was modeled by modifying MOVES inputs to indicate no averaging with electric vehicles. This effectively caps the emissions at the model year 2026 rate.

8.2.1.3.4 ICEV PM rates

PM emissions reductions were modeled for light-duty gasoline vehicles for model years 2027 and later. The modeled reductions were based on present-day gasoline particulate filters (GPFs) as the best current PM reduction technology. GPFs filter PM in the exhaust, thus directly reducing PM emissions. The filter effectiveness differs for Elemental Carbon (EC) PM (MOVES Pollutant ID 112) and for non-EC PM (MOVES pollutant ID 118). To model the addition of GPFs, we apply a proportional reduction to the relevant start and running exhaust PM emission rates. In this case, the reductions are applied to start and running emissions for light-duty cars and trucks for gasoline, diesel and E85 fuels (fuelTypeID in 1,2,5).[152] For class 2b and 3 trucks, the reductions were applied for gasoline trucks only. Note, for MY 2010 and later, the rates for class 2b and 3 diesel trucks already included reductions representing control from diesel particulate filters (DPFs).

8.2.1.3.4.1 PM emission reduction fractions

The reduction fractions applied to both elemental carbon (EC) and non-EC PM are derived from laboratory testing of a lightly loaded underfloor catalyzed gasoline particulate filter. (Bohac and Ludlum 2023) For that study, EC and organic carbon (OC) measurements were made using the NIOSH 870 method. Here we use the observed reduction in EC to determine the reduction fraction for the MOVES EC pollutant. We use the observed OC reduction as the reduction fraction to apply to the MOVES NonECPM pollutant. OC is not identical to NonECPM because OC measurements do not include information about other elemental components of the particulate matter such as hydrogen, nitrogen, oxygen, calcium, and metallic ash components. For modeling purposes, we assume that the other components of non-elemental PM are filtered by the GPF in the same proportion as the OC part.

The reduction factors for the start operating modes come from the study's 25°C FTP cycle tests. For running emissions excluding MOVES operating modes 30 and 40, the reduction factors come from averaging the results of the 60mph and HWFET tests. The reduction fractions for operating modes 30 and 40 are from the US06 test. Finally, to avoid computational issues that arise from setting emission factors to zero, reductions originally reported as 100% were adjusted to 99.9%. The final PM reductions by operating mode are summarized in Table 8-1 below

[152] While GPFs are relevant only for gasoline and E85 vehicles, in MOVES, the emission rates for light-duty gasoline vehicles are replicated to represent light-duty diesel. This has a negligible impact on calendar year 2055 emissions since we model the diesel fraction of the light-duty fleet as less than 0.002% for all model years after 2018."

Table 8-1: PM reduction by MOVES operating mode

Operating Modes	EC Reduction (%)	nonECPM Reduction (%)
0 - 29	99.9	75
30	98.5	80
33 - 39	99.9	75
40	98.5	80
101 - 108	99.9	91

8.2.1.3.4.2 PM reduction phase-in

To model the air quality modeling regulatory case, we applied the PM reduction phase-in fractions shown in Table 8-2.

Table 8-2: PM control fraction by MOVES reg class and model year

Model Year	Reg Class 20	Reg Class 30	Reg Class 41
2026	0	0	0
2027	0.5	0.25	0
2028	0.75	0.375	0
2029	1	0.5	0
2030+	1	1	1

The phase-in was combined with the reduction factors for each operating mode to create weighted reduction factors for each model year. Finally, the weighted reduction factors were applied to the original MOVES base emission rates to create a set of new, lower PM emission rates.

8.2.1.3.4.3 PM update for LEV rates

The phase-in described above overlaps with the California 1 mg/mile PM standard that is relevant for California and for other states that have adopted California requirements under Clean Air Act Section 177. Prior to phasing in GPF-equivalent PM rates, the rates in the MOVES emissionRateByAgeLEV table were lower than the rates in the MOVES default emissionRateByAge table. For passenger cars, the default values are lower than the LEV table values starting in model year 2027, and for light-duty trucks, the default values are lower starting in 2030. Therefore, for the regulatory case modeling, the emissionRateByAgeLEV table was updated by dropping the rates for those years where the new default emission rates are lower than the LEV rates.

8.2.2 Upstream Emission Estimates for AQ Modeling

This section describes emission estimates for the following "upstream" emission sources: EGU emissions (Chapter 8.2.2.1), refinery emissions (Chapter 8.2.2.2), emissions from crude oil production well sites and pipeline pumps (Chapter 8.2.2.3), and emissions from natural gas production well sites and pipeline pumps (Chapter 8.2.2.4). These are sources that change between the reference and LMDV regulatory case and are not onroad. The EGU emissions were modeled without including impacts from the IRA, and thus are larger than what we would expect if the IRA generation mix updates were included in the reference case.

In 2055, total upstream emissions in the LMDV regulatory case would be between 0.3% and 4.4% higher, depending on the pollutant, than the reference. This increase is driven by the increase in emissions from EGUs, but there are also increased emissions projected from natural gas production well sites and pipeline pumps, due to a projected increase in natural gas fueled EGUs. We also project a small decrease in emissions from refineries and crude production wells and pipeline pumps due to assumed activity decreases at refineries related to a decrease in demand for liquid fuels for light- and medium-duty vehicles. Table 8-3 presents the net impact of these emissions increases and decreases.

Table 8-3: Total upstream emissions increases in LMDV regulatory scenario in 2055

Pollutant	Reference Scenario (tons/yr)	LMDV Regulatory Scenario (tons/yr)	Emissions Increase (tons/yr)	% Difference
$PM_{2.5}$	92,358	94,533	2,174	2.4%
NO_X	920,948	933,078	12,130	1.3%
SO_2	326,492	340,772	14,279	4.4%
VOC	2,762,121	2,770,666	8,544	0.3%

There is uncertainty about the impact of reduced demand for petroleum fuels on refinery activity and emissions. For instance, refineries might export the volumes of gasoline and diesel fuel that would otherwise have been consumed in light- and medium-duty vehicles, absent this rulemaking. The illustrative air quality analysis assumes a decrease in refining activity in response to the reduced domestic demand for liquid fuels; however, Table 8-4 presents the net upstream emissions impacts if we had assumed no decrease in refinery activity.

Table 8-4: Total upstream emission increases in 2055 assuming no change in refinery emissions

Pollutant	Reference Scenario (tons/yr)	LMDV Scenario No Decrease in Refinery Activity(tons/yr)	Emissions Increase (tons/yr)	% Difference
$PM_{2.5}$	92,358	94,920	2,561	2.8%
NO_X	920,948	934,481	13,533	1.5%
SO_2	326,492	341,342	14,850	4.5%
VOC	2,762,121	2,771,736	9,615	0.3%

8.2.2.1 Electricity Generating Units (EGUs)

The EGU emissions inventories used in the illustrative air quality analysis were developed from output of the 2022 Reference Case run of the Integrated Planning Model (IPM). This version of IPM included EGU fleet information, and rules and regulations that were final at the time the IPM version was finalized, but not impacts due to the Inflation Reduction Act (IRA).[153]

[153] https://www.epa.gov/power-sector-modeling

More detail on the rules and regulations included in this version of IPM, as well as additional information on the IPM version, can be found in the AQM TSD. The TSD also includes a description of inputs to IPM used for the AQM analysis, including how electricity demand from PEVs was distributed by time of day.[154]

Emissions of select pollutants from EGUs in 2050 (representing 2055 levels) are shown in Table 8-5. The LMDV regulatory case causes an increase in all pollutants, which is expected as the regulatory scenario includes an increase in electric vehicles over what is included in the reference case. The IPM runs used in the proposal's OMEGA analysis were started after the IPM runs used for the air quality analysis and were able to account for some IRA impacts (see Chapter 5.2.3 for more detail). The IPM runs used in the OMEGA analysis projected EGU emissions in 2050 that are much smaller than what was projected for the illustrative air quality analysis (see Table 5-2 in this DRIA).

Table 8-5: EGU emissions increases in AQM inventories in 2055[155]

Pollutant	Reference Scenario (tons/yr)	LMDV Regulatory Scenario (tons/yr)	Emissions Increase (tons/yr)	% Difference
$PM_{2.5}$	54,589	57,033	2,444	4%
NO_X	232,631	243,010	10,379	4%
SO_2	197,668	212,643	14,975	8%
VOC	32,493	34,065	1,572	5%

8.2.2.2 Refineries

The refinery emission inventories used in the illustrative air quality analysis were developed from refinery emissions in the 2016v2 emissions modeling platform that were projected to 2050 using the reference case modeled by EIA in its 2021 Annual Energy Outlook (AEO). (US EIA 2021)[156] (US EPA 2022) Pollutant-specific adjustment factors were developed and then applied to the reference inventory to generate the reference scenario and the LMDV regulatory scenario inventory. These adjustment factors are presented in Table 8-6 and account for impacts on fuel demand that were not included in AEO2021. In the reference case the adjustment factors incorporated EPA's Revised 2023 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions Standards (86 FR 74434, December 30, 2021). In the LMDV regulatory scenario the adjustment factors incorporated assumptions about decrease in fuel demand due to the reduced demand for liquid fuel.

The relationship between AEO2021's low economic growth case and reference case was used to approximate the impact on the petroleum sector of reduced demand for refined products in 2050. The lower refined product demand of the low economic growth case is assumed to reflect

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[154] The regional charging load profiles described in DRIA Chapter 5 were not available at the time the IPM model runs were conducted for the AQM analysis. See the AQM TSD for a description of charging profiles used.
[155] IPM output for a set of years with the furthest out year being 2055. The 2050 output was used in the air quality analysis and was assumed to represent 2055 to avoid any "end of timeframe" issues with using the furthest out year output from the model.
[156] https://www.eia.gov/outlooks/aeo/

the types of changes that could be expected from the lower demand for refined product caused by the LMDV regulatory scenario. The impact on refinery and upstream crude oil production activity as modeled by EIA results in decreases in crude oil and refined product imports and is used to project how the domestic U.S. refining sector would be impacted by reductions in domestic demand for gasoline and diesel. Additional detail on how the adjustment factors were calculated is available in the AQM TSD.

Table 8-6: Adjustment factors to apply to 2050 refinery inventory

Pollutant	Reference Scenario	LMDV Regulatory Scenario
$PM_{2.5}$	0.897	0.877
NO_X	0.899	0.879
SO_2	0.901	0.881
VOC	0.906	0.887

Emissions decreases of select pollutants from refineries in 2055 are shown in Table 8-7. We recognize that there is significant uncertainty in the impact on refinery emissions due to decreased demand. If refineries do not decrease production in response to lower domestic demand (e.g., they increase exports), total upstream emissions impacts would be higher, as shown in Table 8-4.

Table 8-7: Refinery emissions decreases in AQM inventories in 2055

Pollutant	Reference Scenario (tons/yr)	LMDV Regulatory Scenario (tons/yr)	Emissions Decrease (tons/yr)	% Difference
$PM_{2.5}$	18,855	18,468	387	2%
NO_X	67,470	66,067	1,403	2%
SO_2	28,851	28,281	570	2%
VOC	56,946	55,876	1,070	2%

8.2.2.3 Crude Production Well Sites and Pipeline Pumps

The emission inventories for crude production well sites and associated pipeline pumps used in the illustrative air quality analysis were developed from emissions in the 2016v2 emissions modeling platform that were projected to 2050 using the reference case modeled by EIA in its 2021 Annual Energy Outlook (AEO). (US EIA 2021) [157] (US EPA 2022) Emissions were decreased (through application of an adjustment factor) to account for lower activity due to lower domestic demand for liquid fuels. The adjustment factors are presented in Table 8-8. Additional detail on how the adjustment factors were calculated is available in the AQM TSD.

Table 8-8: Adjustment factors to apply to 2050 crude production well and pipeline pump inventory

[157] https://www.eia.gov/outlooks/aeo/

Reference Scenario	LMDV Regulatory Scenario
0.992	0.990

Decreases in emissions of select pollutants from crude production well sites and pipeline pumps in 2055 are shown in Table 8-9.

Table 8-9: Crude production well site and pipeline pump decreases in AQM inventories in 2055

Pollutant	Reference Scenario (tons/yr)	LMDV Regulatory Scenario (tons/yr)	Emissions Decrease (tons/yr)	% Difference
$PM_{2.5}$	4,824	4,814	10	0.2%
NO_X	221,243	220,800	442	0.2%
SO_2	93,203	93,016	186	0.2%
VOC	1,455,550	1,452,639	2,911	0.2%

8.2.2.4 Natural Gas Production Well Sites and Pipeline Pumps

The emission inventories for natural gas production well sites and associated pipeline pumps used in the illustrative air quality analysis were developed from emissions in the 2016v2 emissions modeling platform that were projected to 2050 using the reference case modeled by EIA in its 2021 Annual Energy Outlook (AEO). (US EIA 2021) [158] (US EPA 2022) Emissions were increased (through application of an adjustment factor) to account for increased activity at natural gas production well sites and pipeline pumps consistent with increased demand for natural gas fueled EGUs. These adjustment factors are presented in Table 8-10. Additional detail on how the adjustment factors were calculated is available in the AQM TSD.

Table 8-10: Adjustment factors to apply to 2050 natural gas production well site and pipeline pump inventory

Reference Scenario	LMDV Regulatory Scenario
1.000	1.009

Increases in emissions of select pollutants from natural gas production well sites and pipeline pumps in 2055 are shown in Table 8-9.

Table 8-11: Natural gas production well and pipeline pump increases in AQM inventories in 2055

Pollutant	Reference Scenario (tons/yr)	LMDV Regulatory Scenario (tons/yr)	Emissions Increase (tons/yr)	% Difference

[158] https://www.eia.gov/outlooks/aeo/

$PM_{2.5}$	18,855	18,468	127	2%
NO_X	67,470	66,067	3,596	2%
SO_2	28,851	28,281	61	2%
VOC	56,946	55,876	10,954	2%

8.2.2.5 Limitations of the Upstream Inventory

There is considerable uncertainty with the upstream inventory (and thus the air quality modeling results) because it does not include impacts of the IRA on generation mix projections, which would impact the magnitude and location of EGU emissions as well as the projected natural gas production well site inventories. Incorporating IRA generation mix updates would decrease emissions from EGUs in the reference case, as turnover to cleaner power generation would be accelerated. Additionally, emission increases from EGUs and natural gas production wells in the regulatory case would be smaller due to increased availability of cleaner powered EGUs. As described in 8.2.2.1, the IPM runs used in the proposal's OMEGA analysis were started after the IPM runs used for the air quality analysis and were able to account for some IRA impacts, and projected proposal EGU emissions are much smaller than what was projected for the illustrative air quality analysis (see Table 5-2 and Table 8-5 in this DRIA).

The illustrative air quality analysis assumes that there is no change in mandated renewable fuel volumes and percentages, that refineries will decrease activity rather than export additional fuels, and that the decreased production occurs at the same rate at all refineries. In addition, projections out to 2055 inherently are less certain than projections that do not go out as far into the future.

The upstream emissions inventory does not account for all upstream sources related to vehicles, fuels, and electricity generation, such as charging infrastructure, storage of petroleum fuels, battery manufacture, etc.

8.2.3 Combined Onroad and Upstream Emission Impacts

Total onroad, upstream, and net emissions of select pollutants in 2055 are shown in Table 8-12. The LMDV regulatory case has less combined onroad and upstream emissions than the reference case for many pollutants, including $PM_{2.5}$, NO_X, and VOC, and more combined onroad and upstream emissions of SO_2. The net decreased emissions of $PM_{2.5}$, NO_X and VOC are driven by reductions in the onroad sector, while EGU emissions drive the net increase in SO_2 emissions. We expect that had we been able to include impacts of the IRA provisions that affect generation mix in the IPM runs used to generate EGU emissions for this air quality analysis, increases in SO_2 would be smaller or on net a decrease. DRIA Chapter 9.6.6 presents emissions impacts of the proposal that account for the IRA's projected impacts on the power sector, and these do show a net decrease in all pollutants in 2055.

Table 8-12: Net impacts[a] on criteria pollutant emissions from the LMDV regulatory scenario

	2055 AQM Reference Scenario (tons/yr)	2055 AQM LMDV Regulatory Scenario (tons/yr)	Net Emissions Impact (tons/yr)	Percent Change Emissions Impact

Pollutant	Onroad	Upstream	Total Onroad and Upstream	Onroad	Upstream	Total Onroad and Upstream		
PM2.5	35,737	92,358	128,096	26,833	94,533	121,365	-6,730	-6%
NOx	729,707	920,948	1,650,655	683,096	933,078	1,616,174	-34,481	-2%
SO2	7,280	326,492	333,772	7,112	340,772	347,884	14,111	4%
VOC	498,495	2,762,121	3,260,616	392,534	2,770,666	3,163,200	-97,417	-3%

[a] Emissions reductions are presented as negative numbers and emissions increases as positive numbers.

8.3 Air Quality Modeling Methodology

In this section we present information related to the methods used in the air quality analysis for this proposed rule. Additional information is available in the Air Quality Modeling Technical Support Document (AQM TSD). (US EPA 2023)

8.3.1 Air Quality Model

CMAQ is a non-proprietary computer model that simulates the formation and fate of photochemical oxidants, primary and secondary PM concentrations, acid deposition, and air toxics, over regional and urban spatial scales for given inputs of meteorological conditions and emissions. CMAQ includes numerous science modules that simulate the emission, production, decay, deposition and transport of organic and inorganic gas-phase and particle pollutants in the atmosphere. The CMAQ model is a well-known and well-respected tool and has been used in numerous national and international applications.[159] The air quality modeling completed for the rulemaking proposal used the 2016v2 platform with the most recent multi-pollutant CMAQ code available at the time of air quality modeling (CMAQ version 5.3.2).[160] The 2016 CMAQ runs utilized the CB6r3 chemical mechanism (Carbon Bond with linearized halogen chemistry) for gas-phase chemistry, and AERO7 (aerosol model with non-volatile primary organic aerosol) for aerosols. The CMAQ model is regularly peer-reviewed, CMAQ versions 5.2 and 5.3 beta were most recently peer-reviewed in 2019 for the U.S. EPA. (Versar, Inc 2019)

8.3.2 Model Domain and Configuration

The CMAQ modeling analyses used a domain covering the continental United States, as shown in Figure 8-5. This single domain covers the entire continental U.S. (CONUS) and large portions of Canada and Mexico using 12 km × 12 km horizontal grid spacing. The 2016 simulation used a Lambert Conformal map projection centered at (-97, 40) with true latitudes at 33 and 45 degrees north. The model extends vertically from the surface to 50 millibars (approximately 17,600 meters) using a sigma-pressure coordinate system with 35 vertical layers. Table 8-13 provides some basic geographic information regarding the CMAQ domains and Table 8-14 provides the vertical layer structure for the CMAQ domain.

Table 8-13: Geographic elements of domains used in air quality modeling

	CMAQ Modeling Configuration
Grid Resolution	12 km National Grid
Map Projection	Lambert Conformal Projection
Coordinate Center	97 deg W, 40 deg N

[159] More information available at: https://www.epa.gov/cmaq.

[160] Model code for CMAQ v5.3.2 is available from the Community Modeling and Analysis System (CMAS) at: http://www.cmascenter.org.

True Latitudes	33 deg N and 45 deg N
Dimensions	396 × 246 × 35
Vertical extent	35 Layers: Surface to 50 millibar level (see Table 8-14)

Table 8-14: Vertical layer structure for CMAQ domain

Vertical Layers	Sigma P	Pressure (mb)	Approximate Height (m)
35	0.0000	50.00	17,556
34	0.0500	97.50	14,780
33	0.1000	145.00	12,822
32	0.1500	192.50	11,282
31	0.2000	240.00	10,002
30	0.2500	287.50	8,901
29	0.3000	335.00	7,932
28	0.3500	382.50	7,064
27	0.4000	430.00	6,275
26	0.4500	477.50	5,553
25	0.5000	525.00	4,885
24	0.5500	572.50	4,264
23	0.6000	620.00	3,683
22	0.6500	667.50	3,136
21	0.7000	715.00	2,619
20	0.7400	753.00	2,226
19	0.7700	781.50	1,941
18	0.8000	810.00	1,665
17	0.8200	829.00	1,485
16	0.8400	848.00	1,308
15	0.8600	867.00	1,134
14	0.8800	886.00	964
13	0.9000	905.00	797
12	0.9100	914.50	714
11	0.9200	924.00	632
10	0.9300	933.50	551
9	0.9400	943.00	470
8	0.9500	952.50	390
7	0.9600	962.00	311
6	0.9700	971.50	232
5	0.9800	981.00	154
4	0.9850	985.75	115
3	0.9900	990.50	77
2	0.9950	995.25	38
1	0.9975	997.63	19
0	1.0000	1000.00	0

Figure 8-5: Map of the CMAQ 12 km modeling domain (noted by the purple box).

8.3.3 <u>Model Inputs</u>

The key inputs to the CMAQ model include emissions from anthropogenic and biogenic sources, meteorological data, and initial and boundary conditions. The emissions inputs are summarized above in Chapter 8.2.

The CMAQ meteorological input files were derived from simulations of the Weather Research and Forecasting Model (WRF) version 3.8 for the entire 2016 year. (Skamarock 2008) (US EPA 2019) The WRF Model is a state-of-the-science mesoscale numerical weather prediction system developed for both operational forecasting and atmospheric research applications. (National Center for Atmospheric Research 2022) The meteorological outputs from WRF were processed to create 12 km model-ready inputs for CMAQ using the Meteorology-Chemistry Interface Processor (MCIP) version 4.3. These inputs included hourly varying horizontal wind components (i.e., speed and direction), temperature, moisture, vertical diffusion rates, and rainfall rates for each grid cell in each vertical layer. (Byun, Ching and EPA 1999)

The boundary and initial species concentrations were provided by a northern hemispheric CMAQ modeling platform for the year 2016. (Henderson 2018) (Mathur 2017) The hemispheric-scale platform uses a polar stereographic projection at 108 km resolution to completely and continuously cover the northern hemisphere for 2016. Meteorology is provided by WRF v3.8. Details on the emissions used for hemispheric CMAQ can be found in the 2016 hemispheric emissions modeling platform TSD. (US EPA 2019) The atmospheric processing (transformation and fate) was simulated by CMAQ (v5.2.1) using the CB6r3 and the aerosol model with non-volatile primary organic carbon (AE6nvPOA). The CMAQ model also included the on-line windblown dust emission sources (excluding agricultural land), which are not always included in the regional platform but are important for large-scale transport of dust.

8.3.4 Model Evaluation

The CMAQ predictions for ozone, fine particulate matter, sulfate, nitrate, ammonium, organic carbon, elemental carbon, nitrogen and sulfur deposition, and specific air toxics (acetaldehyde, benzene, and formaldehyde) from the 2016 base scenario were compared to measured concentrations in order to evaluate the ability of the modeling platform to replicate observed concentrations. This evaluation was comprised of statistical and graphical comparisons of paired modeled and observed data. Details on the model performance evaluation, including a description of the methodology, the model performance statistics, and results, are provided in the AQM TSD. (US EPA 2023)

8.3.5 Model Simulation Scenarios

As part of our analysis for this rulemaking, the CMAQ modeling system was used to calculate annual $PM_{2.5}$ concentrations, 8-hour maximum average ozone season concentrations, annual NO_2, SO_2, and CO concentrations, annual and seasonal (summer and winter) air toxics concentrations, and annual nitrogen and sulfur deposition for each of the following emissions scenarios:

- 2016 base year
- 2055 reference
- 2055 light and medium duty regulatory scenario

We use the predictions from the CMAQ model in a relative sense by combining the 2016 base-year predictions with predictions from each future-year scenario and applying these modeled ratios to ambient air quality observations to estimate 8-hour ozone concentrations during the ozone season (May - Sept), daily and annual $PM_{2.5}$ concentrations, and visibility impairment for each of the 2055 scenarios. The ambient air quality observations are average conditions, on a site-by-site basis, for a period centered around the model base year (i.e., 2014-2018).

The projected annual $PM_{2.5}$ concentrations were calculated using the Speciated Modeled Attainment Test (SMAT) approach that utilizes a Federal Reference Method (FRM) mass construction methodology which results in reduced nitrates (relative to the amount measured by routine speciation networks), higher mass associated with sulfates (reflecting water included in FRM measurements), and a measure of organic carbonaceous mass that is derived from the difference between measured $PM_{2.5}$ and its non-carbon components. This characterization of $PM_{2.5}$ mass also reflects crustal material and other minor constituents. The resulting characterization provides a complete mass balance. It does not have any unknown mass that is sometimes presented as the difference between measured $PM_{2.5}$ mass and the characterized chemical components derived from routine speciation measurements. However, the assumption that all mass difference is organic carbon has not been validated in many areas of the U.S. The SMAT methodology uses the following $PM_{2.5}$ species components: sulfates, nitrates, ammonium, organic carbon mass, elemental carbon, crustal, water, and blank mass (a fixed value of 0.5 $\mu g/m^3$). More complete details of the SMAT procedures can be found in the report "Procedures for Estimating Future $PM_{2.5}$ Values for the CAIR Final Rule by Application of the (Revised) Speciated Modeled Attainment Test (SMAT)." (US EPA 2004) For this analysis, several datasets and techniques were updated. These changes are fully described within the technical support document for the Final Transport Rule AQM TSD. (US EPA 2011)

Additionally, we conducted an analysis to compare the absolute differences between the future year reference and regulatory scenario for annual and seasonal acetaldehyde, benzene, formaldehyde, and naphthalene, as well as annual NO_2, SO_2, CO, and nitrate/sulfate deposition. These data were not compared in a relative sense due to the limited observational data available.

8.4 Results of Illustrative Air Quality Analysis

EPA conducted an illustrative air quality modeling analysis of a regulatory scenario involving light- and medium-duty "onroad" vehicle emission reductions and corresponding changes in “upstream” emission sources like EGU (electric generating unit) emissions and refinery emissions. Decisions about the emissions and other elements used in the air quality modeling were made early in the analytical process for the proposed rulemaking. Accordingly, the air quality analysis does not represent the proposal's regulatory scenario, nor does it reflect the expected impacts of the Inflation Reduction Act (IRA). Based on updated power sector modeling that incorporated expected generation mix impacts of the IRA (presented in Chapter 5), we are projecting the IRA will lead to a significantly cleaner power grid; because the air quality analysis presented here does not account for these impacts on EGU emissions, the location and magnitude of the changes in pollutant concentrations should be considered illustrative and not viewed as Agency projections of what we expect will be the total impact of the proposed standards. Nevertheless, the analysis provides some insights into potential air quality impacts associated with emissions increases and decreases from these multiple sectors.

Given the considerable uncertainty associated with the upstream emissions inventory (see Chapter 8.2.2.5), we also modeled a sensitivity case that examined only the air quality impacts of the onroad emissions changes from the LMDV regulatory scenario. This "onroad-only" sensitivity case assumed no change in emissions from upstream sources and is based on the onroad emission inventories described in Chapter 8.2.1.

In this section, we summarize the results of our illustrative air quality modeling based on the projected emission impacts of the LMDV regulatory scenario as well as the onroad-only sensitivity case. Air quality modeling was done for the future year 2055 when the program would be fully implemented and when most of the regulated fleet would have turned over. The "reference" scenario represents projected 2055 air quality without the illustrative regulatory scenario and the "control" scenario represents projected 2055 emissions with the illustrative LMDV regulatory scenario. As described in Chapter 8.2, the illustrative LMDV regulatory scenario assumes a light- and medium-duty fleet that phased-in to reach 50 percent BEV sales in 2030 and remained constant at 50 percent sales for model years 2030-2055 and a phase-in of gasoline particulate filters beginning in model year 2027.

8.4.1 PM$_{2.5}$

This section summarizes projected changes in PM$_{2.5}$ concentrations in 2055 from the LMDV regulatory scenario. As noted in Chapter 8.4, this analysis is illustrative and the location and magnitude of concentration changes between the reference case and the LMDV regulatory scenario are uncertain, particularly because the analysis does not account for the cleaner power grid we expect to result from the IRA. Figure 8-6 presents the absolute changes in annual average PM$_{2.5}$ concentrations in 2055 between the reference and LMDV regulatory scenarios and indicates that there would be widespread decreases, and in some areas there would be increases.

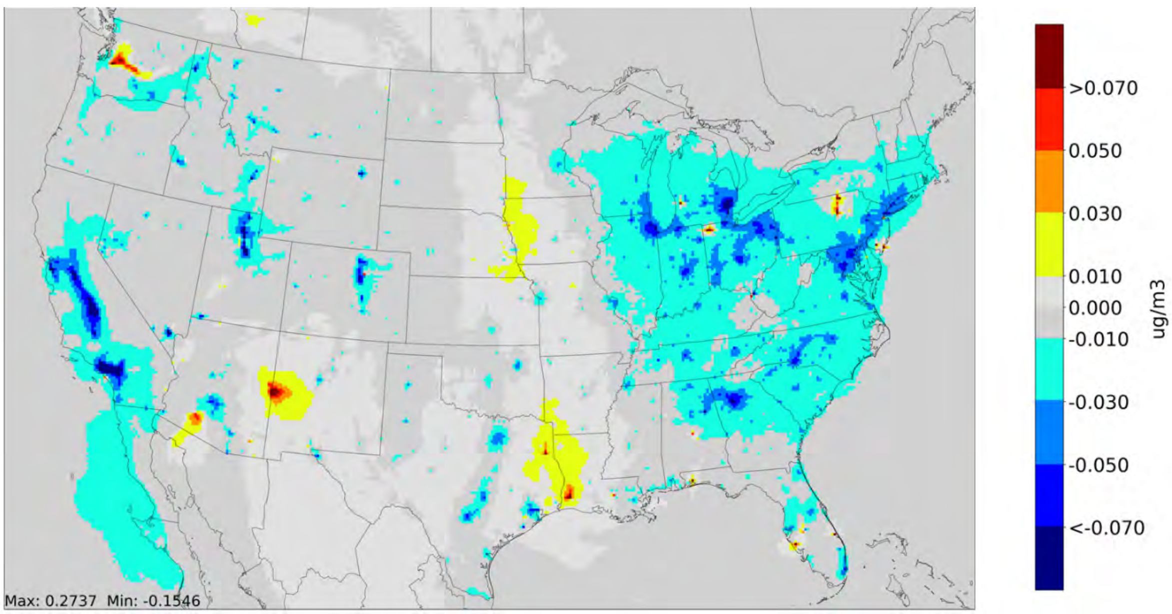

Figure 8-6: Projected illustrative changes in annual average PM$_{2.5}$ concentrations in 2055 due to LMDV regulatory scenario.

The LMDV regulatory scenario would decrease annual average PM$_{2.5}$ concentrations by an average of 0.01 $\mu g/m^3$ in 2055, with a maximum decrease of 0.16 $\mu g/m^3$ and a maximum increase of 0.27 $\mu g/m^3$. The population-weighted average change in annual average PM$_{2.5}$ concentrations would be 0.03 $\mu g/m^3$ in 2055.

We also modeled an "onroad-only" sensitivity case. Figure 8-7 presents the absolute changes in annual average PM$_{2.5}$ concentrations in 2055 between the reference and onroad-only sensitivity scenarios. This demonstrates that annual average PM$_{2.5}$ concentrations would decrease across much of the country when considering only onroad vehicle emissions (i.e., without including any changes to emissions from upstream sources like EGUs and refineries).

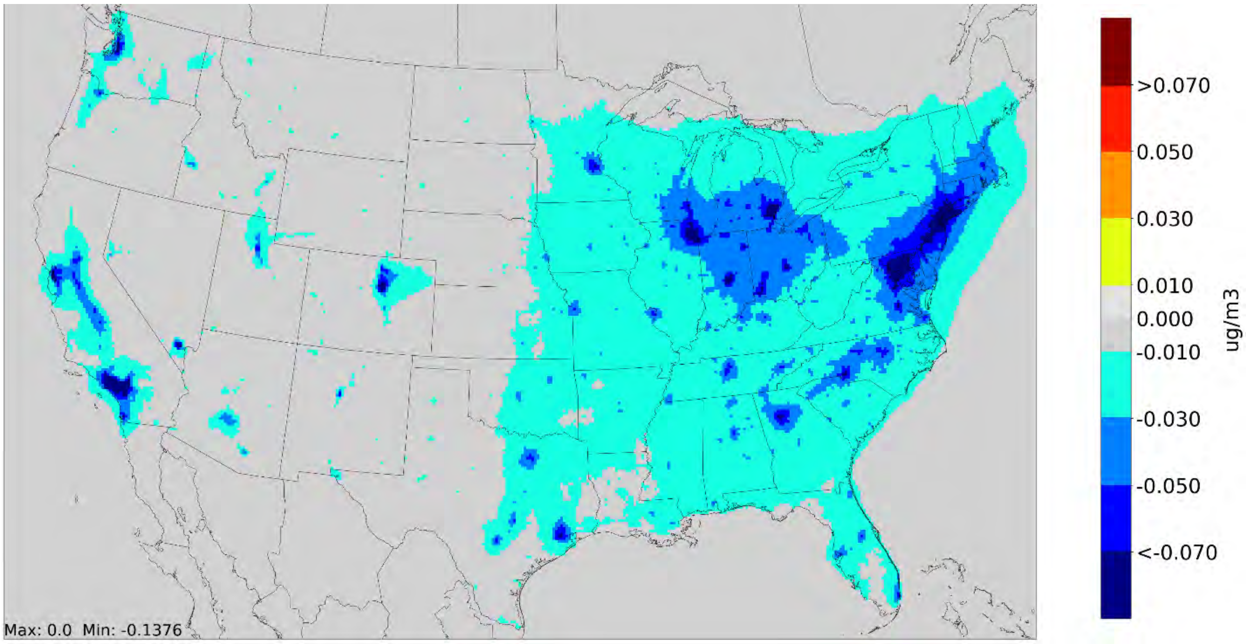

Figure 8-7: Projected illustrative changes in annual average $PM_{2.5}$ concentrations in 2055 from "onroad-only" emissions changes.

When only the onroad emissions impacts of the LMDV regulatory scenario are considered, annual average $PM_{2.5}$ concentrations would decrease by an average of 0.01 $\mu g/m^3$ in 2055, with a maximum decrease of 0.14 $\mu g/m^3$. The population-weighted average change in annual average $PM_{2.5}$ concentrations would be 0.04 $\mu g/m^3$ in 2055.

8.4.2 Ozone

This section summarizes projected changes in ozone concentrations in 2055 from the LMDV regulatory scenario. As noted in Chapter 8.4, this analysis is illustrative and the location and magnitude of concentration changes between the reference case and the LMDV regulatory scenario are uncertain, particularly because the analysis does not account for the cleaner power grid we expect to result from the IRA. Figure 8-8 presents the absolute changes in 8-hour ozone maximum average concentrations over the ozone season (April - September) in 2055 between the reference and LMDV regulatory scenarios and indicates that there would be widespread decreases, and in some areas there would be increases.

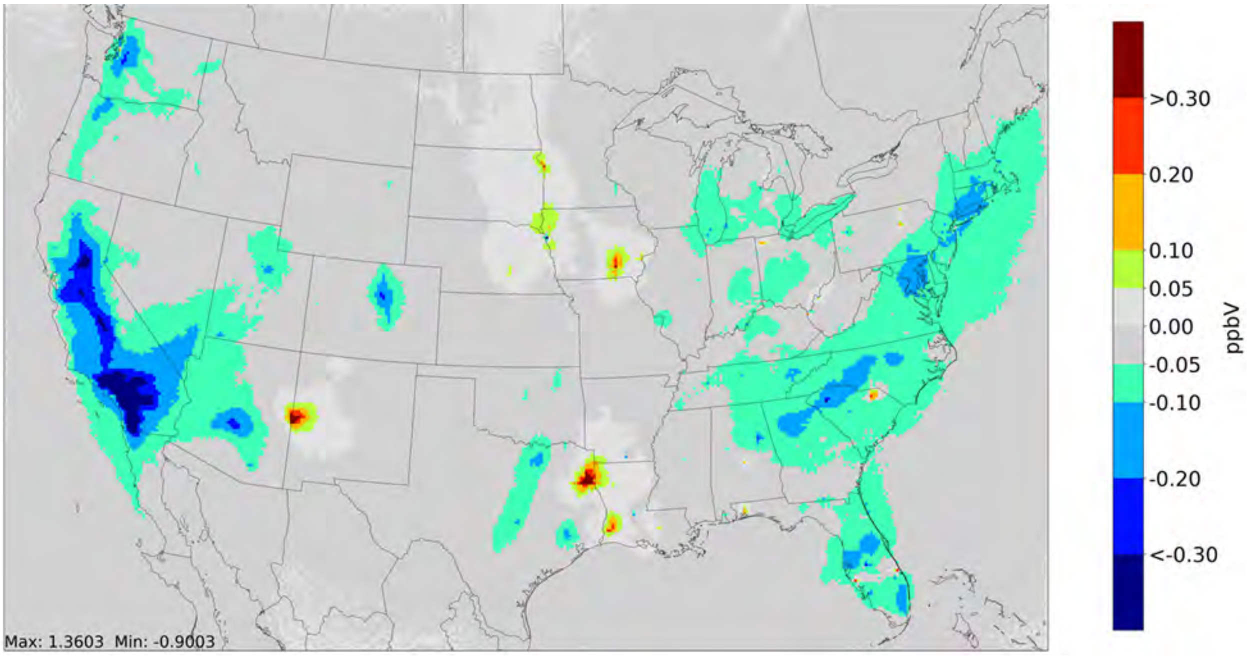

Figure 8-8: Projected illustrative changes in 8-hour maximum average ozone concentrations in 2055 due to LMDV regulatory scenario.

The LMDV regulatory scenario would decrease 8-hour maximum average ozone concentrations by an average of 0.04 ppb in 2055, with a maximum decrease of 0.90 ppb and a maximum increase of 1.36 ppb. The population-weighted average change in 8-hour maximum average ozone concentrations would be 0.10 ppb in 2055.

We also modeled an "onroad-only" sensitivity case. Figure 8-7 presents the absolute changes in 8-hour maximum average ozone concentrations in 2055 between the reference and onroad-only sensitivity scenarios. This demonstrates that ozone concentrations would decrease across much of the country when considering only onroad vehicle emissions (i.e., without including any changes to emissions from upstream sources like EGUs and refineries).

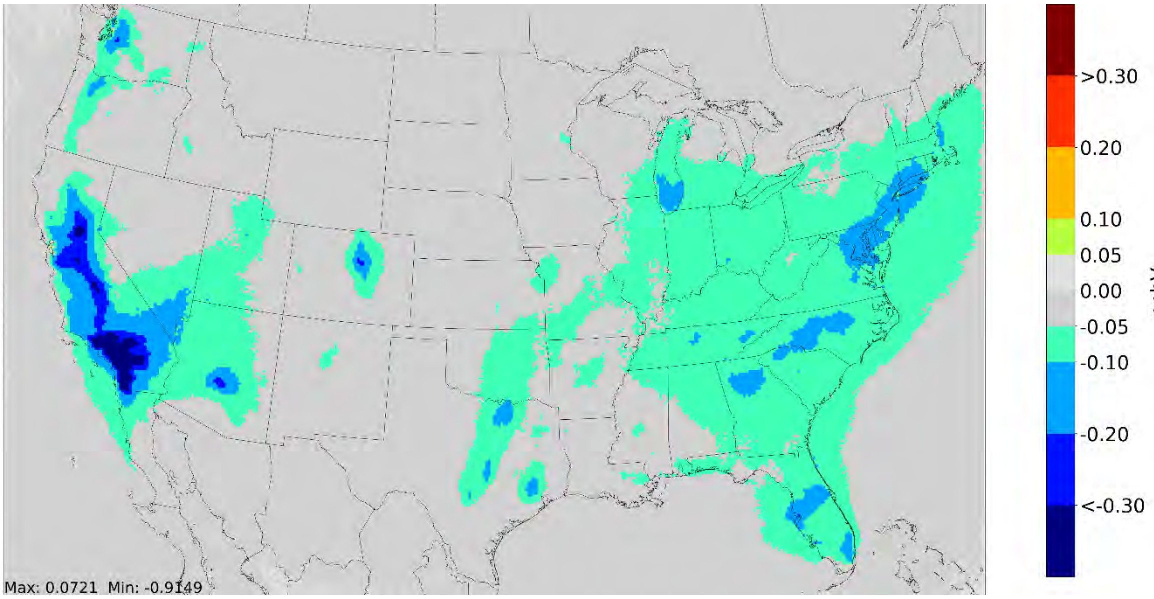

Figure 8-9: Projected illustrative changes in 8-hour maximum average ozone concentrations in 2055 from "onroad-only" emissions changes.

When only the onroad emissions impacts of the LMDV regulatory scenario are considered, 8-hour maximum average ozone concentrations would decrease by an average of 0.05 ppb in 2055, with a maximum decrease of 0.91 ppb. The population-weighted average change in 8-hour maximum average ozone concentrations would be 0.11 ppb in 2055.

8.4.3 NO_2

This section summarizes projected changes in NO_2 concentrations in 2055 from the LMDV regulatory scenario. As noted in Chapter 8.4, this analysis is illustrative and the location and magnitude of concentration changes between the reference case and the LMDV regulatory scenario are uncertain, particularly because the analysis does not account for the cleaner power grid we expect to result from the IRA. Figure 8-10 presents the absolute changes in annual average NO_2 concentrations in 2055 and indicates that there would be widespread decreases, and in some areas there would be increases.

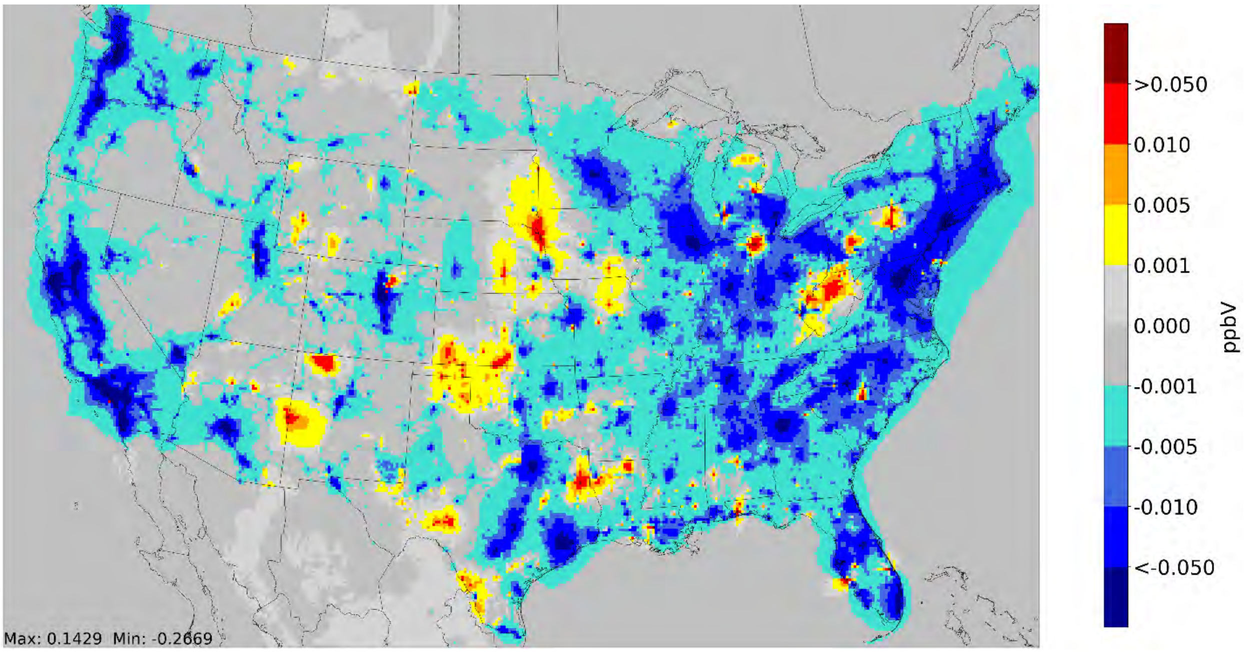

Figure 8-10: Projected illustrative changes in annual average NO_2 concentrations in 2055 due to LMDV regulatory scenario.

We also modeled an "onroad-only" sensitivity case. Figure 8-11 presents the absolute changes in annual average NO_2 concentrations in 2055 between the reference and onroad-only sensitivity scenarios. This demonstrates that NO_2 concentrations would decrease across much of the country when considering only onroad vehicle emissions (i.e., without including any changes to emissions from upstream sources like EGUs and refineries).

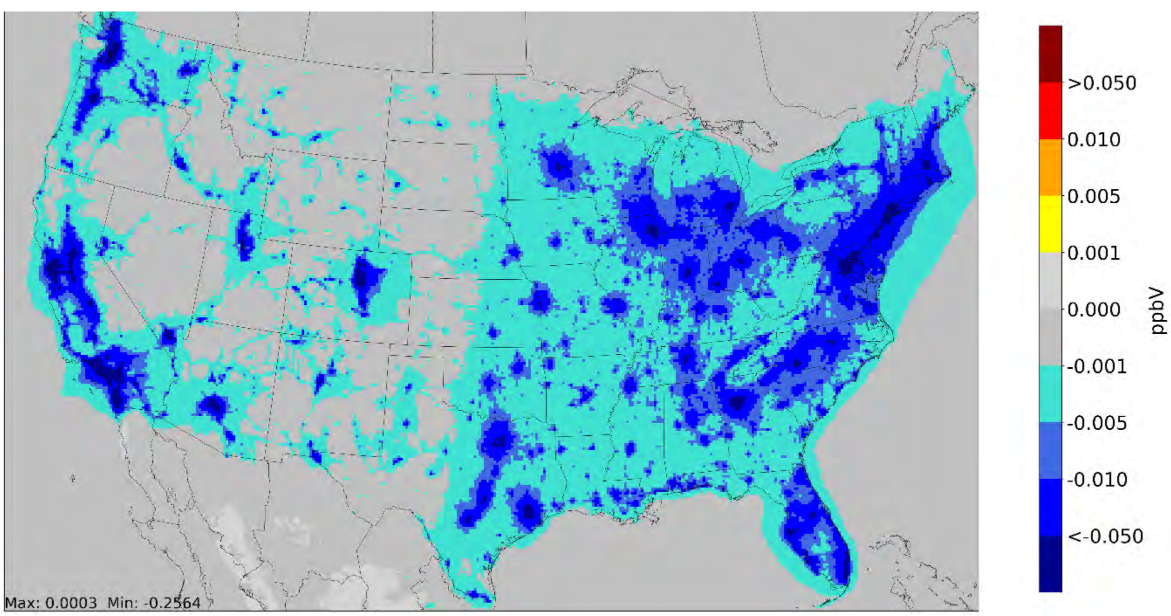

Figure 8-11: Projected illustrative changes in annual average NO_2 concentrations in 2055 from "onroad-only" emissions changes.

8.4.4 SO2

This section summarizes projected changes in SO_2 concentrations in 2055 from the LMDV regulatory scenario. As noted in Chapter 8.4, this analysis is illustrative and the location and magnitude of concentration changes between the reference case and the LMDV regulatory scenario are uncertain, particularly because the analysis does not account for the cleaner power grid we expect to result from the IRA. Figure 8-12 presents the absolute changes in annual average SO_2 concentrations in 2055 and indicates that in some areas there would be decreases and in some areas there would be increases.

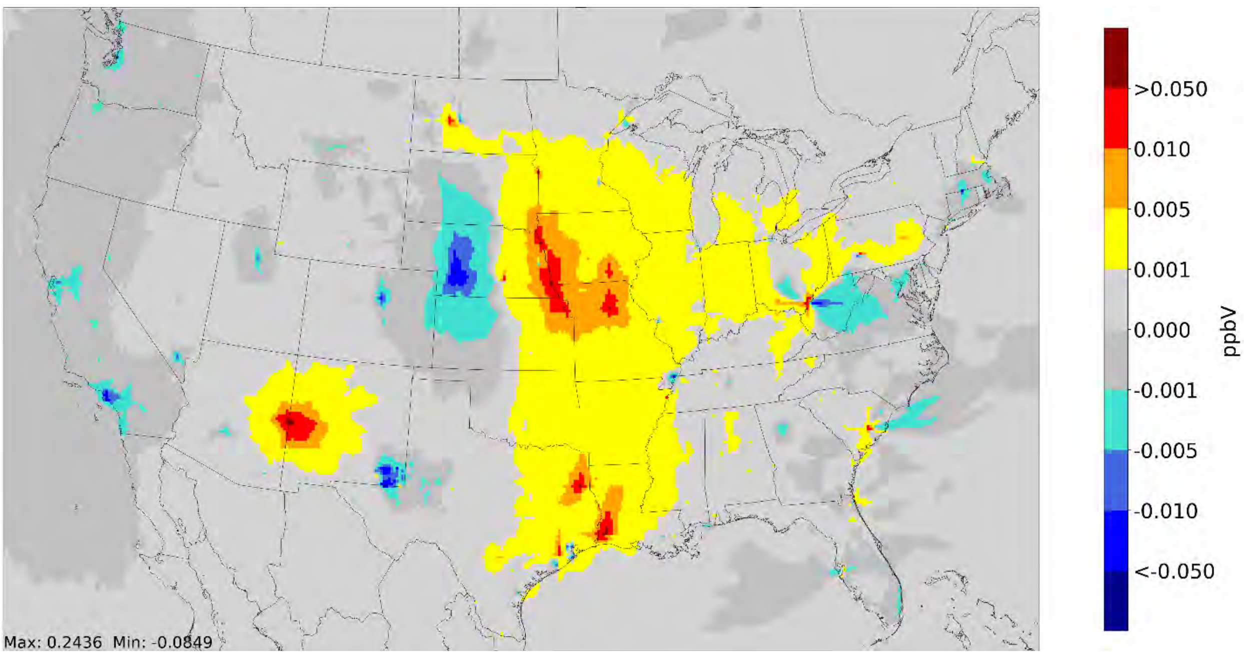

Figure 8-12: Projected illustrative changes in annual average SO_2 concentrations in 2055 due to LMDV regulatory scenario.

We also modeled an "onroad-only" sensitivity case. Figure 8-13 presents the absolute changes in annual average SO_2 concentrations in 2055 between the reference and onroad-only sensitivity scenarios. This demonstrates that SO_2 concentrations would decrease in a few areas of the country when considering only onroad vehicle emissions (i.e., without including any changes to emissions from upstream sources like EGUs and refineries).

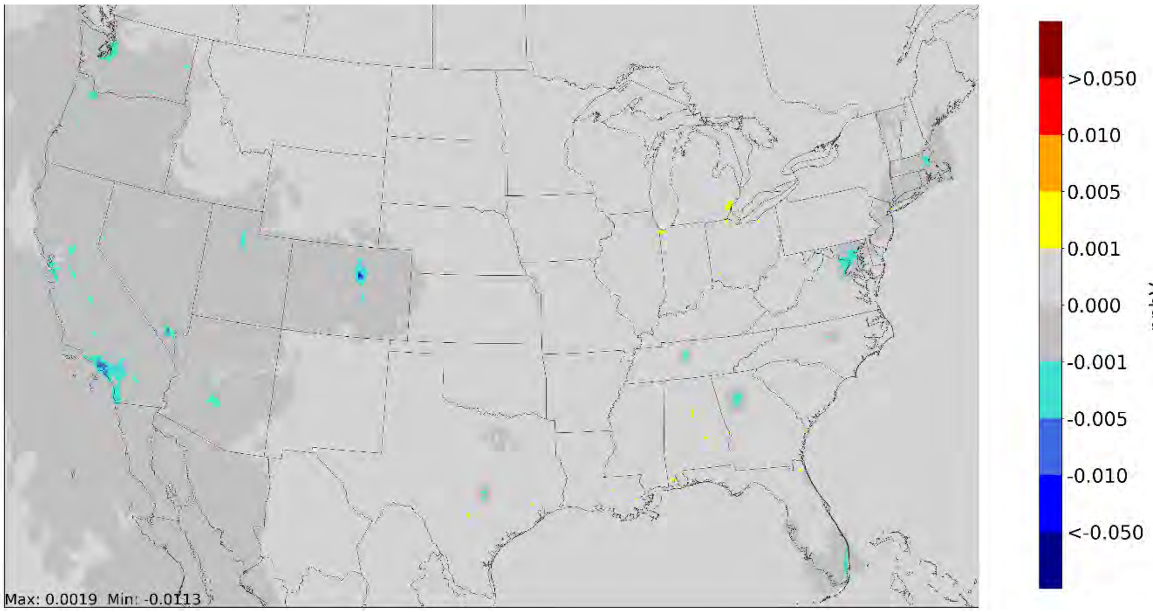

Figure 8-13: Projected illustrative changes in annual average SO_2 concentrations in 2055 from "onroad-only" emissions changes.

8.4.5 <u>Air Toxics</u>

This section summarizes projected changes in concentrations of select air toxics in 2055 from the LMDV regulatory scenario. As noted in Chapter 8.4, this analysis is illustrative and the location and magnitude of concentration changes between the reference case and the LMDV regulatory scenario are uncertain, particularly because the analysis does not account for the cleaner power grid we expect to result from the IRA. Figure 8-14 to Figure 8-17 present the absolute changes in annual average acetaldehyde, benzene, formaldehyde, and naphthalene concentrations in 2055 between the reference and LMDV regulatory scenarios and indicates that there would be widespread decreases, and in some areas there would be increases.

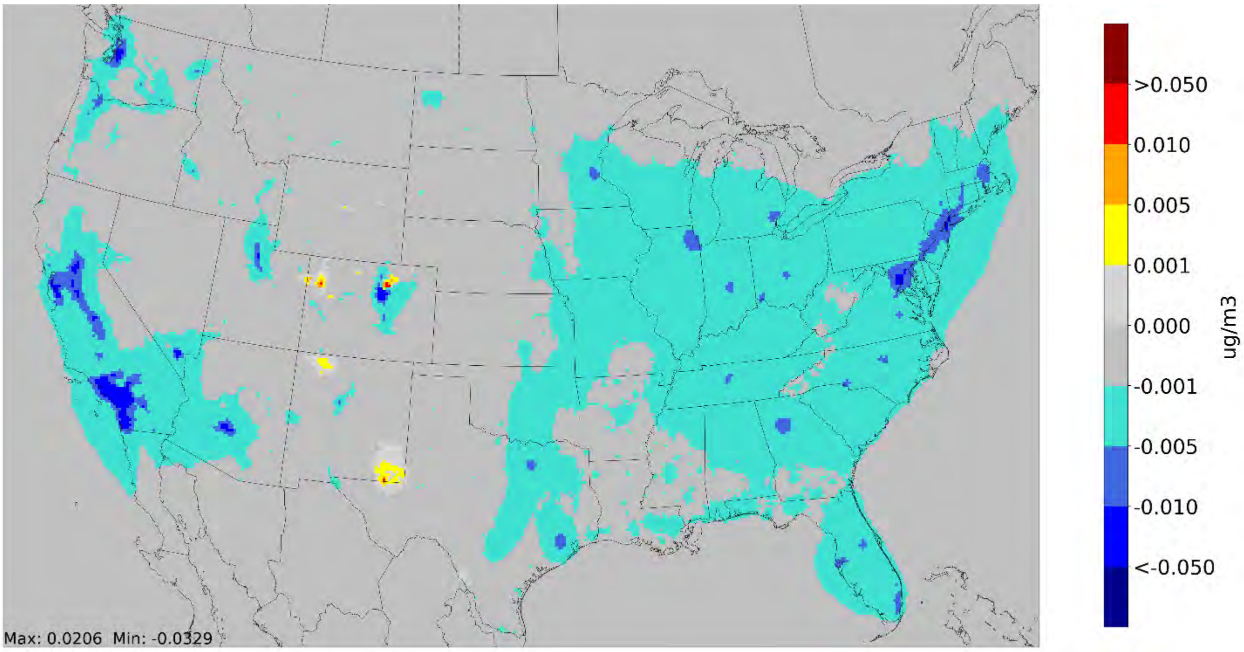

Figure 8-14: Projected illustrative changes in annual average acetaldehyde concentrations in 2055 due to LMDV regulatory scenario.

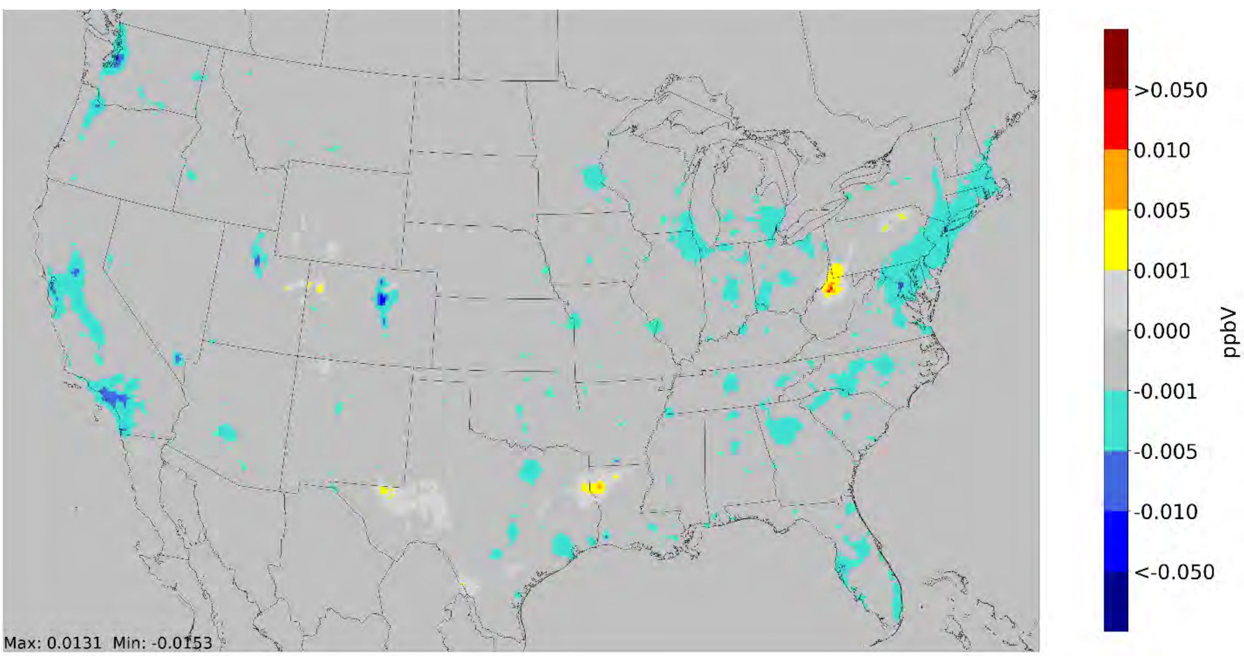

Figure 8-15: Projected illustrative changes in annual average benzene concentrations in 2055 due to LMDV regulatory scenario.

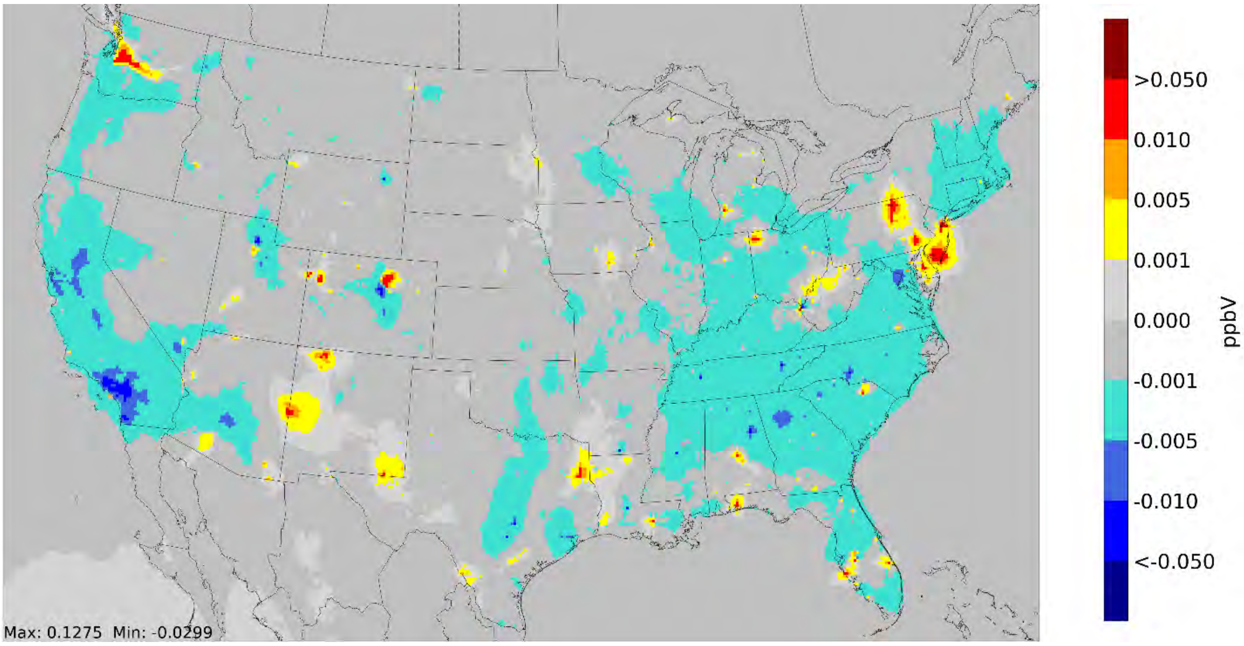

Figure 8-16: Projected illustrative changes in annual average formaldehyde concentrations in 2055 due to LMDV regulatory scenario.

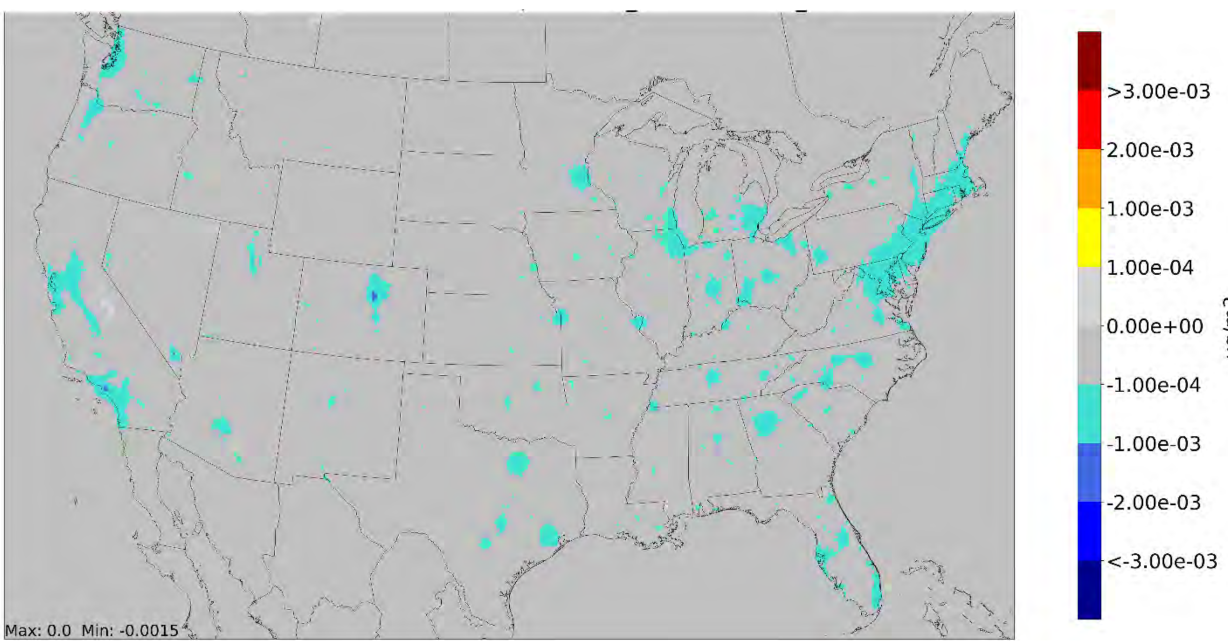

Figure 8-17: Projected illustrative changes in annual average naphthalene concentrations in 2055 due to LMDV regulatory scenario.

We also modeled an "onroad-only" sensitivity case. Figure 8-18 through Figure 8-20 present the absolute changes in annual average air toxic concentrations in 2055 between the reference and onroad-only sensitivity scenarios. This demonstrates that annual average air toxics concentrations would decrease across much of the country when considering only onroad vehicle emissions (i.e., without including any changes to emissions from upstream sources like EGUs and refineries).

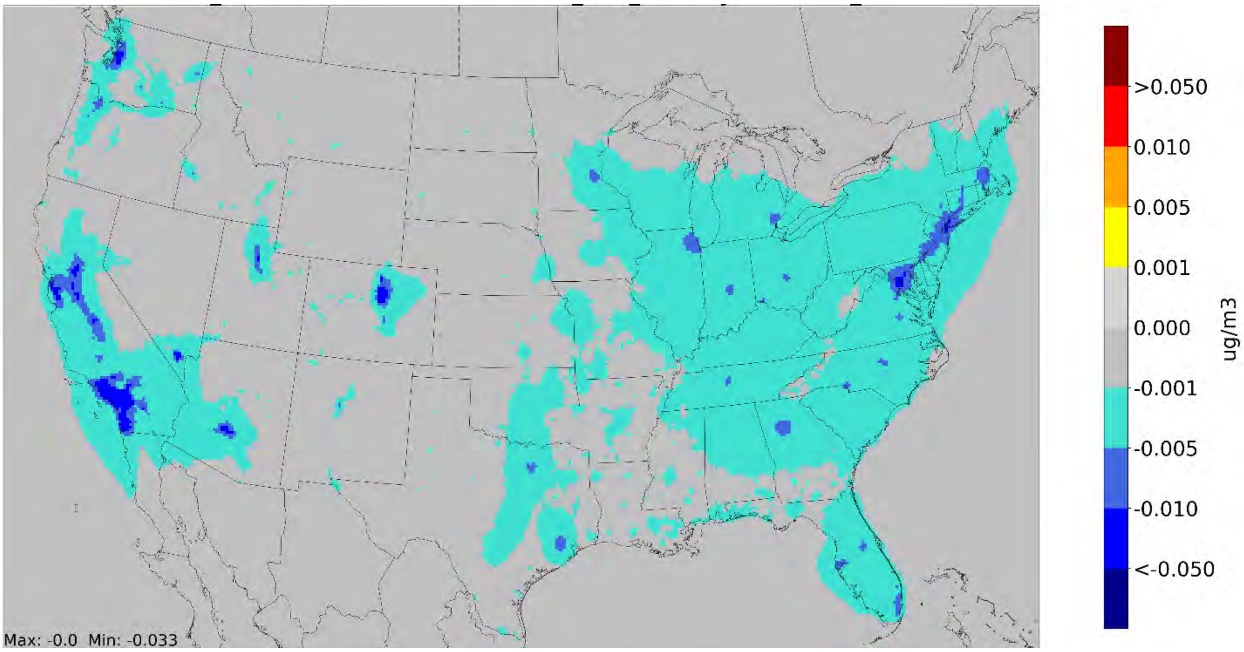

Figure 8-18: Projected illustrative changes in annual average acetaldehyde concentrations in 2055 from "onroad-only" emissions changes.

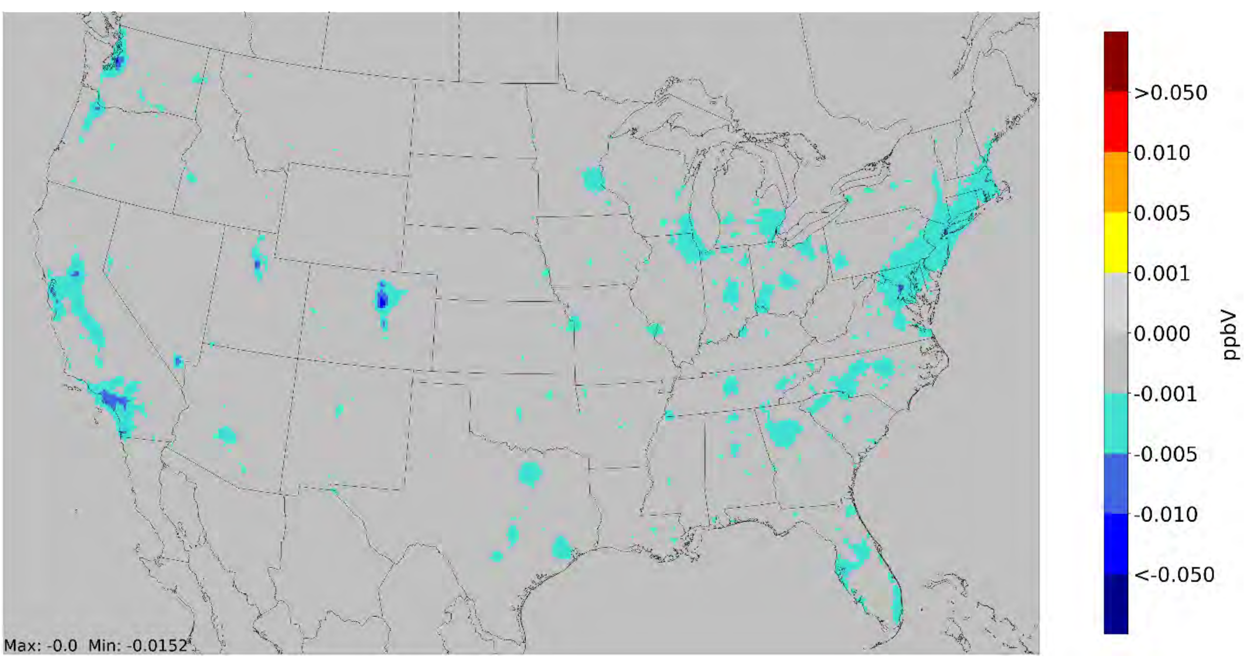

Figure 8-19: Projected illustrative changes in annual average benzene concentrations in 2055 from "onroad-only" emissions changes.

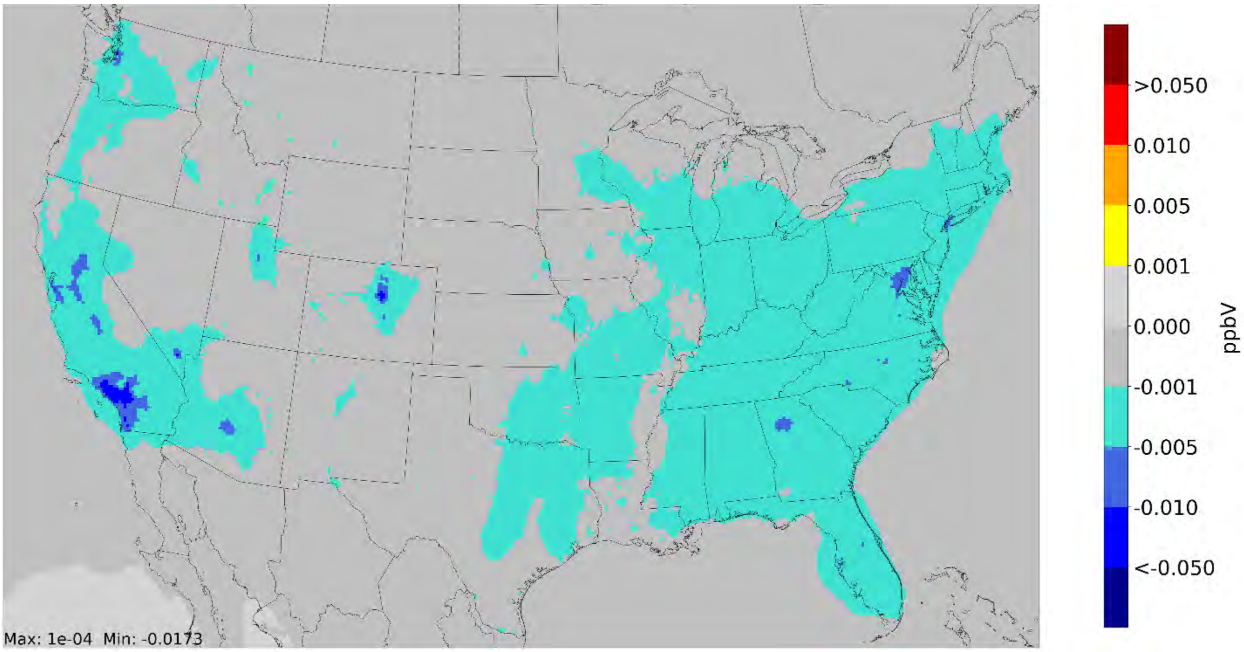

Figure 8-20: Projected illustrative changes in annual average formaldehyde concentrations in 2055 from "onroad-only" emissions changes.

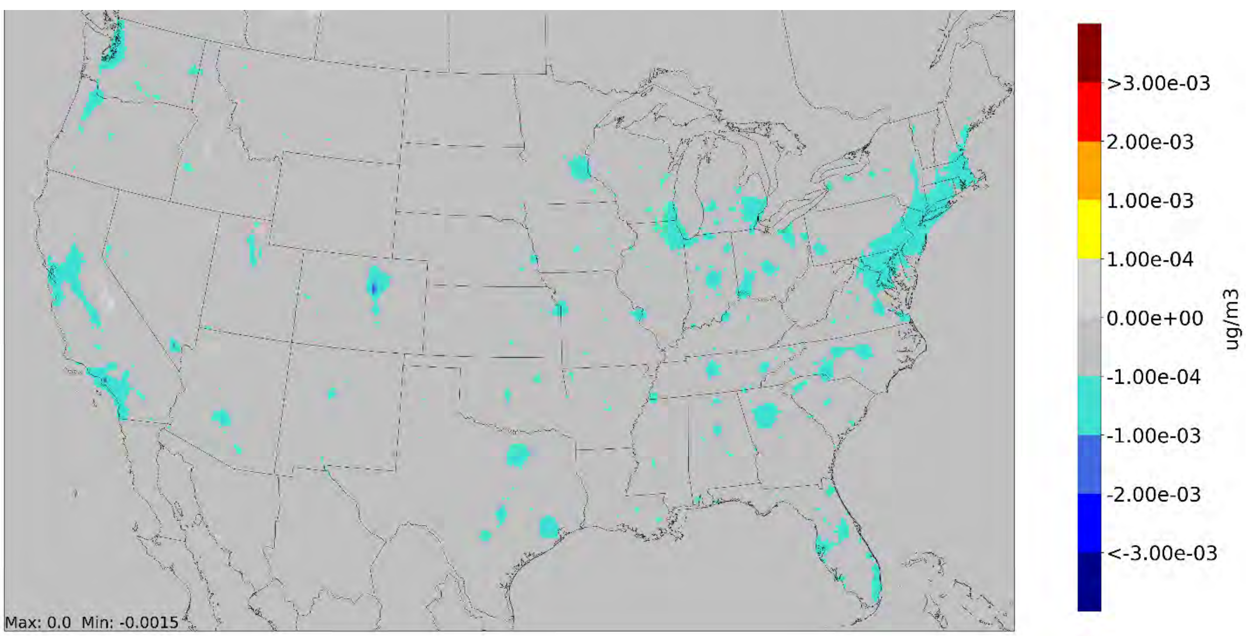

Figure 8-21: Projected illustrative changes in annual average naphthalene concentrations in 2055 from "onroad-only" emissions changes.

8.4.6 Deposition

This section summarizes projected changes in nitrogen (N) and sulfur (S) deposition in 2055 from the LMDV regulatory scenario. As noted in Chapter 8.4, this analysis is illustrative and the location and magnitude of concentration changes between the reference case and the LMDV regulatory scenario are uncertain, particularly because the analysis does not account for the cleaner power grid we expect to result from the IRA.

Figure 8-22 presents the absolute changes in annual N deposition in 2055 and indicates that there would be widespread decreases, and in some areas there would be increases. Figure 8-23 presents the absolute changes in annual S deposition in 2055 and indicates that in some areas there would be increases.

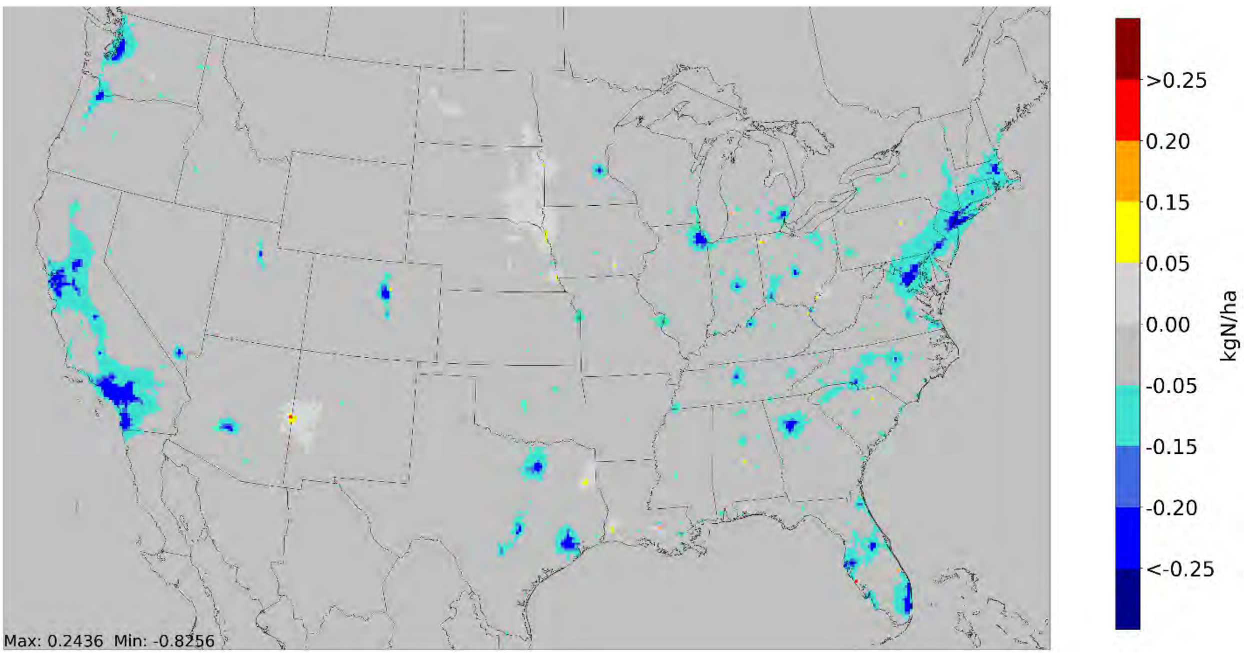

Figure 8-22: Projected illustrative changes in annual nitrogen deposition in 2055 due to LMDV regulatory scenario.

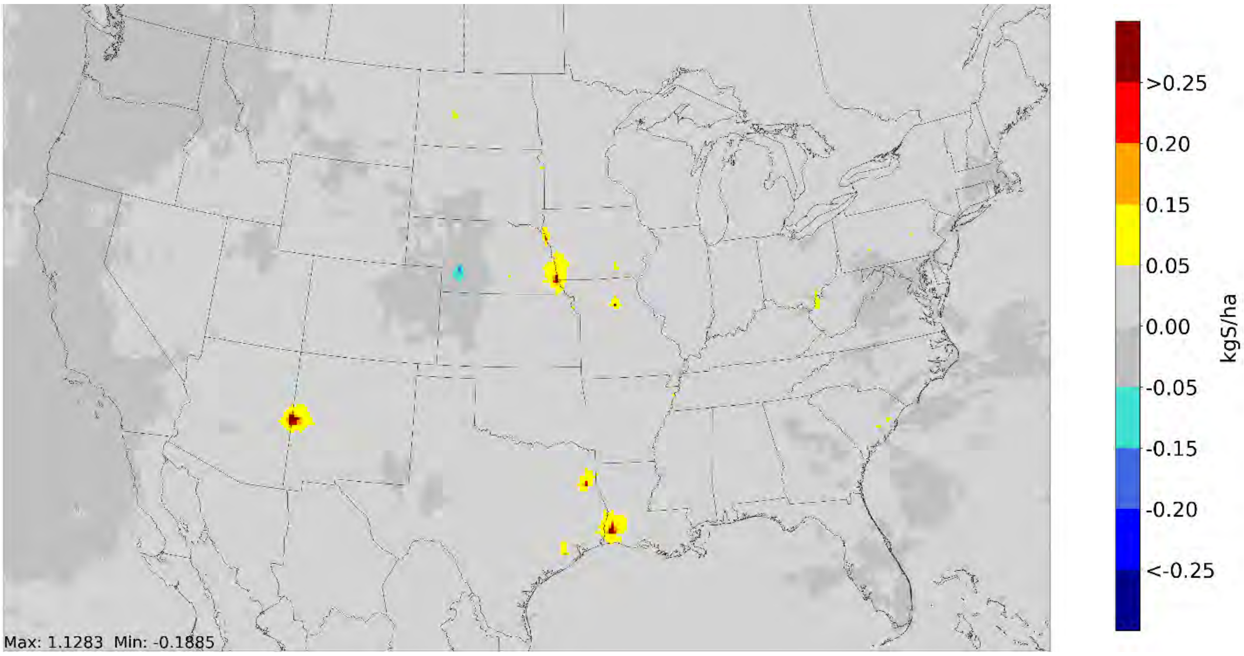

Figure 8-23: Projected illustrative changes in annual sulfur deposition in 2055 due to LMDV regulatory scenario.

We also modeled an "onroad-only" sensitivity case. Figure 8-24 presents the absolute changes in annual N deposition in 2055 between the reference and onroad-only sensitivity scenarios and Figure 8-25 presents the absolute changes in annual S deposition.

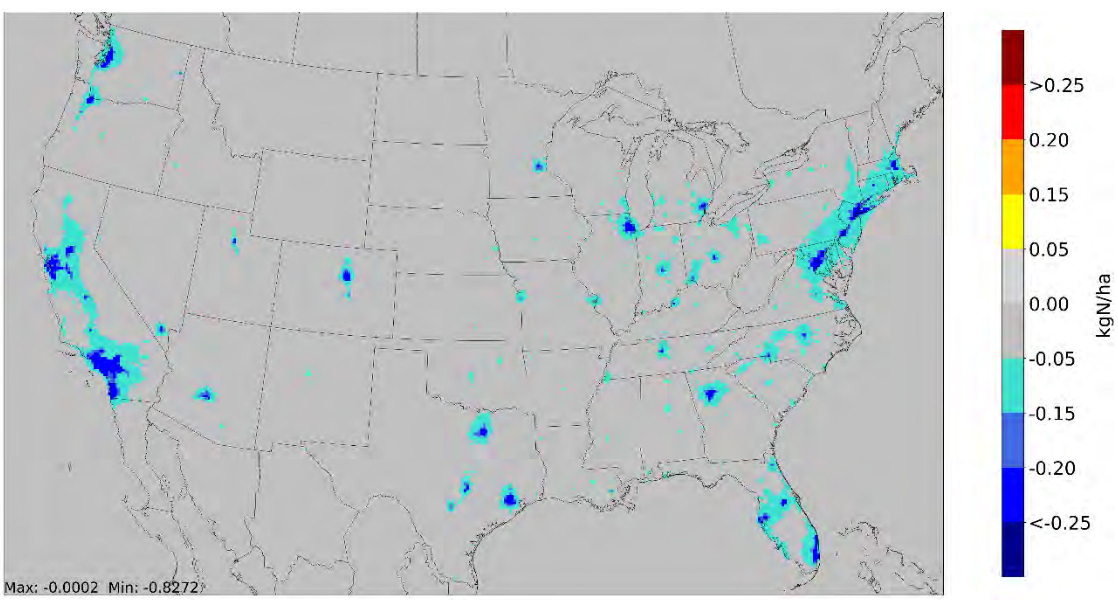

Figure 8-24: Projected illustrative changes in annual nitrogen deposition in 2055 from "onroad-only" emissions changes.

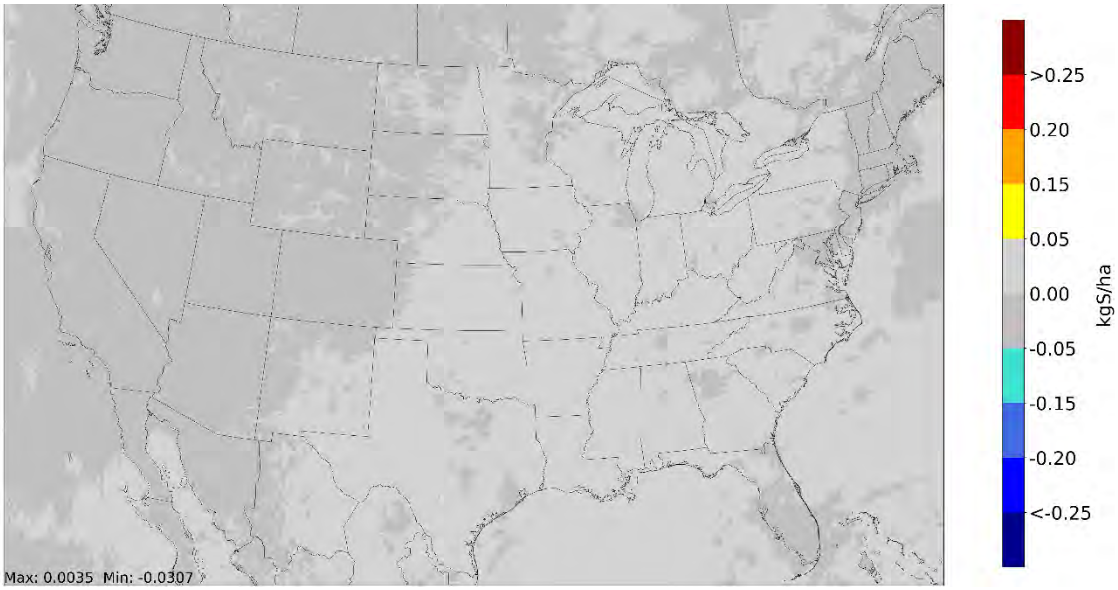

Figure 8-25: Projected illustrative changes in annual sulfur deposition in 2055 from "onroad-only" emissions changes.

8.5 Illustrative Ozone and Particulate Matter Health Benefits

The illustrative air quality modeling analysis does not represent the proposal's regulatory scenario, and it does not account for the impacts of the IRA. In contrast, the OMEGA-based emissions analysis (see DRIA Chapter 9) does represent the specifics of the proposal and accounts for IRA provisions that affect the power sector. As a result, we used the OMEGA-based emissions analysis and benefit-per-ton (BPT) values to estimate the criteria pollutant ($PM_{2.5}$) health benefits of the proposed standards. DRIA Chapter 7.4 describes the benefit-per-ton valuation methodology and DRIA Chapter 10 presents the $PM_{2.5}$-related health benefits.

Nevertheless, the illustrative air quality modeling analysis provides some useful insights into potential air quality impacts associated with emissions increases and decreases from multiple sectors, and it supports the conclusion that in 2055, the proposal would result in widespread decreases in ozone and $PM_{2.5}$ that would lead to substantial improvements in public health and welfare.

Using the illustrative air quality modeling results, we have quantified and monetized health impacts in 2055, representing the LMDV regulatory scenario described in DRIA Chapter 8.2. The approach we used to estimate health benefits is consistent with the approach described in the technical support document (TSD) that was published for the 2023 PM NAAQS Reconsideration Proposal (US EPA 2023).

Table 8-15 reports the $PM_{2.5}$- and ozone-attributable effects we quantified and those we did not quantify in this illustrative benefits analysis. The list of benefit categories not quantified is not exhaustive. The table below omits welfare effects such as acidification and nutrient enrichment.

Table 8-15: Health effects of ambient ozone and $PM_{2.5}$

Category	Effect	Effect Quantified	Effect Monetized	More Information
Premature mortality from exposure to $PM_{2.5}$	Adult premature mortality from long-term exposure (age >17 or >64)	✓	✓	PM ISA
	Infant mortality (age <1)	✓	✓	PM ISA
Nonfatal morbidity from exposure to $PM_{2.5}$	Non-fatal heart attacks (>18)	✓	✓[a]	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)	✓	✓[a]	PM ISA
	Emergency department visits – respiratory (all)	✓	✓[a]	PM ISA
	Emergency hospital admissions (>65)	✓	✓	PM ISA
	Non-fatal lung cancer (>29)2	✓	✓	PM ISA
	Out-of-hospital cardiac arrest (all)	✓	✓	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
	Minor restricted-activity days (18-64)	✓	✓	PM ISA
	Other cardiovascular effects (e.g., other ages)	—	—	PM ISA[b]
	Other respiratory effects (e.g., pulmonary function, non-asthma ER visits, non-bronchitis chronic diseases, other ages and populations)	—	—	PM ISA[b]
	Other nervous system effects (e.g., autism, cognitive decline, dementia)	—	—	PM ISA[b]
	Metabolic effects (e.g., diabetes)	—	—	PM ISA[b]
	Reproductive and developmental effects (e.g., low birth weight, pre-term births, etc.)	—	—	PM ISA[b]
	Cancer, mutagenicity, and genotoxicity effects	—	—	PM ISA[b]
Mortality from exposure to ozone	Premature respiratory mortality from short-term exposure (0-99)	✓	✓	Ozone ISA
	Premature respiratory mortality from long-term exposure (age 30–99)	✓	✓	Ozone ISA
Nonfatal morbidity from exposure to ozone	Hospital admissions—respiratory (ages 65-99)	✓	✓	Ozone ISA
	Emergency department visits—respiratory (ages 0-99)	✓	✓	Ozone ISA
	Asthma onset (0-17)	✓	✓	Ozone ISA
	Asthma symptoms/exacerbation (asthmatics age 5-17)	✓	✓	Ozone ISA
	Allergic rhinitis (hay fever) symptoms (ages 3-17)	✓	✓	Ozone ISA
	Minor restricted-activity days (age 18–65)	✓	✓	Ozone ISA
	School absence days (age 5–17)	✓	✓	Ozone ISA
	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]

[a] Valuation estimate excludes initial hospital and/or emergency department visits.

[b] Not quantified due to data availability limitations and/or because current evidence is only suggestive of causality.

Below we report the estimated number and economic value of reduced premature deaths and illnesses in 2055 attributable to the illustrative regulatory scenario along with the 95 percent confidence interval. Table 8-16 reports the number of reduced deaths and illnesses associated with reductions in $PM_{2.5}$, along with their monetized economic value. Table 8-17 reports the number of reduced ozone-related deaths and illness, along with their monetized economic value. Table 8-18 reports total benefits associated with the illustrative regulatory scenario in 2055, reflecting alternative combinations of the economic value of $PM_{2.5}$- and ozone-related premature deaths summed with the economic value of illnesses for each discount rate.

Table 8-16: Quantified and monetized avoided $PM_{2.5}$-related premature mortalities and illnesses of the illustrative scenario in 2055 (95% confidence interval)[a]

Avoided PM Outcomes		Point Estimate		Valuation (Millions, 2020$)
All-Cause Mortality	(Wu et al. 2020) (65-99)	730 (640 to 810)	3%[b]	$8,600 ($800 to $23,000)
			7%	$7,700 ($720 to $20,000)
	(Pope III et al. 2019) (18-99)	1,400 (1,000 to 1,800)	3%	$17,000 ($1,500 to $45,000)
			7%	$15,000 ($1,400 to $41,000)
	(Woodruff 2008) (0-0)	1.0 (-0.65 to 2.7)		$14 ($-7.5 to $54)
ER visits, respiratory	ER visits, All Cardiac Outcomes	220 (-83 to 500)		$0.29 ($-0.11 to $0.68)
	ER visits, respiratory	380 (75 to 800)		$0.39 ($0.077 to $0.81)
Hospital Admissions	HA, Alzheimers Disease	360 (270 to 450)		$5.1 ($3.8 to $6.3)
	HA, Cardio-, Cerebro- and Peripheral Vascular Disease	110 (77 to 130)		$1.9 ($1.4 to $2.4)
	HA, Parkinsons Disease	42 (22 to 63)		$0.63 ($0.32 to $0.93)
	HA, Respiratory-2 HA, All Respiratory	64 (22 to 100)		$1.2 ($0.26 to $2.1)
Respiratory Incidence	Incidence, Asthma	1,500 (1,400 to 1,500)	3%	$75 ($70 to $80)
			7%	$47 ($43 to $50)
	Incidence, Hay Fever/Rhinitis	9,600 (2,300 to 17,000)		$6.7 ($1.6 to $12)
	Incidence, Lung Cancer	52 (16 to 87)	3%	$1.6 ($0.49 to $2.7)
			7%	$1.2 ($0.37 to $2.0)
	Incidence, Out of Hospital Cardiac Arrest	11 (-4.3 to 24)	3%	$0.44 ($-0.18 to $1.0)
			7%	$0.43 ($-0.18 to $0.98)
	Asthma Symptoms, Albuterol use	280,000 (-140,000 to 690,000)		$0.11 ($0.055 to $0.28)
Additional Morbidity Effects	Acute Myocardial Infarction, Nonfatal	23 (14 to 33)	3%	$1.3 ($0.77 to $1.9)
			7%	$1.3 ($0.75 to $1.8)
	Incidence, Stroke	41 (11 to 71)		$1.6 ($0.42 to $2.8)
	Minor Restricted Activity Days	480,000 (390,000 to 570,000)		$41 ($21 to $62)
	Work Loss Days	81,000 (68,000 to 93,000)		$16 ($13 to $18)

[a] Values rounded to two significant figures.

[b] We discount the value of those avoided health outcomes that are expected to accrue over more than a single year.

Table 8-17: Quantified and monetized avoided ozone-related premature mortalities and illnesses of the illustrative scenario in 2055 (95% confidence interval)[a]

Avoided Ozone Outcomes			Avoided Outcomes		Valuation (Millions, 2020$)
Avoided Premature Respiratory Mortalities	Long-term Exposure	(Turner 2016)	330 (230 to 420)	3%[b]	$3,800 ($350 to $10,000)
				7%	$3,500 ($310 to $9,400)
	Short-Term Exposure	(Katsouyanni 2009) and (Zanobetti 2008), pooled	15 (5.9 to 23)		$190 ($16 to $560)
Morbidity Effects	Long-term Exposure	Asthma Onset	2,200 (1,900 to 2,500)	3%	$110 ($95 to $130)
				7%	$69 ($59 to $78)
		Allergic Rhinitis Symptoms	13,000 (6,700 to 19,000)		$8.9 ($4.7 to $13)
	Short-Term Exposure	Hospital Admissions - Respiratory	43 (-11 to 96)		$1.8 ($-0.48 to $4.1)
		ER Visits - Respiratory	720 (200 to 1,500)		$0.73 ($0.20 to $1.5)
		Asthma Symptoms	400,000 (-50,000 to 840,000)		$110 ($-13 to $220)
		MRADs	210,000 (84,000 to 330,000)		$18 ($6.6 to $33)
		School Absences	150,000 (-21,000 to 310,000)		$18 ($-2.5 to $37)

[a] Values rounded to two significant figures.

[b] We discount the value of those avoided health outcomes that are expected to accrue over more than a single year.

Table 8-18: Total $PM_{2.5}$ and ozone benefits of the illustrative scenario in 2055 (95% confidence interval, billions of 2020 dollars)[a,b]

	$PM_{2.5}$	Ozone	Total
Benefits using $PM_{2.5}$-related mortality estimate from Pope III et al., 2019 and ozone-related mortality estimate from Turner et al., 2016			
3% Discount Rate	\$17 (\$1.6 - \$45)	\$4.4 (\$0.33 - \$12)	\$21 (\$1.9 - \$57)
7% Discount Rate	\$15 (\$1.4 - \$41)	\$4.0 (\$0.26 - \$11)	\$19 (\$1.7 - \$52)
Benefits using $PM_{2.5}$-related mortality estimate from Wu et al., 2020 and a pooled ozone-related mortality estimated from Katsouyanni et al., 2009 and Zanobetti et al., 2008			
3% Discount Rate	\$8.8 (\$0.90 - \$23)	\$0.75 (\$0.00 - \$2.0)	\$9.5 (\$0.90 - \$25)
7% Discount Rate	\$7.9 (\$0.80 - \$21)	\$0.71 (\$0.00 - \$1.9)	\$8.6 (\$0.76 - \$23)

[a] Values rounded to two significant figures.

[b] The benefits associated with the standards presented here do not include the full complement of health and environmental benefits that, if quantified and monetized, would increase the total monetized benefits.

In any complex analysis using estimated parameters and inputs from numerous models, there are likely to be many sources of uncertainty. The health benefits TSD that was published for the 2023 PM NAAQS Reconsideration Proposal 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. When the uncertainties from each stage of the analysis are compounded, even small uncertainties can have large effects on the total quantified benefits.

Chapter 8 References

86 FR 74434 . 2021.

Advanced Clean Trucks . 2021. 13 Cal Code Regs, S 963 and 1963.1 through 1963.5

Beardsley, Megan. 2023. "Updates to MOVES for the Mult-Pollutant Emissions Standards for Model Years 2027 and Later Light-Duty and Medium-Duty Vehicles." Memorandum to Docket EPA-HQ-OAR-2022-0829. February 10.

Bohac, Stanislav V., and Scott Ludlum. 2023. "Characterization of a Lightly Loaded Underfloor Catalyzed Gasoline Particulate Filter in a Turbocharged Light Duty Truck." Journal of Engineering fro Gas Turbines and Power 021024-1 - 021024-7.

Byun, D.W., J.K.S. Ching, and US EPA. 1999. "Science Algorithms of EPA Models-3 Community Multiscale Air Quality (CMAQ) Modeling System."

Cook, Rich, Sharon Phillips, Madeleine Strum, Alison Eyth, and James Thurman. 2020. "Contribution of mobile sources to secondary formation of carbonyl compounds." Journal of the Air and Waste Management Association.

Henderson, B. et al. 2018. "Hemispheric-CMAQ Application and Evaluation for 2016." 2019 CMAS Conference .

Katsouyanni, K, Samet, JM, Anderson, HR, Atkinson, R, Le Tertre, A, Medina, S, Samoli, E, Touloumi, G, Burnett, RT, Krewski, D, Ramsay, T, Dominici, F, Peng, RD, Schwartz, J, Zanobetti, A and Committee, HEIHR (2009). 2009. "Air pollution and health: a European and North American approach (APHENA)." Res Rep Health Eff Inst 142: 5-90.

Mathur, R. et al. 2017. "Extending the Community Multiscale Air Quality (CMAQ) Modeling System to Hemispheric Scales: Overview of Process Considerations and Initial Applications." Atmospheric Chemistry Physics 12449-12474.

National Center for Atmospheric Research. 2022. Weather Research & Forecasting Model (WRF), v4.42. Accessed 2023. https://www.mmm.ucar.edu/models/wrf.

Pope III et al., 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.

Skamarock, W.C. et al. 2008. "A Description of the Advanced Research WRF Version 3."

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). 2016. "Long-term ozone exposure and mortality in a large prospective study." American Journal of Respiratory and Critical Care Medicine 193 (10): 1134-1142.

US EIA. 2021. Annual Energy Outlook 2021. February 3. Accessed 2022. https://www.eia.gov/outlooks/archive/aeo21/.

US EPA. 2018. 2018 Air Toxics Screening Assessment Results. https://www.epa.gov/AirToxScreen/2018-airtoxscreen-assessment-results.

—. 2022. 8-Hour Ozone (2008) Nonattainment Area Summary. December 31. Accessed January 20, 2023. https://www3.epa.gov/airquality/greenbook/hnsum.html.

—. 2022. 8-Hour Ozone (2015) Nonattainment Area Summary. December 31. Accessed January 20, 2023. https://www3.epa.gov/airquality/greenbook/jnsum.html.

—. 2022. EPA to Reconsider Previous Administrator's Decision to Retain 2015 Ozone Standards. October 11. Accessed January 20, 2023. https://www.epa.gov/ground-level-ozone-pollution/epa-reconsider-previous-administrations-decision-retain-2015-ozone.

US EPA. 2023. "Estimating PM2.5- and Ozone-Attributable Health Benefits. Technical Support Document (TSD) for the 2023 PM NAAQS Reconsideration Proposal." EPA-HQ-OAR-2019-0587, .

US EPA. 2011. "Final Cross State Air Pollution Rule Air Quality Modeling TSD."

—. 2022. Green Book Data Download. December 31. Accessed January 20, 2023. https://www.epa.gov/green-book/green-book-data-download.

—. 2022. Green Book Data Download. 12 31. Accessed January 20, 2023. https://www.epa.gov/green-book/green-book-data-download.

US EPA. 2019. "Meteorological Model Performance for Annual 2016 Simulation WRF v3.8."

—. 2020. "Motor Vehicle Emission Simulator: MOVES3." Ann Arbor: Office of Transportation and Air Quality. US Environmental Protection. https://www.epa.gov/moves.

US EPA. 2007. "MSAT RIA."

—. 2023. National Ambient Air Quality Standards (NAAQS) for PM. Accessed January 20, 2023. https://www.epa.gov/pm-pollution/national-ambient-air-quality-standards-naaqs-pm.

—. 2020. Ozone National Ambient Air Quality Standards (NAAQS). December 23. Accessed January 20, 2023. https://www.epa.gov/ground-level-ozone-pollution/ozone-national-ambient-air-quality-standards-naaqs.

—. 2022. PM-2.5 (1997) Nonattainment Area Summary. Accessed January 20, 2023. https://www3.epa.gov/airquality/greenbook/qnsum.html.

—. 2022. PM-2.5 (2006) Nonattainment Area Summary. December 31. Accessed January 20, 2023. https://www3.epa.gov/airquality/greenbook/rnsum.html.

—. 2022. PM-2.5 (2012) Nonattainment Area Summary. December 31. Accessed January 20, 2023. https://www3.epa.gov/airquality/greenbook/knsum.html.

US EPA. 2022. "Preparation of Emissions Inventories for the 2016v2 North American Emissions Modeling Platform Technical Support Document."

US EPA. 2004. "Procedures for Estimating Future PM2.5 Values for the CAIR Final Rule by Application of the (Revised) Speciated Modeled Attainment Test (SMAT) Updated 11/8/04."

—. 2022. Report on the Environment, technical documentation for acid deposition. https://cfpub.epa.gov/roe/indicator.cfm?i=1.

—. 2023. Science Inventory. https://cfpub.epa.gov/si/index.cfm.

—. 2022. Sulfur Dioxide (2010) Nonattainment Area Summary. December 31. Accessed January 20, 2023. https://www3.epa.gov/airquality/greenbook/tnsum.html.

US EPA. 2022. "Technical Support Document EPA Air Toxics Screening Assessment. 2017 AirToxScreen TSD. ."

US EPA. 2023. "Technical Support Document: Illustrative Air Quality Modeling Analysis for the Light and Medium Duty 2027 Multipollutant Proposed Rule."

US EPA. 2019. "Technical Support Document: Preparation of Emissions Inventories for the Version 7.1 2016 hemispheric Emissions Modeling Platform."

—. 2015. "U.S. Environmental Protection Agency Peer Review Handbook." EPA-100-B15-001. https://www.epa.gov/sites/default/files/2020-08/documents/epa_peer_review_handbook_4th_edition.pdf.

Versar, Inc. 2019. "The Sixth External Peer Review of the Community Multiscale Air Quality (CMAQ) Modeling System." https://www.epa.gov/sites/production/files/2019-08/documents/sixth_cmaq_peer_review_comment_report_6.19.19.pdf.

Woodruff, T.J., J. Grillo, and K.C. Schoendorf. 2008. "Air pollution and postneonatal infant mortality in the United States, 1999–2002." Environmental Health Perspectives 116 (1): 110-115.

Wu et al., 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.

Zanobetti, A and Schwartz, J. 2008. "Mortality displacement in the association of ozone with mortality: an analysis of 48 cities in the United States ." Am J Respir Crit Care Med 177 (2): 184-189.

Chapter 9: OMEGA Physical Effects of the Proposed Standards and Alternatives

This chapter describes the methods and approaches used within the OMEGA model to estimate physical effects of the proposed standards. Physical effects refer to emission inventories, fuel consumption, oil imports, vehicle miles traveled including effects associated with the rebound effect, and safety effects. The cost and benefits of the proposal are tied directly to these physical effects and are discussed in Chapter 10 of this draft RIA.

9.1 The OMEGA "Context"

OMEGA makes use of projections of fleet size, market shares, fuel prices, vehicle miles travelled (VMT), etc., from the Annual Energy Outlook. Any AEO can be used provided the input files are made available to OMEGA. For this analysis, EPA has used AEO 2021. (U.S. EIA 2021) AEO 2021 was done assuming that the future fleet would comply with the 2020 SAFE FRM. Hence, when running OMEGA, the first scenario run is best meant to reflect the SAFE FRM standards. That way, future fleet VMT and rebound VMT will be calculated relative to that projected future, as described below.

9.2 The Analysis Fleet and the Legacy Fleet

OMEGA uses as a "base year fleet" a comprehensive list of vehicles sold in a recent model year. This base year fleet includes all models of vehicles, their sales, and a long list of attributes such as their curb weights, their footprints and the primary GHG technologies on those vehicles. For this analysis, EPA is using the MY 2019 fleet as the base year fleet. When OMEGA runs, it begins with the 2020 calendar year as the first year of the analysis and uses the fleet of vehicles contained in the base year fleet as the starting point for the analysis. These MY 2020 and later vehicles are referred to as the "analysis fleet."

Vehicles that exist in the fleet prior to the first year of the analysis (i.e., MY 2020) are referred to as the "legacy fleet." Those vehicles are "aged out" of the fleet over the course of running the analysis. The legacy fleet vehicles are not changed in any way within OMEGA other than being scrapped (aging out) and driving fewer miles per year.

Figure 9-1 shows ICE vehicle stock--liquid-fueled vehicles including HEVs--and Figure 9-2 shows BEV stock. The ICE vehicle stock can be seen to be aging out of the fleet as the BEV stock grows. Figure 9-3 shows the total vehicle stock with growth representing economic and population growth going forward.

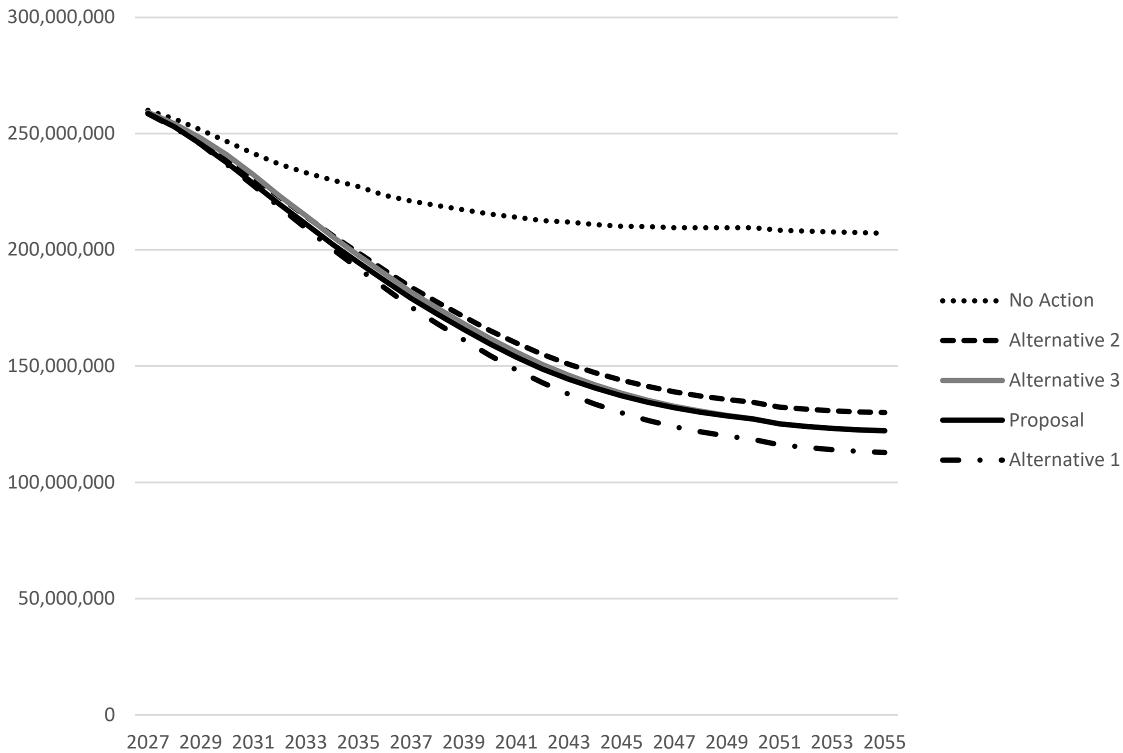

Figure 9-1 ICE vehicle stock used in OMEGA effects calculations

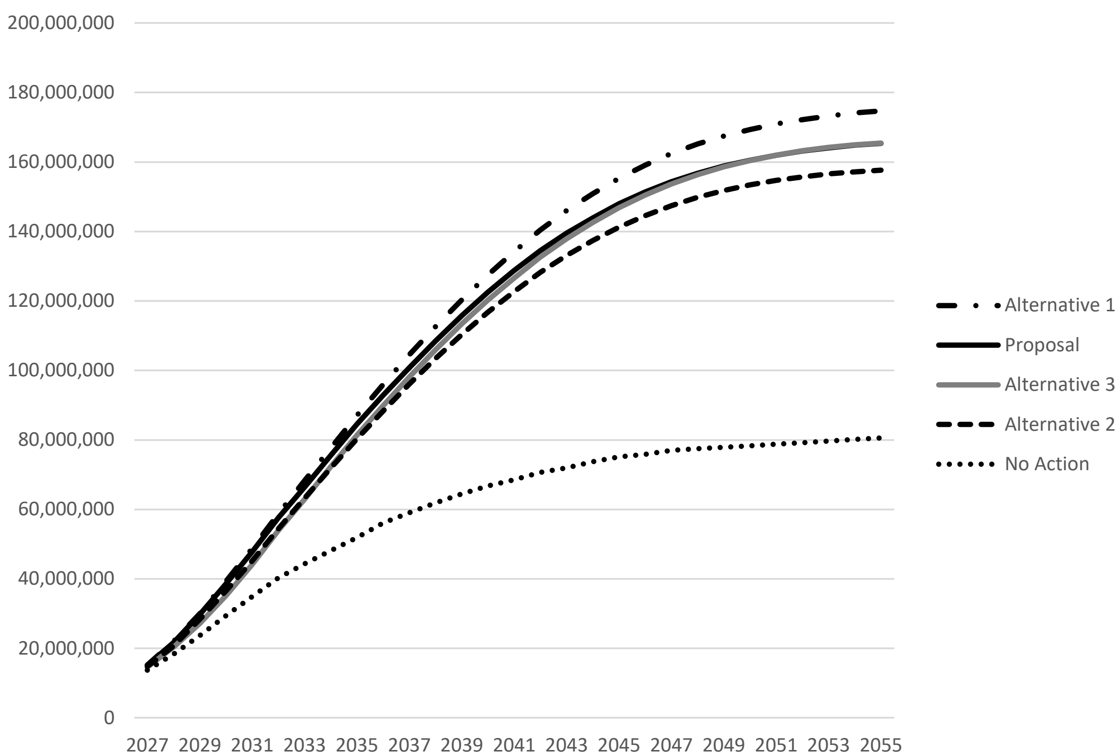

Figure 9-2 BEV stock used in OMEGA effects calculations

9.3 Estimating Vehicle, Fleet and Rebound VMT

OMEGA uses a static set of mileage accumulation rates based on body style. OMEGA uses three self-explanatory body styles: sedan_wagon; cuv_suv_van; and, pickup. All vehicles in both the analysis and legacy fleets are characterized as being of one of these body styles. The rates at which each body style is aged-out of the fleet, or re-registered, and the miles driven by age are shown in Table 9-1 for light-duty and in Table 9-2 for medium-duty. The same values are used in both the analysis and the legacy fleets based on vehicle age.

Table 9-1 Mileage accumulation and re-registration rates used for light-duty

	Mileage Accumulation			Re-Registration Rate		
Age	Sedan_Wagon	CUV_SUV_Van	Pickup	Sedan_Wagon	CUV_SUV_Van	Pickup
0	15,922	16,234	18,964	100.0%	100.0%	100.0%
1	15,379	15,805	17,986	98.8%	98.8%	97.8%
2	14,864	15,383	17,076	97.7%	97.7%	96.3%
3	14,378	14,966	16,231	96.1%	96.1%	94.3%
4	13,917	14,557	15,449	94.5%	94.5%	93.1%
5	13,481	14,153	14,726	93.0%	93.0%	91.5%
6	13,068	13,756	14,060	91.1%	91.1%	89.3%
7	12,677	13,366	13,448	89.1%	89.1%	87.0%
8	12,305	12,982	12,886	86.9%	86.9%	84.1%
9	11,952	12,605	12,372	84.0%	84.0%	79.6%
10	11,615	12,234	11,903	80.0%	80.0%	74.2%
11	11,294	11,870	11,476	75.6%	75.6%	69.2%
12	10,986	11,512	11,088	70.6%	70.6%	64.1%
13	10,690	11,161	10,737	65.3%	65.3%	58.3%
14	10,405	10,816	10,418	59.5%	59.5%	53.5%
15	10,129	10,477	10,131	53.1%	53.1%	48.6%
16	9,860	10,146	9,871	45.8%	45.8%	44.2%
17	9,597	9,820	9,635	38.3%	38.3%	39.8%
18	9,338	9,501	9,421	30.8%	30.8%	35.2%
19	9,081	9,189	9,226	24.1%	24.1%	30.9%
20	8,826	8,883	9,047	18.3%	18.3%	26.7%
21	8,570	8,583	8,882	13.9%	13.9%	22.8%
22	8,313	8,290	8,726	10.7%	10.7%	20.2%
23	8,051	8,004	8,577	8.2%	8.2%	17.5%
24	7,785	7,724	8,433	6.3%	6.3%	15.8%
25	7,511	7,450	8,290	5.1%	5.1%	14.5%
26	7,229	7,183	8,146	4.2%	4.2%	13.9%
27	6,938	6,923	7,998	3.4%	3.4%	12.5%
28	6,635	6,669	7,842	2.8%	2.8%	11.1%
29	6,319	6,421	7,676	2.4%	2.4%	10.3%
30	5,988	6,180	7,497	0.0%	0.0%	9.3%
31	5,641	5,946	7,302	0.0%	0.0%	8.3%
32	5,277	5,718	7,089	0.0%	0.0%	7.3%
33	4,893	5,496	6,853	0.0%	0.0%	6.2%
34	4,488	5,281	6,593	0.0%	0.0%	5.0%
35	4,061	5,072	6,305	0.0%	0.0%	3.8%
36	3,610	4,870	5,987	0.0%	0.0%	2.7%
37	3,133	4,674	5,635	0.0%	0.0%	0.0%

Table 9-2 Mileage accumulation and re-registration rates used for medium-duty

	Mileage Accumulation		Re-Registration Rate	
Age	CUV_SUV_Van	Pickup	CUV_SUV_Van	Pickup
0	15,352	15,352	100%	100%
1	14,843	14,843	99%	99%
2	14,264	14,264	98%	98%
3	13,795	13,795	96%	96%
4	13,372	13,372	95%	95%
5	12,976	12,976	93%	93%
6	12,578	12,578	91%	91%
7	12,210	12,210	88%	88%
8	11,853	11,853	86%	86%
9	11,509	11,509	81%	81%
10	11,183	11,183	76%	76%
11	10,866	10,866	71%	71%
12	10,562	10,562	66%	66%
13	10,276	10,276	60%	60%
14	9,986	9,986	55%	55%
15	9,696	9,696	50%	50%
16	9,415	9,415	46%	46%
17	9,136	9,136	41%	41%
18	8,862	8,862	37%	37%
19	8,594	8,594	32%	32%
20	8,337	8,337	28%	28%
21	8,084	8,084	24%	24%
22	7,838	7,838	22%	22%
23	7,599	7,599	19%	19%
24	7,364	7,364	17%	17%
25	7,131	7,131	16%	16%
26	6,904	6,904	15%	15%
27	6,682	6,682	14%	14%
28	6,460	6,460	13%	13%
29	6,241	6,241	12%	12%
30	6,029	6,029	1%	1%

9.3.1 OMEGA "Context" VMT

When running OMEGA, the mileage accumulation rates and re-registration rates shown in Table 9-1 and Table 9-2 are used for all vehicles in both the analysis and legacy fleets at the indicated ages. To ensure that the "context" VMT (i.e., the total VMT of the analysis and legacy fleets) travels the number of miles projected by EIA's Annual Energy Outlook, OMEGA adjusts the VMT of every vehicle such that the total fleet VMT in any calendar year will equal that projected in AEO. This is done by determining ratio of the AEO projection for a given calendar year to that given calendar year's total VMT within OMEGA estimated using the static mileage accumulation rates shown in Table 9-1 and Table 9-2. That ratio is then applied to every vehicle's "static" VMT to arrive at a "context" VMT. This way, the fleet context VMT within OMEGA will be equivalent to the fleet VMT projected by AEO. Importantly, this context VMT does not yet include any rebound VMT, which is discussed below.

$$VehicleVMT_{context} = VehicleVMT_{static} \times \frac{FleetVMT_{AEO}}{FleetVMT_{OMEGA}}$$

Where,

$VehicleVMT_{context}$ = miles driven in OMEGA scenario 0 (the SAFE FRM in this case)

$VehicleVMT_{static}$ = miles driven using values shown in Table 9-1

$FleetVMT_{static}$ = the projected annual VMT in the AEO report being used

$FleetVMT_{OMEGA}$ = the calculated annual VMT within OMEGA using VehicleVMTstatic values

9.3.2 Context Fuel Costs Per Mile

The VMT rebound effect is discussed in detail in Chapter 4.2 Estimates of "rebound" miles driven depends, traditionally, on changing fuel prices and their effect on the number of miles people drive--as fuel prices rise and the cost per mile of driving increases, people drive less. OMEGA, we estimate the rebound effect not based on changing fuel prices, but rather on the changing cost per mile of driving for vehicles of different fuel consumption. In other words, someone that has purchased a new vehicle that consumes less fuel per mile might drive that vehicle more than if they would have continued to drive their prior vehicle that consumed more fuel per mile. As such, OMEGA's estimate of rebound VMT does not include any rebound VMT in the legacy fleet since the fuel consumption characteristics of the legacy fleet are not changing.

For the analysis fleet, OMEGA first determines the fuel cost per mile for each base year fleet vehicle in every calendar year included in the analysis. This way, the base year fleet vehicle's fuel consumption characteristics are not changing through the years but its fuel costs per mile are due to changing fuel prices. These fuel costs per mile for every vehicle in the base year fleet are then used as the context fleet, or context vehicle, fuel costs per mile.

In subsequent OMEGA scenarios, which include unique GHG standards that can result in unique fuel consumption characteristics for all vehicles, the fuel costs per mile for those vehicles are similarly determined. Since each vehicle in OMEGA is "derived" from a base year fleet vehicle, the fuel costs per mile for every vehicle can be compared to its context fuel cost per mile.

9.3.3 Rebound VMT

As discussed in Chapter 4.2, rebound VMT depends on the elasticity of demand for more driving. The input values used in the analysis were -0.1 for ICE vehicles and zero for BEV vehicles. We have used a value of zero for BEV vehicles since we do not project improvements to BEV battery and fuel consumption efficiencies in OMEGA. The rebound effect can then be calculated as:

$$VehicleVMT_{rebound} = VehicleVMT_{context} \times Elasticity \times \frac{\left(CPM_{policy} - CPM_{context}\right)}{CPM_{context}}$$

Where,

$VehicleVMT_{rebound}$ = the rebound miles driven

$VehicleVMT_{context}$ = the context VMT discussed above

$Elasticity$ = elasticity of demand

CPM_{policy} = the cost per mile in the policy scenario

$CPM_{context}$ = the cost per mile in the context scenario (the SAFE in this case)

And to calculate vehicle miles traveled in the policy scenario:

$$VehicleVMT_{policy} = VehicleVMT_{context} + VehicleVMT_{rebound}$$

Where,

$VehicleVMT_{policy}$ = the policy VMT

$VehicleVMT_{context}$ = the context VMT discussed above

$VehicleVMT_{rebound}$ = the rebound miles driven

9.3.4 Summary of VMT in the Analysis

The analysis fleet VMT will vary depending on the rebound elasticities used and the level of GHG standards, the latter of which impact the fuel consumption characteristics of the future fleet. The OMEGA No Action VMT and the projected fleet VMT under the proposed and alternative standards are shown in Table 9-3. Table 9-4 shows the rebound VMT.

Table 9-3 VMT summary, light-duty and medium-duty (billion miles)

Calendar Year	OMEGA No Action	OMEGA Proposal	OMEGA Alternative 1	OMEGA Alternative 2	OMEGA Alternative 3
2027	3,230	3,230	3,230	3,230	3,230
2028	3,251	3,252	3,252	3,252	3,251
2029	3,272	3,273	3,273	3,273	3,272
2030	3,295	3,296	3,297	3,296	3,295
2031	3,316	3,317	3,319	3,317	3,317
2032	3,328	3,329	3,332	3,329	3,329
2033	3,350	3,352	3,354	3,351	3,351
2034	3,371	3,373	3,376	3,373	3,373
2035	3,385	3,387	3,389	3,386	3,386
2036	3,408	3,410	3,413	3,409	3,410
2037	3,420	3,423	3,425	3,421	3,422
2038	3,444	3,446	3,448	3,445	3,446
2039	3,457	3,460	3,462	3,458	3,459
2040	3,480	3,483	3,485	3,481	3,482
2041	3,493	3,496	3,497	3,494	3,495
2042	3,515	3,518	3,519	3,516	3,517
2043	3,538	3,541	3,542	3,539	3,540
2044	3,552	3,555	3,556	3,552	3,554
2045	3,575	3,578	3,578	3,575	3,577
2046	3,599	3,602	3,602	3,599	3,601
2047	3,612	3,615	3,615	3,612	3,614
2048	3,636	3,639	3,638	3,636	3,638
2049	3,658	3,661	3,661	3,659	3,660
2050	3,682	3,685	3,685	3,683	3,684
2051	3,686	3,689	3,688	3,687	3,688
2052	3,690	3,693	3,692	3,691	3,692
2053	3,694	3,696	3,696	3,694	3,695
2054	3,697	3,700	3,699	3,698	3,699
2055	3,701	3,704	3,703	3,702	3,703

Table 9-4 Rebound VMT relative to no action, light-duty and medium-duty (billion miles)

Calendar Year	OMEGA Proposal	OMEGA Alternative 1	OMEGA Alternative 2	OMEGA Alternative 3
2027	-0.015	-0.0018	0.0044	-0.062

2028	0.15	0.4	0.19	-0.006
2029	0.35	1.2	0.33	0.08
2030	0.62	1.9	0.49	0.21
2031	0.92	2.7	0.77	0.40
2032	1.2	3.5	1.1	0.68
2033	1.6	4.1	1.3	1.1
2034	1.9	4.4	1.4	1.3
2035	2.0	4.6	1.4	1.5
2036	2.3	4.6	1.3	1.8
2037	2.7	4.6	1.1	1.9
2038	2.8	4.7	0.93	2.0
2039	2.9	4.7	0.80	2.1
2040	3.1	4.6	0.68	2.1
2041	3.0	4.3	0.56	2.0
2042	3.0	4.1	0.44	1.9
2043	2.9	3.8	0.33	1.8
2044	2.9	3.5	0.26	1.8
2045	2.9	3.3	0.22	1.8
2046	2.9	3.0	0.21	1.8
2047	2.9	2.8	0.24	1.8
2048	2.9	2.6	0.30	1.8
2049	2.9	2.5	0.42	1.8
2050	2.9	2.4	0.51	1.8
2051	2.8	2.2	0.61	1.7
2052	2.8	2.1	0.71	1.7
2053	2.7	2.0	0.80	1.7
2054	2.7	1.8	0.93	1.7
2055	2.7	1.8	1.1	1.8

9.4 Estimating Safety Effects

OMEGA estimates safety effects consistent with methods used in past light-duty GHG analyses and consistent with the methods developed by NHTSA for use in the CAFE Compliance and Effects Modeling System (CCEMS). In fact, the inputs used in OMEGA are identical to inputs used by NHTSA in CCEMS and used by EPA in the 2021 light-duty GHG final rule. (86 FR 74434 2021) NHTSA is the government entity tasked with regulating vehicle safety and, as such, NHTSA has the foremost experts in the field. EPA has worked closely with NTHSA through the years of joint GHG/CAFE regulatory development and has weighed in extensively on the statistical analyses used in estimating vehicle safety effects. That said, EPA has always used modeling parameters in OMEGA that are identical to those used by NHTSA in the CCEMS.

As noted, OMEGA uses vehicle travel fatality rates and safety values associated with mass reduction that have been generated by NHTSA. These fatality rates and safety values and how they are generated are described at length in the regulatory documents supporting NHTSA's 2022 CAFE final rule. (2022 CAFE FRIA 2022) (2022 CAFE TSD 2022) The discussion here does not attempt to provide that same level of detail and is meant only to summarize the NHTSA analysis to help in understanding the input values used in OMEGA.

The safety analysis is meant to capture effects associated with three factors:

- Changes in vehicle mass or weight;
- Changes associated with fleet composition including car, CUV, SUV, pickup shares and fleet turnover; and,

- The potential for additional safety impacts associated with additional driving (i.e., the “rebound effect” as mentioned in Chapter 9.3.3) that might arise from lower fuel costs resulting from more stringent GHG standards.

In the following, we first cover the base fatality rates of vehicles in the legacy fleet.. We then cover the changes to those fatality rates associated with changes in vehicle mass and changes in the analysis fleet composition. We then summarize the calculation approach to estimating fatalities within OMEGA and present results.

9.4.1 Fatality Rates used in OMEGA

To estimate the impact of the standards on safety, NHTSA uses statistical models that explicitly incorporate variation in the safety performance of individual vehicle model years. They use a model for fatalities that tracks vehicles from when they are produced and sold, enter the fleet, gradually age and are ultimately retired from service. NHTSA also considers how newer technologies are likely to affect the safety of both individual vehicles and the combined fleet. The overall safety of the light-duty vehicle fleet during any future calendar year is determined by the safety performance of the individual model year cohorts comprising it at the ages they will have reached during that year, the representation of each model year cohort in that (calendar) year’s fleet, and a host of external factors that fluctuate over time, such as driver demographics and behavior, economic conditions, traffic levels, and emergency response and medical care. Combining forecasts of future crash rates for individual model year cohorts at different ages with the composition of the vehicle fleet produces baseline forecasts of fatalities. Regulatory alternatives that establish new standards for future model years can change these forecasts by altering the representation of different model year cohorts making up the future light-duty fleet (2022 CAFE FRIA 2022). NHTSA’s work produces estimates of fatality rates for each model year making up the fleet during each future calendar year, and the process is continued until calendar year 2050. Multiplying these rates by the estimated number of miles driven by vehicles of each model year in use during a future calendar year produces baseline estimates of total fatalities. As an example, Figure 9-3 illustrates the recent history and baseline forecast of the overall fatality rate for occupants of cars and light trucks. According to NHTSA, the sharp rise in the fatality rate for 2020 coincided with the steep drop in car and light truck VMT during that year due to the COVID-19 pandemic and accompanying restrictions on activity, combined with an increased number of fatalities in 2020. These rates are also used as the basis for estimating future fatalities and for estimating changes in safety resulting from reductions in the mass of new vehicles, additional rebound-effect driving, and changes in the numbers of cars and light trucks from different model years making up each calendar year’s fleet. The underlying causes and methods for estimating each of those three sources of changes in safety are discussed in detail in various sub-sections of Chapter 7 of the Technical Support Document (TSD) accompanying NHTSA’s 2022 final rule (2022 CAFE TSD 2022).

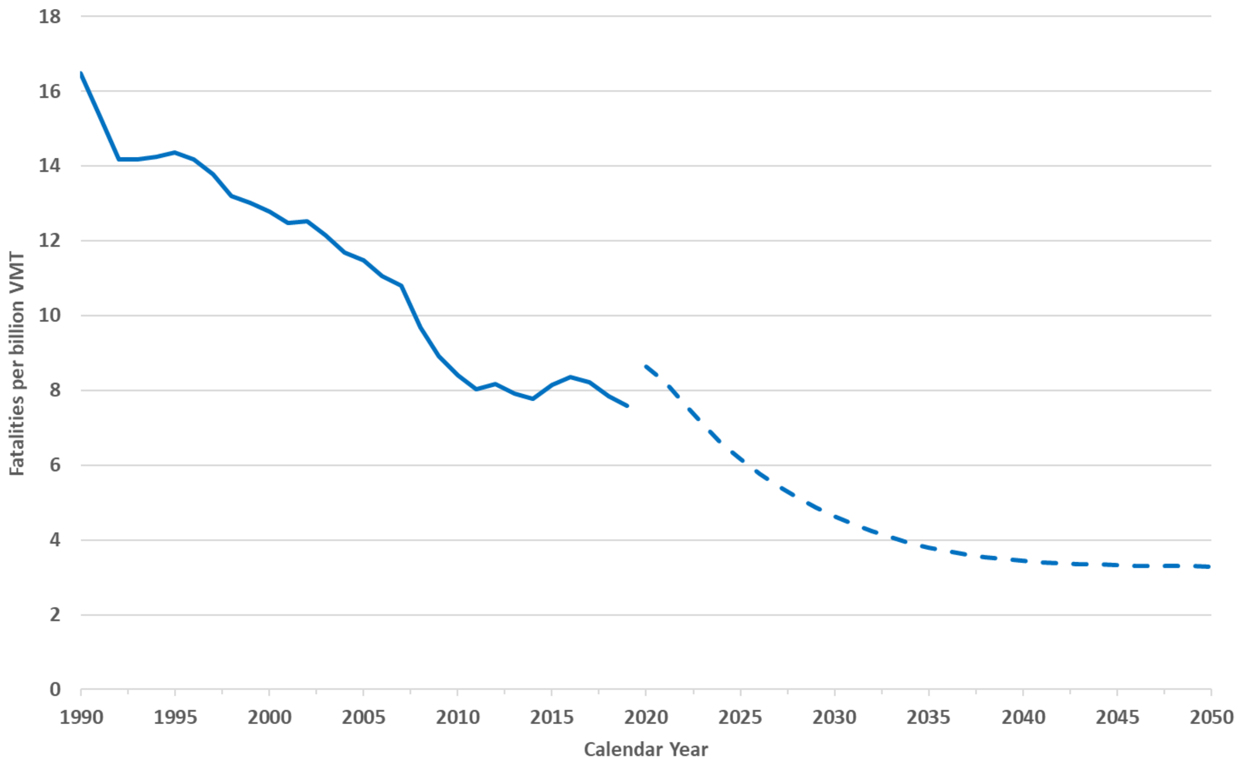

Figure 9-3 Recent and projected future fatality rates for cars and light trucks (2022 CAFE FRIA 2022, 109)

9.4.2 Calculating Safety Effects tied to Vehicle Weight Changes

To calculate the safety effects associated with changes to vehicle weight, OMEGA makes use of fatality rate changes per billion miles of vehicle travel associated with vehicles of different body styles—as with base fatality rates these are developed by NHTSA—and weight changes determined within OMEGA as vehicles change to meet future GHG standards. The first of these factors are, as noted, developed by NHTSA through an analytical process that is detailed in their 2022 final RIA and TSD (2022 CAFE FRIA 2022) (2022 CAFE TSD 2022). OMEGA makes use of the input parameters used by NHTSA in CCEMS model runs supporting their 2022 final rule. Those values are shown in Table 9-4.

Table 9-5 Safety values used in OMEGA (2022 CAFE FRIA 2022)

Body style	NHTSA Safety Class	Threshold (lbs)	Change per 100 lbs below threshold	Change per 100 lbs at or above threshold
sedan	PC	3201	0.012	0.0042
pickup	LT/SUV	5014	0.0031	-0.0061
cuv_suv	CUV/Minivan	3872	-0.0025	-0.0025

For example, the base fatality rate for a pickup would change by -0.0061 for every 100 pounds of weight reduced over 5,014 pounds. However, if that vehicle had a starting weight of 5,064 pounds and its weight was reduced by 100 pounds, then the first 50 of those pounds would reduce the base fatality rate by -0.00305 (-0.0061 per 100 pounds but for only 50 pounds) and the next 50 pounds would increase the base fatality rate by 0.00155 (0.0031 per 100 pounds but for only 50 pounds). In other words, reducing pickup weight above 5,014 pounds reduces fatalities while reducing pickup weight below 5,104 increases fatalities. In contrast, increasing pickup weight above 5,014 pounds increases fatalities while increasing pickup weight below 5,014 pounds reduces fatalities.

Therefore, OMEGA first determines the weight change of the given vehicle. This is calculated as the curb weight of the vehicle in the policy scenario (i.e., the final weight) relative to the curb weight of the vehicle in the base year fleet.

$$DeltaWeight = FinalWeight - BaseYearWeight$$

Where,

DeltaWeight = the change in weight, where a weight reduction will be a negative value

FinalWeight = the weight of the vehicle in the policy scenario

BaseYearWeight = the weight of the vehicle in the base year fleet

Knowing the delta weight, OMEGA then determines the weight change above and below the threshold for the body style of the given vehicle. Importantly, because OMEGA sometimes increases the curb weight of vehicles (e.g., due to conversion to BEV), whether the weight change is positive (increased weight) or negative (decreased weight) is important given the safety values and their signs as shown in Table 9-4.

To determine the pounds changed below the threshold, and whether they involve increased or decreased weight, OMEGA uses the logic shown below:

If: *Threshold* < *BaseWeight* and *Threshold* < *FinalWeight*:

Then: $DeltaPounds_{below} = 0$

Else if: *BaseWeight* < *Threshold* and *FinalWeight* < *Threshold*:

Then: $DeltaPounds_{below} = FinalWeight - BaseWeight$

Else if: *BaseWeight* < *Threshold* < *FinalWeight*:

Then: $DeltaPounds_{below} = Threshold - BaseWeight$

Else if: *FinalWeight* < *Threshold* < *BaseWeight*:

Then: $DeltaPounds_{below} = FinalWeight - Threshold$

To determine the pounds changed above the threshold, and whether they involve increased or decreased weight, OMEGA uses the logic shown below:

If: *BaseWeight* < *Threshold* and *FinalWeight* < *Threshold*

Then: $DeltaPounds_{above} = 0$

Else if: *Threshold* <= *BaseWeight* and *Threshold* <= *FinalWeight*

Then: $DeltaPounds_{above}$ = *FinalWeight* - *BaseWeight*

Else if: *BaseWeight* <= *Threshold* <= *FinalWeight*:

Then: $DeltaPounds_{above}$ = *FinalWeight* - *Threshold*

Else if: *FinalWeight* <= *Threshold* <= *BaseWeight*:

Then: $DeltaPounds_{above}$ = *Threshold* - *BaseWeight*

With the weight change above and below the threshold, OMEGA calculates the fatality rate changes as shown below:

$$RateChange_{below} = ChangePer100Pounds_{below} \times (-DeltaPounds_{below})$$

$$RateChange_{above} = ChangePer100Pounds_{above} \times (-DeltaPounds_{above})$$

Where,

RateChange = the change in fatality rate below/above the weight threshold for the given body style as shown in Table 9-4; the base fatality rate that is changed by this rate change is discussed in the next section.

ChangePer100Pounds = the applicable value for the given body style as shown in Table 9-4

DeltaPounds = the applicable value according to the logic described above.

9.4.3 Calculating Fatalities

OMEGA first calculates the fatality rate of a given vehicle in the given policy scenario. This is done using the equation below.

$$FatalityRate_{policy} = FatalityRate_{base} \times (1 + RateChange_{below}) \times (1 + RateChange_{above})$$

Where,

$FatalityRate_{policy}$ = the fatality rate per billion miles traveled in the policy scenario

$FatalityRate_{base}$ = the fatality rate per billion miles traveled in the base case (Chapter 9.4.1)

RateChange = the appliable result for the calculations described above (Chapter 9.4.2)

The number of fatalities in the given policy scenario are then calculated as:

$$Fatalities_{policy} = FatalityRate_{policy} \times VMT_{policy}/10^9$$

Where,

$Fatalities_{policy}$ = the number of fatalities in the policy scenario

$FatalityRate_{policy}$ = the fatality rate in the policy, as described above

VMT_{policy} = the vehicle miles traveled in the policy, as described in Chapter 9.3

9.4.4 Summary of Safety Effects in the Analysis

Table 9-6 shows the number of fatalities estimated in the No Action case (i.e., the EPA 2021 FRM remains in place) and the Proposal and Alternatives. Table 9-7 shows fatality rate impacts per billion miles of vehicle travel.

Table 9-6 Fatalities per year, light-duty and medium-duty

Calendar Year	No Action	Proposal	Alternative 1	Alternative 2	Alternative 3	Proposal % Change	Alternative 1 % Change	Alternative 2 % Change	Alternative 3 % Change
2027	20,432	20,438	20,438	20,436	20,434	0.03%	0.03%	0.02%	0.01%
2028	19,857	19,865	19,869	19,863	19,859	0.04%	0.06%	0.03%	0.01%
2029	19,334	19,344	19,356	19,341	19,336	0.05%	0.11%	0.04%	0.01%
2030	18,887	18,898	18,916	18,894	18,890	0.06%	0.16%	0.04%	0.02%
2031	18,470	18,486	18,508	18,482	18,479	0.09%	0.21%	0.06%	0.05%
2032	18,056	18,079	18,105	18,074	18,074	0.12%	0.27%	0.10%	0.10%
2033	17,732	17,766	17,793	17,760	17,762	0.19%	0.35%	0.16%	0.17%
2034	17,451	17,494	17,521	17,485	17,492	0.25%	0.40%	0.20%	0.23%
2035	17,177	17,226	17,251	17,216	17,225	0.29%	0.43%	0.23%	0.28%
2036	17,005	17,060	17,082	17,047	17,058	0.32%	0.45%	0.24%	0.31%
2037	16,835	16,896	16,916	16,879	16,893	0.36%	0.48%	0.26%	0.34%
2038	16,775	16,839	16,859	16,822	16,835	0.38%	0.50%	0.28%	0.36%
2039	16,717	16,783	16,803	16,767	16,779	0.39%	0.51%	0.30%	0.37%
2040	16,751	16,818	16,837	16,802	16,814	0.40%	0.52%	0.31%	0.38%
2041	16,764	16,831	16,850	16,816	16,829	0.40%	0.51%	0.31%	0.39%
2042	16,832	16,898	16,916	16,884	16,896	0.40%	0.50%	0.31%	0.38%
2043	16,918	16,985	17,001	16,971	16,983	0.40%	0.49%	0.31%	0.39%
2044	16,967	17,034	17,049	17,020	17,033	0.40%	0.49%	0.32%	0.39%
2045	17,056	17,124	17,138	17,110	17,123	0.39%	0.48%	0.32%	0.39%
2046	17,153	17,221	17,233	17,207	17,220	0.40%	0.47%	0.32%	0.39%
2047	17,198	17,266	17,278	17,252	17,266	0.40%	0.46%	0.31%	0.40%
2048	17,296	17,366	17,377	17,351	17,367	0.40%	0.46%	0.32%	0.41%
2049	17,404	17,476	17,486	17,460	17,476	0.41%	0.47%	0.32%	0.41%
2050	17,525	17,599	17,608	17,582	17,599	0.42%	0.47%	0.32%	0.42%
2051	17,568	17,643	17,653	17,626	17,644	0.43%	0.48%	0.33%	0.43%
2052	17,599	17,676	17,686	17,658	17,678	0.43%	0.49%	0.33%	0.45%
2053	17,633	17,711	17,723	17,693	17,714	0.45%	0.51%	0.35%	0.46%
2054	17,668	17,750	17,762	17,731	17,753	0.46%	0.53%	0.36%	0.48%
2055	17,706	17,790	17,803	17,771	17,794	0.47%	0.55%	0.37%	0.50%

Table 9-7 Fatality rate impacts, light-duty and medium-duty (fatalities per billion miles)

Calendar Year	No Action	Proposal	Alternative 1	Alternative 2	Alternative 3	Proposal % Change	Alternative 1 % Change	Alternative 2 % Change	Alternative 3 % Change

2027	6.33	6.33	6.33	6.33	6.33	0.03%	0.03%	0.02%	0.01%
2028	6.11	6.11	6.11	6.11	6.11	0.04%	0.05%	0.02%	0.01%
2029	5.91	5.91	5.91	5.91	5.91	0.04%	0.08%	0.03%	0.01%
2030	5.73	5.73	5.74	5.73	5.73	0.04%	0.10%	0.03%	0.01%
2031	5.57	5.57	5.58	5.57	5.57	0.06%	0.13%	0.04%	0.04%
2032	5.43	5.43	5.43	5.43	5.43	0.09%	0.16%	0.07%	0.07%
2033	5.29	5.30	5.30	5.30	5.30	0.14%	0.23%	0.12%	0.14%
2034	5.18	5.19	5.19	5.18	5.19	0.19%	0.27%	0.15%	0.19%
2035	5.07	5.09	5.09	5.08	5.09	0.23%	0.30%	0.19%	0.23%
2036	4.99	5.00	5.01	5.00	5.00	0.25%	0.32%	0.21%	0.26%
2037	4.92	4.94	4.94	4.93	4.94	0.28%	0.34%	0.23%	0.29%
2038	4.87	4.89	4.89	4.88	4.89	0.30%	0.36%	0.25%	0.30%
2039	4.84	4.85	4.85	4.85	4.85	0.31%	0.37%	0.27%	0.31%
2040	4.81	4.83	4.83	4.83	4.83	0.31%	0.39%	0.29%	0.32%
2041	4.80	4.81	4.82	4.81	4.81	0.31%	0.39%	0.30%	0.33%
2042	4.79	4.80	4.81	4.80	4.80	0.31%	0.38%	0.30%	0.33%
2043	4.78	4.80	4.80	4.80	4.80	0.32%	0.39%	0.30%	0.33%
2044	4.78	4.79	4.79	4.79	4.79	0.32%	0.39%	0.31%	0.34%
2045	4.77	4.79	4.79	4.79	4.79	0.31%	0.38%	0.31%	0.34%
2046	4.77	4.78	4.78	4.78	4.78	0.32%	0.39%	0.31%	0.34%
2047	4.76	4.78	4.78	4.78	4.78	0.32%	0.39%	0.31%	0.35%
2048	4.76	4.77	4.78	4.77	4.77	0.32%	0.39%	0.31%	0.36%
2049	4.76	4.77	4.78	4.77	4.77	0.33%	0.40%	0.31%	0.36%
2050	4.76	4.78	4.78	4.77	4.78	0.34%	0.41%	0.31%	0.38%
2051	4.77	4.78	4.79	4.78	4.78	0.35%	0.42%	0.31%	0.39%
2052	4.77	4.79	4.79	4.78	4.79	0.36%	0.44%	0.32%	0.40%
2053	4.77	4.79	4.80	4.79	4.79	0.37%	0.46%	0.32%	0.42%
2054	4.78	4.80	4.80	4.79	4.80	0.39%	0.48%	0.33%	0.43%
2055	4.78	4.80	4.81	4.80	4.81	0.40%	0.50%	0.34%	0.45%

9.5 Estimating Fuel Consumption in OMEGA

9.5.1 Drive Cycles for Onroad Fuel Consumption

To develop a best mix of regulatory cycles representing typical onroad vehicle operation, EPA used two sources: the MOVES light-duty drive cycles and associated weights, and aggregate vehicle behavior gleaned from California Real Emissions Assessment Logging (REAL) data.

The MOVES model uses 18 representative cycles. For each cycle, the time, distance, and energy expenditure at each speed was calculated, then binned in 0.5 mph increments. Additionally, the average speed and positive kinetic energy ("PKE;" a measure of driver aggressiveness) was calculated. The energy expenditure was calculated using the equivalent test weight (ETW) and road load of a nominal vehicle. Nominal vehicle characteristics were determined using the MOVES average passenger car and light truck parameters, weighted by vehicle miles traveled (VMT). The statistics for all cycles were combined and weighted based on the VMT associated with each cycle. The end result indicated an average speed of 36.6 mph and a PKE of 3700 km/hr^2.

From the California REAL data, the average vehicle speed and positive kinetic energy was determined across a range of vehicles. These data indicated an average speed higher than that from the MOVES model data (41.1 mph), but a similar PKE (3900 km/hr^2).

To represent onroad behavior, EPA began with the energy expenditure distribution from the MOVES data, as shown in Figure 9-8. The MOVES energy expenditure distribution is shown compared to the energy expenditure distribution of the "city" (FTP) and highway (HW) cycles, weighted 55%/45%. As can be seen, the 55/45 FTP/HW cycle has peak energy expenditure at a noticeably lower MJ/mile value, leading to a substantially lower cumulative energy expenditure. (The small peaks in the 55/45 FTP/HW cycle correspond to accelerations of positive and negative 3.3 mph/sec, accelerations at which these cycles are truncated.)

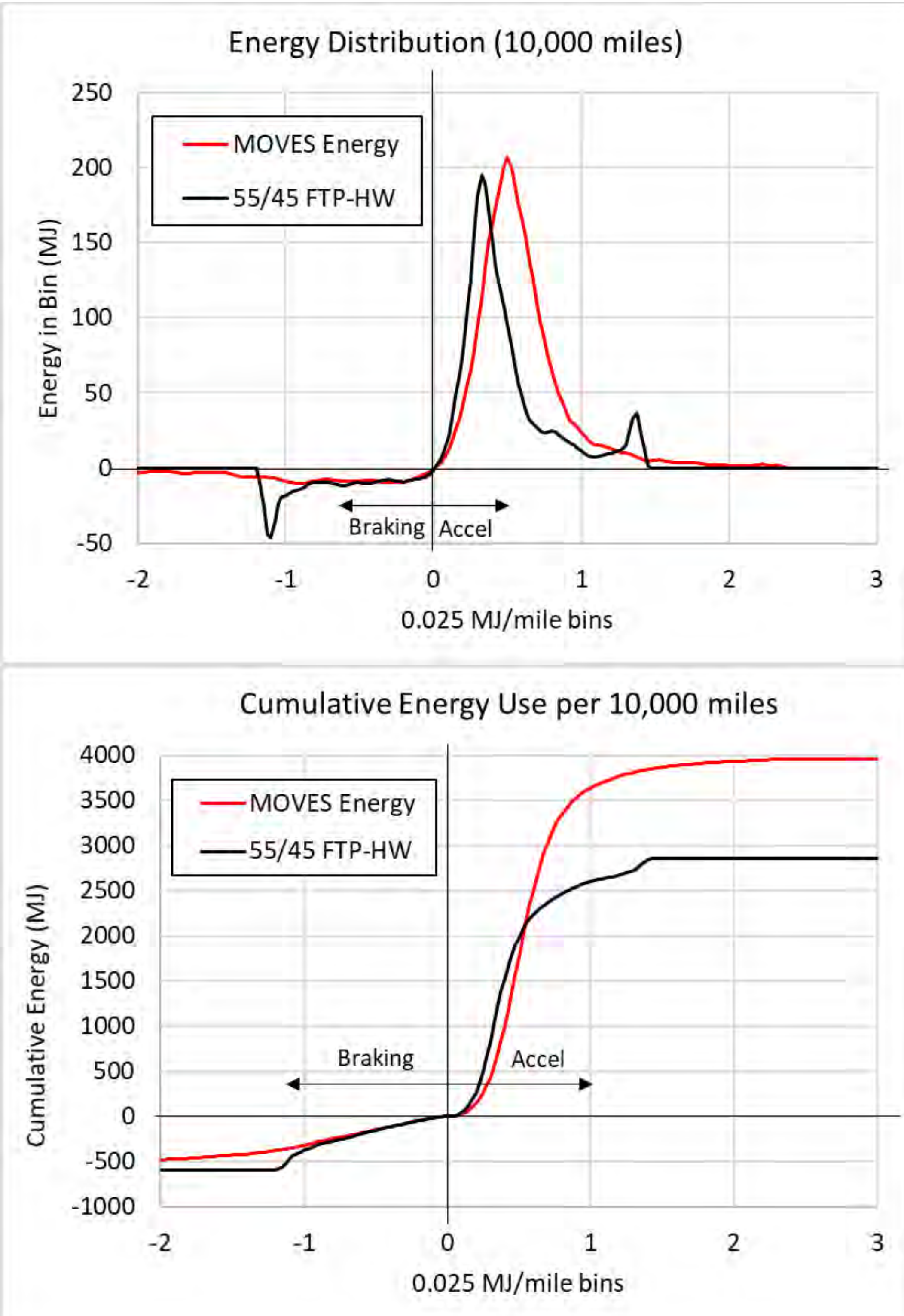

Figure 9-4 Energy distribution (top) and cumulative energy use (bottom) over 10,000 miles for the MOVES onroad data, compared to FTP/HW regulatory cycles, weighted 55%/45%.

To develop a better mix of cycles to represent onroad operation, EPA looked primarily at the energy distribution, but also factored in the distribution of speeds and the PKE. At the end, a mix of cycles was chosen that best matched these multiple optimization criteria.

EPA evaluated reweighting the bags of the FTP, and incorporating portions of the US06 cycle. Reweighting the FTP did not improve the energy distribution match between vehicle operation across cycles and representative onroad operation used to estimate energy use and fuel consumption. However, incorporating the high acceleration and high-speed portions of the US06 did improve the energy distribution match with the MOVES data. Moreover, with the inclusion of the US06 cycle, incorporating the HW cycle conferred no benefit, and this cycle was dropped.

After considering the effects of various cycle mixes, EPA selected a mix of cycles where the weighting was 27% FTP, 6% US06 bag 1 (a high acceleration "city" bag), and 67% US06 bag 2 (a high speed "highway" bag). The energy expenditure distribution for this new cycle mix is shown in Figure 9-9, again compared to the MOVES data. As can be seen, the energy distribution of this cycle mix is much better aligned with the MOVES data, and the total positive energy expended is nearly identical.

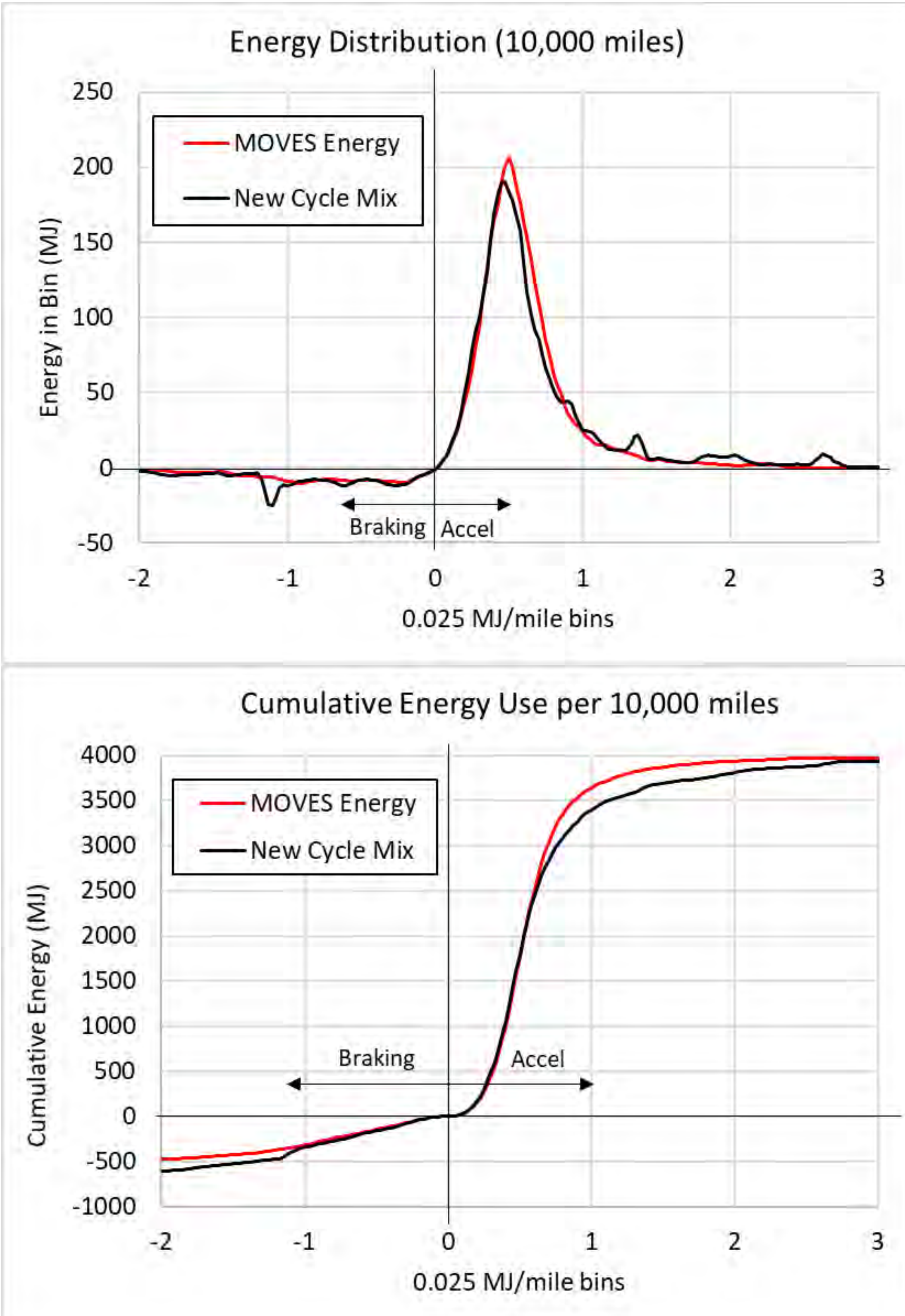

Figure 9-5 Energy distribution (top) and cumulative energy use (bottom) over 10,000 miles for the new cycle mix (27% FTP, 6% US06 bag 1, 67% US06 bag 2) compared to the MOVES onroad data.

In choosing this new cycle mix, EPA also considered the speed distribution of the mix and the PKE. This mix of cycles had a PKE of 4300 km/hr^2 (slightly higher than the MOVES or REAL data) and an average speed of 40.6 mph. This average speed is higher than that of the MOVES data, and closer to (but lower than) the REAL data. The speed distribution for this mix is shown in Figure 9-10.

As can be inferred from Figure 9-10, the FTP and US06 cycles have substantial periods of operation within a small speed window, giving the speed distribution the clear double-humped shape. However, the overall speed profile remains similar that from the MOVES data.

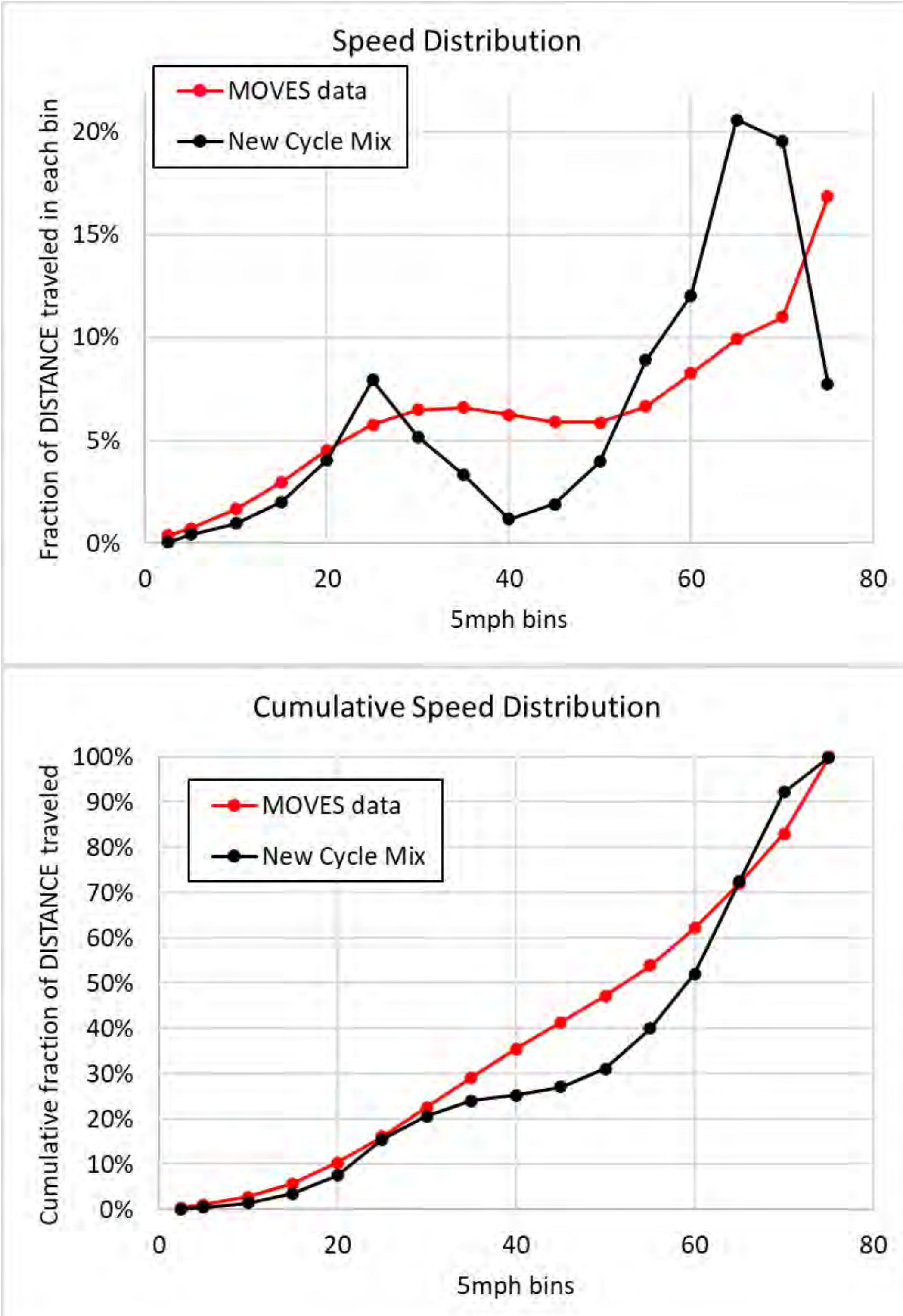

Figure 9-6 Speed distribution for the new cycle mix (27% FTP, 6% US06 bag 1, 67% US06 bag 2) compared to the MOVES onroad data.

To estimate fuel consumption impacts, OMEGA considers both the fuel(s) used by a given vehicle and the share of miles driven by the vehicle on that fuel or fuels. For a fossil fuel-only vehicle (including HEVs) or a BEV, the share of miles driven on the primary fuel would be 100 percent. For a PHEV, the share of miles driven on each fuel, the primary fuel (presumably liquid fuel), and the secondary fuel (presumably electricity), are considered.

First, the vehicle miles traveled for the given vehicle on each fuel is calculated as below.

$$VMT_{vehicle;fuel} = VMT_{vehicle} \times FuelShare$$

Where,

$VMT_{vehicle;fuel}$ = the VMT of the vehicle on a given fuel

$VMT_{vehicle}$ = the VMT of the vehicle

FuelShare = the share of miles driven on a given fuel

9.5.2 Electricity Consumption

For BEVs, the fuel share value will be 1, or 100 percent of VMT using electricity. To estimate fuel consumption, the VMT is multiplied by the rate of energy consumption, or kWh/mile during onroad operation. The rate of energy consumption during onroad operation is calculated using the 2-cycle certification rate of energy consumption and a traditional 2-cycle to onroad gap value, as below.

$$\left(\frac{kWh}{mile}\right)_{vehicle;\,onroad} = \left(\frac{kWh}{mile}\right)_{vehicle;\,2-cycle} \div 0.7$$

Where,

$(kWh/mile)_{vehicle;onroad}$ = rate of energy consumption during onroad operation

$(kWh/mile)_{vehicle;2\text{-}cycle}$ = the rate of energy consumption during the certification 2-cycle test

0.7 = the factor to account for losses associated with roadway and environmental factors not captured on the 2-cycle certification test

Electricity consumption is then calculated as:

$$FuelConsumption_{vehicle;electricity} = VMT_{vehicle;electricity} \times \left(\frac{kWh}{mile}\right)_{vehicle;\,onroad}$$

Where,

$FuelConsumption_{vehicle;\,electricity}$ = the electricity consumption of the given vehicle

$VMT_{vehicle;\,electricity}$ = the vehicle miles traveled on electricity

$(kWh/mile)_{vehicle;\,onroad}$ = the vehicle rate of energy consumption onroad

9.5.3 Liquid-Fuel Consumption

For liquid fuel consumption, OMEGA calculates the onroad fuel consumption rate making use of the onroad CO2/mile and the CO2 content of a gallon of gasoline, as below.

$$\left(\frac{Gallons}{mile}\right)_{vehicle;onroad} = \frac{\left(\frac{CO2}{mile}\right)_{vehicle;\,2-cycle}}{0.8} \div \left(\frac{CO2}{gallon}\right)_{vehicle;\,2-cycle}$$

Where,

$(Gallons/mile)_{vehicle;onroad}$ = the fuel consumption rate of the given vehicle onroad

$(CO2/mile)_{vehicle;\,2\text{-}cycle}$ = the CO2/mile of the given vehicle on the

$(CO2/gallon)_{vehicle;\,2\text{-}cycle}$ = the CO2 emitted from combustion of a gallon of fuel (8,887 for gasoline, 10,180 for diesel)

0.8 = the factor to account for losses associated with roadway and environmental factors not captured on the 2-cycle certification test

Liquid-fuel consumption is then calculated as below.

$$FuelConsumption_{vehicle;liquid} = VMT_{vehicle;liquid} \times \left(\frac{Gallons}{mile}\right)_{vehicle;\,onroad}$$

Where,

$FuelConsumption_{vehicle;\,liquid}$ = the liquid-fuel consumption of the given vehicle

$VMT_{vehicle;\,liquid}$ = the vehicle miles traveled on liquid-fuel

$(Gallons/mile)_{vehicle;\,onroad}$ = the vehicle rate of liquid-fuel consumption onroad

9.5.4 Summary of Fuel Consumption in the Analysis

Table 9-8 Fuel consumption impacts, proposed standards, light-duty and medium-duty

Calendar Year	Liquid Fuel (billion gallons)	Electricity (TWh)	Liquid Fuel % Change	Electricity % Change
2027	-0.89	8.9	-0.62%	12%
2028	-2.2	21	-1.6%	21%
2029	-4	38	-3.0%	29%
2030	-6.1	56	-4.8%	35%
2031	-8.6	78	-7.1%	42%
2032	-12	100	-9.9%	49%
2033	-15	130	-13%	57%
2034	-18	160	-16%	64%
2035	-21	190	-20%	70%
2036	-23	210	-23%	73%
2037	-26	230	-26%	78%
2038	-29	260	-29%	83%
2039	-31	280	-32%	87%
2040	-34	300	-35%	92%
2041	-36	320	-37%	96%
2042	-38	340	-39%	98%
2043	-40	360	-41%	102%
2044	-41	370	-43%	103%
2045	-42	380	-44%	104%
2046	-44	390	-46%	107%
2047	-45	400	-47%	107%
2048	-46	410	-47%	109%
2049	-47	420	-48%	110%
2050	-48	430	-49%	110%
2051	-48	430	-49%	111%
2052	-48	430	-49%	111%
2053	-49	440	-50%	111%
2054	-49	440	-50%	111%
2055	-49	440	-50%	110%
Sum	-900	8100		
One Terawatt hour (TWh) is equal to 1 billion kilowatt hours (kWh)				

Table 9-9 Fuel consumption impacts, Alternative 1 standards, light-duty and medium-duty

Calendar Year	Liquid Fuel (billion gallons)	Electricity (TWh)	Liquid Fuel % Change	Electricity % Change
2027	-0.93	9.3	-0.65%	13%
2028	-2.5	23	-1.8%	23%
2029	-4.4	39	-3.4%	31%
2030	-7	61	-5.6%	39%
2031	-9.8	84	-8.1%	45%
2032	-13	110	-11.1%	52%
2033	-17	140	-15%	61%
2034	-20	170	-18%	69%
2035	-23	200	-22%	76%
2036	-26	230	-25%	79%
2037	-29	260	-29%	85%
2038	-32	280	-32%	91%
2039	-35	310	-36%	96%
2040	-38	330	-39%	101%
2041	-40	360	-41%	106%
2042	-42	370	-44%	109%
2043	-44	400	-46%	113%
2044	-46	410	-48%	115%
2045	-47	420	-49%	116%
2046	-49	440	-51%	119%
2047	-49	450	-51%	119%
2048	-51	460	-52%	121%
2049	-52	470	-53%	122%
2050	-52	470	-54%	123%
2051	-53	480	-54%	123%
2052	-53	480	-54%	123%
2053	-53	490	-55%	123%
2054	-54	490	-55%	123%
2055	-54	490	-55%	123%
Sum	-1000	8900		
One Terawatt hour (TWh) is equal to 1 billion kilowatt hours (kWh)				

Table 9-10 Fuel consumption impacts, Alternative 2 standards, light-duty and medium-duty

Calendar Year	Liquid Fuel (billion gallons)	Electricity (TWh)	Liquid Fuel % Change	Electricity % Change
2027	-0.65	6.4	-0.45%	9%
2028	-1.6	15	-1.2%	15%
2029	-3.2	29	-2.4%	23%
2030	-4.9	44	-3.8%	28%
2031	-7	64	-5.8%	34%
2032	-9.6	86	-8.3%	40%
2033	-13	110	-11%	49%
2034	-16	140	-14%	56%
2035	-19	170	-17%	62%
2036	-21	190	-20%	65%
2037	-23	210	-23%	71%
2038	-26	230	-26%	76%
2039	-28	260	-29%	80%
2040	-31	280	-31%	84%
2041	-33	300	-34%	89%
2042	-34	310	-36%	91%
2043	-36	330	-38%	94%
2044	-37	340	-39%	95%
2045	-38	350	-40%	96%
2046	-40	360	-41%	99%
2047	-40	370	-42%	99%
2048	-42	380	-43%	100%
2049	-42	390	-44%	101%
2050	-43	390	-44%	102%
2051	-43	400	-44%	102%
2052	-44	400	-45%	102%
2053	-44	400	-45%	102%
2054	-44	400	-45%	101%
2055	-44	400	-45%	101%
Sum	-810	7400		
One Terawatt hour (TWh) is equal to 1 billion kilowatt hours (kWh)				

Table 9-11 Fuel consumption impacts, Alternative 3 standards, light-duty and medium-duty

Calendar Year	Liquid Fuel (billion gallons)	Electricity (TWh)	Liquid Fuel % Change	Electricity % Change
2027	-0.53	5.4	-0.37%	7%
2028	-1.3	13	-1.0%	13%
2029	-2.3	22	-1.8%	17%
2030	-3.9	36	-3.1%	23%
2031	-6.3	58	-5.2%	31%
2032	-9.3	85	-8.1%	40%
2033	-13	110	-11%	49%
2034	-16	140	-15%	58%
2035	-19	170	-18%	65%
2036	-22	190	-21%	68%
2037	-25	220	-25%	74%
2038	-28	250	-28%	80%
2039	-30	270	-31%	85%
2040	-33	290	-34%	90%
2041	-35	320	-36%	95%
2042	-37	330	-39%	97%
2043	-39	350	-41%	101%
2044	-41	370	-42%	103%
2045	-42	380	-44%	104%
2046	-44	390	-45%	107%
2047	-44	400	-46%	107%
2048	-46	410	-47%	109%
2049	-47	420	-48%	111%
2050	-48	430	-49%	112%
2051	-48	440	-49%	112%
2052	-48	440	-49%	112%
2053	-49	440	-50%	112%
2054	-49	440	-50%	112%
2055	-49	440	-50%	111%
Sum	-870	7900		
One Terawatt hour (TWh) is equal to 1 billion kilowatt hours (kWh)				

9.6 Estimating Emission Inventories in OMEGA

To estimate emission inventory effects due to a potential policy, OMEGA uses, as inputs, a set of vehicle and electricity generating unit (EGU) emission rates. In a circular process, we first generate emission inventories using very detailed emissions models that estimate inventories from vehicles (EPA's MOVES model) and EGUs (EPA’s Power Sector Modeling Platform, v.6.21). The generation of those inventories is described in Chapter 8 and Chapter 5, respectively. However, upstream inventories (EGUs) made use of a set of bounding runs that l ooked at two possible futures--one with a low level of fleet electrification and another with a higher level of electrification. These bounding runs represented our best estimate of these two possible futures--the continuation of the 2021 FRM (lower) and our proposal (upper)--at the time that those model runs were conducted. With those bounded sets of inventories, and the associated fuel demands within them (i.e., electricity demands for EGUs), we can calculate emission rates for the two ends of these bounds. Using those rates, we can interpolate, using the given OMEGA policy scenario's fuel demands, to generate a unique set of emission rates for that OMEGA policy scenario. Using those unique rates, OMEGA then generates emission inventories for any future OMEGA policy scenario depending on the liquid fuel and electricity demands of that specific policy.

For vehicle emissions, EPA made use of two sets of MOVES emission inventory runs--one assuming no future use of gasoline particulate filters and one assuming such use. Using the miles traveled (for tailpipe, tire wear and brake wear emissions) and liquid fuel consumed (for evaporative and fuel spillage emissions), we can then generate sets of emission rates for use in OMEGA. Using those rates, which are specific to fuel types and vehicle types (car vs. truck, etc.), we can then generate unique emission inventories for the given OMEGA policy scenario. This is important given the changing nature of the transportation fleet (BEV vs ICE, car vs CUV vs pickup) and the way those change for any possible policy scenario and the many factors within that impact the future fleet composition and the very different vehicle emission rates for BEV vs ICE vehicles. This is especially true given the consumer choice elements within OMEGA and the wide variety of input parameters that can have significant impacts on the projected future fleet.

9.6.1 Calculating EGU Emission Rates in OMEGA

As described in Chapter 5 and presented in Chapter 5.2.3, EPA has generated EGU inventories for the no-action case and the proposal. Those inventories are presented in Tables 5-2 and 5-3 and are shown graphically in the accompanying charts. To generate those inventories, EPA first ran OMEGA to estimate PEV energy demands into the future. Those energy demands were used in the modeling of EGU inventories presented in Chapter 5. EPA then uses the resultant inventories along with the associated "Generation" values shown in Tables 5-2 and 5-3, appropriately, and the estimated PEV energy demands from OMEGA used in generating the EGU inventory results, to generate a set of curves as a function of years from 2020. The set of curves consist of US generation, US PEV consumption and EGU emission rate curves for each of the pollutants presented in Chapter 5. The resultant curves for select pollutants are shown in Table 9-12.

Table 9-12 Select EGU emission rate curves used in OMEGA

case	Pollutant	Emission Rate (g/kWh)
2021 FRM	PM2.5	-0.00044234 * (CY - 2020) + 0.01622
2021 FRM	NOx	-0.0030907 * (CY - 2020) + 0.097841
2021 FRM	SOx	-0.0029835 * (CY - 2020) + 0.083245
2021 FRM	VOC	-0.00019251 * (CY - 2020) + 0.0078643
2021 FRM	CO2	-8.50323 * (CY - 2020) + 286.645
2021 FRM	CH4	-0.000575 * (CY - 2020) + 0.017952
2021 FRM	N2O	-8.0208e-05 * (CY - 2020) + 0.0024539
proposal	PM2.5	-0.00044425 * (CY - 2020) + 0.016266
proposal	NOx	-0.0030975 * (CY - 2020) + 0.09796
proposal	SOx	-0.0029965 * (CY - 2020) + 0.083798
Proposal	VOC	-0.00019149 * (CY - 2020) + 0.0077913
proposal	CO2	-8.50171 * (CY - 2020) + 287.643
proposal	CH4	-0.00057841 * (CY - 2020) + 0.018106
proposal	N2O	-8.0707e-05 * (CY - 2020) + 0.0024761
Note: CY = calendar year; g/kWh = grams per kilowatt hour; all values use 6 significant digits.		

$$US\ Electricity\ Generation_{lowPEV} = 82{,}260{,}700{,}000 * (CY - 2020) + 3{,}903{,}690{,}000{,}000$$

$$US\ Electricity\ Generation_{highPEV} = 92{,}384{,}200{,}000 * (CY - 2020) + 3{,}861{,}790{,}000{,}000$$

$$US\ PEV\ Consumption_{lowPEV} = 13{,}975{,}600{,}000 * (CY - 2020) + 27{,}523{,}300{,}000$$

Where,

lowPEV = low PEV penetration, i.e., the 2021 FRM

highPEV = high PEV penetration, i.e., the proposal

CY = calendar year

Using these curves, OMEGA can calculate the US electricity generation in any year of the analysis as well as the PEV consumption used in estimating the EGU inventories presented in Chapter 5.

To estimate the unique EGU emission rates for any given OMEGA scenario, OMEGA first determines the PEV consumption estimate for a given year, which is driven by the level of the standards and the expected PEV penetration rate, among other impacts (consumer acceptance, critical materials, etc.). OMEGA then subtracts from the estimated US generation value for that year, calculated using the above US Electricity Generation curve, the PEV consumption estimate used in generating the inventories, calculated using the above US PEV Consumption curve, then adds to that result the OMEGA estimated PEV consumption for the given year in the given OMEGA scenario. That result is then used as a new US generation value, unique to the given OMEGA scenario.

$$\begin{aligned} Generation_{scenario} &= Generation_{lowPEV} - US\ PEV\ Consumption_{lowPEV} \\ &\quad + US\ PEV\ Consumption_{scenario} \end{aligned}$$

OMEGA then calculates the EGU emission rate for each pollutant in the low PEV (2021 FRM) case and the high PEV (proposal) scenarios, both of which are calculated using the rate curves shown in Table 9-12. OMEGA then interpolates a set of EGU emission rates unique to the given scenario as below.

$$\begin{aligned} Rate_{scenario} &= Rate_{lowPEV} \\ &\quad - (Generation_{lowPEV} - Generation_{scenario}) \\ &\quad \times \frac{(Rate_{lowPEV} - Rate_{highPEV})}{(Generation_{lowPEV} - Generation_{highPEV})} \end{aligned}$$

Where, for a given pollutant in a given year of a given OMEGA scenario,

$Rate_{scenario}$ = the EGU emission rate in the scenario

$Rate_{lowPEV}$ = the EGU emission rate calculated using the 2021 FRM rate curves in Table 9-12

$Rate_{highPEV}$ = the EGU emission rate calculated using the proposal rate curves in Table 9-12

$Generation_{lowPEV}$ = US electricity generation using the low PEV curve

$Generation_{highPEV}$ = US electricity generation using the high PEV curve

$Generation_{scenario}$ = US electricity generation in the scenario using the equation above

9.6.2 Calculating Refinery Emission Rates in OMEGA

As presented and discussed in Chapter 8.2.2 of this DRIA, the illustrative AQM done by EPA showed refinery emission inventories as shown in Table 9-13.

Table 9-13 Refinery emissions in AQM inventories in 2055

Pollutant	2016 (tons/year)	Reference Scenario (tons/yr)	LMDV Regulatory Scenario (tons/yr)
PM2.5	78,332	18,855	18,468
NOX	19,958	67,470	66,067
SO2	30,065	28,851	28,281
VOC	67,853	56,946	55,876

Using AEO 2021, Table 11, we estimated that the U.S. produced 194 billion gallons of gasoline and diesel fuel in calendar year 2021 which represented 64 percent of the refined products produced by U.S. refineries, the rest being liquified petroleum gas, jet fuel, home heating oil and other. Using these 2021 gallons and attributing them to the 2016 inventories (in the absence of 2016 gallons or 2021 inventories), we arrived at 2016 refinery emission rates as shown in Table 9-14 (e.g., for $PM_{2.5}$, 78,332 tons/year x 907185 grams/ton divided by 194 billion gallons divided by 0.64 gasoline and diesel share = 0.578 grams/gallon, where rounding might result in slight differences). We followed the same procedure to estimate refinery emission rates in the LMDV regulatory scenario by dividing the tons/year shown in Table 9-13 by the estimated gallons of gasoline and diesel fuel associated with those inventories, or 131 billion gallons (see Chapter 5.1 of the Air Quality Analysis TSD). Those refinery emission rates are also shown in Table 9-14. Using the refinery emission rates shown in Table 9-14, we then calculated linear curves between the years 2016 and 2055, with years from 2016 as the independent variable, for use as inputs to OMEGA. Those refinery emission rate curves are shown in Table 9-15.

Table 9-14 Refinery emission rates estimated using AQM results

Pollutant	2016 (grams/gallon)	LMDV Regulatory Scenario (grams/gallon)
NOx	0.578	0.456
PM2.5	0.147	0.128
SOx	0.222	0.195
VOC	0.500	0.386

Table 9-15 Refinery emission rate curves used in OMEGA

Pollutant	Emission Rate (grams/gallon)
NOx	-0.00311 * (CY - 2016) + 0.578
PM2.5	-0.00050 * (CY - 2016) + 0.147
SOx	-0.00068 * (CY - 2016) + 0.222
VOC	-0.00294 * (CY - 2016) + 0.500

Importantly, the AQM for refineries as presented in Chapter 8 of this DRIA includes only the pollutants discussed there and briefly here. This means that we do not estimate GHG-related refinery emission impacts in OMEGA at this time. Note also that OMEGA applies a 93 percent factor to reduced liquid-fuel demand to account for the share of reduced demand resulting in reduced domestic refining of liquid fuel. In other words, 93 percent of the reduced liquid fuel demand results in reduced domestic refining. We also ran a sensitivity that assumes that reduced liquid fuel demand would have no impact on domestic refining. In that sensitivity, we would be assuming that the excess liquid fuel would be exported for use elsewhere.

9.6.3 Vehicle Emission Rates in OMEGA

As detailed in a memo to the docket, EPA developed an updated version of MOVES3, MOVES3.R1, for use in estimating vehicle emissions for this proposal. (Beardsley 2023) To create inputs for OMEGA, EPA ran MOVES3.R1 model for two scenarios: gasoline engines with and without gasoline particulate filters (GPFs). The emission rates for these scenarios differed in that in the scenario with GPFs, the emission rates for exhaust PM were calculated by applying the GPF reduction factors described in Chapter 8 for MY 2030 and later. We ran MOVES in inventory mode to create inventory and activity output by calendar year, model year, fuel type, source type and regulatory class for brake wear, tire wear, start, running and evaporative emissions for criteria emission precursors and air toxics. In these runs, the only air toxics affected by GPFs were particle-phase PAHs, which are chained to exhaust PM in MOVES. We consolidated the PAH output to separately report emissions for naphthalene and for a potency-weighted (U.S. EPA 2021) sum of the 15 other PAHs estimated by MOVES.

These two sets of MOVES output were then used to generate vehicle emission rate curves for use as OMEGA inputs. Since MOVES generates emission inventories, and the applicable miles traveled or gallons consumed attributes associated with those inventories, we can calculate nationwide vehicle emission rates from them. This is done by calculating a linear relationship between the vehicle miles traveled, or gallons consumed, and the inventory attribute. This process generates over 1,400 vehicle emission rate curves including curves for each of the pollutants and start years shown in Table 9-16 with rates for exhaust PM2.5 shown in Table 9-16 through Table 9-20 for cars, light-duty trucks, medium-duty vans and medium-duty pickups, respectively. A start year refers to the model year for which a certain set of emission rate curves would apply, until a subsequent start year becomes more appropriate and is, therefore, used instead.

Table 9-16 Pollutants for which vehicle emission rate curves were generated for use in OMEGA

Start Years	RegClass: SourceType	Vehicle attribute	Fuel	Pollutant
1995, 2000, 2005, 2010, 2015, 2017, 2020, 2025, 2030	Car:passenger car Truck:passenger truck Mediumduty:passenger truck Mediumduty:light Commercial truck Mediumduty:short-haul single unit class3 Mediumduty:long-haul single unit class3 Mediumduty:motor home	Miles traveled	Gasoline; Diesel	Exhaust CO
				Exhaust NMOG
				Exhaust NOx
				Exhaust CH4
				Exhaust N2O
				Exhaust PM2.5
			Gasoline; Diesel; Electricity	Brakewear PM2.5
				Tirewear PM2.5
			Gasoline; Diesel	Exhaust Acetaldehyde
				Exhaust Acrolein
				Exhaust Benzene
				Exhaust 1,3 Butadiene
				Exhaust Ethylbenzene
				Exhaust Formaldehyde
				Exhaust Naphthalene
				Exhaust 15 PAH
		Gallons consumed	Gasoline	Evaporative permeation NMOG
				Evaporative fuel vapor venting NMOG
				Evaporative fuel leaks NMOG
				Refueling displacement NMOG
				Refueling spillage NMOG
				Evaporative permeation Benzene
				Evaporative fuel vapor venting Benzene
				Evaporative fuel leaks Benzene
				Refueling displacement Benzene
			Gasoline; Diesel	Refueling spillage Benzene
			Gasoline	Evaporative permeation Ethylbenzene
				Evaporative fuel vapor venting Ethylbenzene
				Evaporative fuel leaks Ethylbenzene
				Refueling displacement Ethylbenzene
			Gasoline; Diesel	Refueling spillage Ethylbenzene
			Diesel	Refueling spillage Naphthalene
			Gasoline; Diesel	Exhaust SOx

Table 9-17 Exhaust PM2.5 emission rates, cars, grams/mile

MYs starting in	Fuel	No GPF (No Action)	With GPF (Proposal)
1995	pump gasoline	2.0575e-05 * age + 0.02556	Same as No GPF
1995	pump diesel	1.5354e-05 * age + 0.024823	Same as No GPF
2000	pump gasoline	0.00039934 * age + 0.0036308	Same as No GPF
2000	pump diesel	0.00037089 * age + 0.0033971	Same as No GPF
2005	pump gasoline	0.00011892 * age + 0.00082091	Same as No GPF
2005	pump diesel	9.7804e-05 * age + 0.00067925	Same as No GPF
2010	pump gasoline	0.00016215 * age + 0.00090948	Same as No GPF
2010	pump diesel	0.00012123 * age + 0.00067543	Same as No GPF
2015	pump gasoline	0.00028219 * age + 0.0017636	Same as No GPF
2015	pump diesel	0.00021421 * age + 0.001328	Same as No GPF
2017	pump gasoline	0.00020321 * age + 0.0017372	Same as No GPF
2017	pump diesel	0.00015369 * age + 0.0013093	Same as No GPF
2025	pump gasoline	0.0001862 * age + 0.0019928	Same as No GPF
2025	pump diesel	0.00014096 * age + 0.0014835	Same as No GPF
2030	pump gasoline	0.00018462 * age + 0.0019789	9.67e-06 * age + 9.8351e-05
2030	pump diesel	0.0001397 * age + 0.0014724	7.2475e-06 * age + 7.259e-05

Table 9-18 Exhaust PM2.5 emission rates, light-duty trucks, grams/mile

MYs starting in	Fuel	No GPF (No Action)	With GPF (Proposal)
1995	pump gasoline	((-1.6181e-05 * age) + 0.025071)	Same as No GPF
1995	pump diesel	((-3.6539e-06 * age) + 0.023303)	Same as No GPF
2000	pump gasoline	((0.00035199 * age) + 0.0083178)	Same as No GPF
2000	pump diesel	((0.00034587 * age) + 0.0079013)	Same as No GPF
2005	pump gasoline	((0.00013083 * age) + 0.0021268)	Same as No GPF
2005	pump diesel	((0.0001082 * age) + 0.0017689)	Same as No GPF
2010	pump gasoline	((0.00017035 * age) + 0.0021839)	Same as No GPF
2010	pump diesel	((0.00012752 * age) + 0.0016461)	Same as No GPF
2015	pump gasoline	((0.00030918 * age) + 0.0030238)	Same as No GPF
2015	pump diesel	((0.00023035 * age) + 0.0022633)	Same as No GPF
2017	pump gasoline	((0.00020713 * age) + 0.0030495)	Same as No GPF
2017	pump diesel	((0.00015328 * age) + 0.0022712)	Same as No GPF
2025	pump gasoline	((0.0001385 * age) + 0.0025349)	Same as No GPF
2025	pump diesel	((0.00010184 * age) + 0.0018502)	Same as No GPF
2030	pump gasoline	((0.0001346 * age) + 0.0025428)	((6.675e-06 * age) + 0.00012137)
2030	pump diesel	((9.8859e-05 * age) + 0.0018471)	((4.8951e-06 * age) + 8.7975e-05)

Table 9-19 Exhaust PM2.5 emission rates, medium-duty vans, grams/mile

MYs starting in	Fuel	No GPF (No Action)	With GPF (Proposal)
1995	pump gasoline	((-4.0895e-05 * age) + 0.071214)	Same as No GPF
1995	pump diesel	((-2.8641e-06 * age) + 0.8262)	Same as No GPF
2000	pump gasoline	((0.0010187 * age) + 0.02384)	Same as No GPF
2000	pump diesel	((-3.1844e-06 * age) + 0.40352)	Same as No GPF
2005	pump gasoline	((0.00075617 * age) + 0.012341)	Same as No GPF
2005	pump diesel	((-1.6069e-06 * age) + 0.27546)	Same as No GPF
2010	pump gasoline	((0.00012855 * age) + 0.010032)	Same as No GPF
2010	pump diesel	((-1.4331e-07 * age) + 0.0071294)	Same as No GPF
2015	pump gasoline	((0.00022315 * age) + 0.0074172)	Same as No GPF
2015	pump diesel	((1.712e-05 * age) + 0.0015567)	Same as No GPF
2017	pump gasoline	((0.00022617 * age) + 0.0074237)	Same as No GPF
2017	pump diesel	((1.7119e-05 * age) + 0.001591)	Same as No GPF
2025	pump gasoline	((0.00019164 * age) + 0.0081221)	Same as No GPF
2025	pump diesel	((1.6182e-05 * age) + 0.0015786)	Same as No GPF
2030	pump gasoline	((0.00018797 * age) + 0.0081354)	((2.1309e-05 * age) + 0.0015281)
2030	pump diesel	((1.5947e-05 * age) + 0.0015789)	((1.5947e-05 * age) + 0.0015789)

Table 9-20 Exhaust PM2.5 emission rates, medium-duty pickups, grams/mile

MYs starting in	Fuel	No GPF (No Action)	With GPF (Proposal)
1995	pump gasoline	((-4.0885e-05 * age) + 0.072197)	Same as No GPF
1995	pump diesel	((-2.7119e-06 * age) + 0.8453)	Same as No GPF
2000	pump gasoline	((0.001036 * age) + 0.02352)	Same as No GPF
2000	pump diesel	((3.9354e-06 * age) + 0.41363)	Same as No GPF
2005	pump gasoline	((0.0007791 * age) + 0.012255)	Same as No GPF
2005	pump diesel	((6.2951e-06 * age) + 0.28231)	Same as No GPF
2010	pump gasoline	((0.00014385 * age) + 0.010083)	Same as No GPF
2010	pump diesel	((6.9872e-07 * age) + 0.0072549)	Same as No GPF
2015	pump gasoline	((0.00023683 * age) + 0.0075087)	Same as No GPF
2015	pump diesel	((1.8142e-05 * age) + 0.001583)	Same as No GPF
2017	pump gasoline	((0.00023969 * age) + 0.0075258)	Same as No GPF
2017	pump diesel	((1.8142e-05 * age) + 0.0016193)	Same as No GPF
2025	pump gasoline	((0.00020168 * age) + 0.0083007)	Same as No GPF
2025	pump diesel	((1.6845e-05 * age) + 0.0016144)	Same as No GPF
2030	pump gasoline	((0.00019659 * age) + 0.0083401)	((2.1961e-05 * age) + 0.0015587)
2030	pump diesel	((1.6298e-05 * age) + 0.0016213)	((1.6298e-05 * age) + 0.0016213)

As shown in Table 9-16, rates were also generated for all pollutants, regulatory classes and fuels. Those other rates are not shown here.

9.6.4 Calculating Upstream Emission Inventories

To calculate upstream emission inventories, OMEGA operates on individual vehicles making use of the VMT_{policy} on each applicable fuel in the given OMEGA scenario.

For upstream emissions from EGUs, OMEGA first calculates the given vehicle's fuel consumption according to the $FuelConsumption_{vehicle;electricity}$ equation shown above. OMEGA then estimates the required EGU generation by accounting for grid losses as below.

$$FuelGeneration_{vehicle;electricity} = \frac{FuelConsumption_{vehicle;electricity}}{transmission\ efficiency}$$

Where,

$FuelGeneration_{vehicle;electricity}$ = the estimated EGU generation requirement to satisfy the fuel consumption of the vehicle

$FuelConsumption_{vehicle;electricity}$ = the electricity consumption of the given vehicle (described above)

transmission efficiency = the estimated efficiency of grid transmission (0.935 in this case)

The estimated generation value is then multiplied by the EGU emission rates as described above to estimate the upstream emissions according to the equation below.

$$Tons_{vehicle;pollutant} = FuelGeneration_{vehicle;electricity} \times \frac{Rate_{pollutant;scenario}}{grams\ per\ ton}$$

Where,

$Tons_{vehicle;pollutant}$ = The inventory tons (US or metric) of the given pollutant

$FuelGeneration_{vehicle;electricity}$ = the estimated EGU generation requirement to satisfy the fuel consumption for the vehicle (see above)

$Rate_{pollutant;scneario}$ = the EGU emission rate for the given pollutant in the given scenario

grams per ton = 1,000,000 for metric tons (GHGs) or 907,185 for US (short) tons (criteria air pollutants)

A similar process is used for refinery emissions associated with liquid-fuel consumption although the transmission efficiency is 1 for liquid-fuels making fuel generation value equivalent to the fuel consumption value described in Chapter 9.5.3. Additionally, a factor to account for the portion of fuel savings (reduced liquid fuel consumption) leading to reduced refining is also applied as discussed in Chapter 9.6.2.

9.6.5 Calculating Vehicle Emission Inventories

A similar process to that described above for upstream emissions is used for vehicle emission with the exception that exhaust emission rates and both brake wear and tire wear emission rates are multiplied by the VMT_{policy} value while evaporative, spillage and leakage emission rates are multiplied by the liquid-fuel consumption values described in Chapter 9.5.3. Exhaust emission inventories are then added to evaporative, spillage and leakage emission inventories to arrive at vehicle emission inventories.

9.6.6 Summary of Inventories and Inventory Impacts

9.6.6.1 Greenhouse Gas Inventory Impacts

Table 9-21 Greenhouse gas emission inventory impacts, Proposed standards, light-duty and medium-duty (million metric tons) *

Calendar Year	Vehicle			EGU		
	CO2	CH4	N2O	CO2	CH4	N2O
2027	-8	-0.00016	-0.00015	2.2	0.00013	0.000018
2028	-20	-0.00038	-0.00033	4.9	0.00030	0.000041
2029	-36	-0.00069	-0.00059	9	0.00052	0.000071
2030	-54	-0.00100	-0.00088	12	0.00075	0.000100
2031	-77	-0.00140	-0.00130	16	0.00100	0.000140
2032	-100	-0.00190	-0.00170	21	0.00130	0.000170
2033	-130	-0.00240	-0.00220	25	0.00150	0.000210
2034	-160	-0.00290	-0.00260	30	0.00180	0.000240
2035	-190	-0.00350	-0.00310	33	0.00200	0.000260
2036	-210	-0.00390	-0.00350	34	0.00200	0.000270
2037	-230	-0.00440	-0.00390	36	0.00210	0.000280
2038	-260	-0.00490	-0.00430	38	0.00220	0.000290
2039	-280	-0.00530	-0.00470	38	0.00220	0.000290
2040	-300	-0.00570	-0.00510	39	0.00220	0.000290
2041	-320	-0.00620	-0.00540	38.0	0.00210	0.000280
2042	-340	-0.00650	-0.00570	37.0	0.00200	0.000260
2043	-360	-0.00690	-0.00600	36.0	0.00190	0.000240
2044	-370	-0.00710	-0.00620	34.0	0.00170	0.000220
2045	-380	-0.00740	-0.00650	31.0	0.00150	0.000190
2046	-390	-0.00770	-0.00670	29.0	0.00130	0.000170
2047	-400	-0.00780	-0.00680	26.0	0.00110	0.000130
2048	-410	-0.00810	-0.00700	22.0	0.00087	0.000100
2049	-420	-0.00830	-0.00720	19.0	0.00063	0.000065
2050	-420	-0.00840	-0.00730	15.0	0.00037	0.000029
2051	-430	-0.00850	-0.00740	16.0	0.00037	0.000029
2052	-430	-0.00860	-0.00750	16.0	0.00038	0.000029
2053	-430	-0.00870	-0.00760	16.0	0.00038	0.000029
2054	-440	-0.00880	-0.00770	16.0	0.00038	0.000030
2055	-440	-0.00880	-0.00770	16.0	0.00038	0.000030
Sum	-8,000	-0.16000	-0.14000	710	0.03500	0.004500

*GHG emission rates were not available for calculating GHG inventories from refineries.

Table 9-22 Greenhouse gas emission inventory impacts, Alternative 1 standards, light-duty and medium-duty (million metric tons) *

Calendar Year	Vehicle			EGU		
	CO2	CH4	N2O	CO2	CH4	N2O
2027	-8	-0.00017	-0.00015	2.3	0.00014	0.000019
2028	-22	-0.00041	-0.00036	5.4	0.00033	0.000045
2029	-40	-0.00070	-0.00061	9	0.00055	0.000075
2030	-63	-0.00110	-0.00095	13	0.00082	0.000110
2031	-87	-0.00150	-0.00130	18	0.00110	0.000150
2032	-120	-0.00200	-0.00180	22	0.00130	0.000180
2033	-150	-0.00250	-0.00230	27	0.00170	0.000220
2034	-180	-0.00310	-0.00280	32	0.00190	0.000260
2035	-210	-0.00370	-0.00330	35	0.00210	0.000280
2036	-230	-0.00420	-0.00370	38	0.00220	0.000300
2037	-260	-0.00470	-0.00420	40	0.00230	0.000310
2038	-290	-0.00520	-0.00470	41	0.00240	0.000320
2039	-310	-0.00570	-0.00510	42	0.00240	0.000320
2040	-340	-0.00620	-0.00550	43	0.00240	0.000320
2041	-360	-0.00670	-0.00590	42	0.00230	0.000310
2042	-380	-0.00710	-0.00620	41	0.00220	0.000290
2043	-400	-0.00750	-0.00650	40	0.00210	0.000270
2044	-410	-0.00780	-0.00680	37	0.00190	0.000240
2045	-420	-0.00810	-0.00700	35	0.00170	0.000220
2046	-430	-0.00840	-0.00730	32	0.00150	0.000180
2047	-440	-0.00860	-0.00740	29	0.00120	0.000150
2048	-450	-0.00880	-0.00760	25	0.00098	0.000110
2049	-460	-0.00900	-0.00780	21	0.00070	0.000073
2050	-470	-0.00920	-0.00800	17	0.00042	0.000033
2051	-470	-0.00930	-0.00810	17	0.00042	0.000033
2052	-480	-0.00940	-0.00820	18	0.00042	0.000033
2053	-480	-0.00950	-0.00820	18	0.00043	0.000033
2054	-480	-0.00960	-0.00830	18	0.00043	0.000034
2055	-480	-0.00960	-0.00840	18	0.00043	0.000034
Sum	-8,900	-0.17000	-0.15000	780	0.03900	0.005000
*GHG emission rates were not available for calculating GHG inventories from refineries.						

Table 9-23 Greenhouse gas emission inventory impacts, Alternative 2 standards, light-duty and medium-duty (million metric tons) *

Calendar Year	Vehicle			EGU		
	CO2	CH4	N2O	CO2	CH4	N2O
2027	-6	-0.00012	-0.00011	1.6	0.00010	0.000013
2028	-14	-0.00027	-0.00024	3.5	0.00021	0.000029
2029	-28	-0.00055	-0.00047	7	0.00041	0.000055
2030	-43	-0.00082	-0.00072	10	0.00059	0.000080
2031	-63	-0.00120	-0.00110	13	0.00081	0.000110
2032	-86	-0.00160	-0.00140	17	0.00100	0.000140
2033	-110	-0.00210	-0.00190	22	0.00130	0.000180
2034	-140	-0.00260	-0.00240	26	0.00150	0.000210
2035	-170	-0.00310	-0.00280	29	0.00170	0.000230
2036	-180	-0.00350	-0.00320	31	0.00180	0.000240
2037	-210	-0.00400	-0.00360	33	0.00190	0.000260
2038	-230	-0.00440	-0.00400	34	0.00200	0.000260
2039	-250	-0.00480	-0.00440	35	0.00200	0.000270
2040	-270	-0.00530	-0.00470	35	0.00200	0.000260
2041	-290	-0.00570	-0.00500	35	0.00190	0.000260
2042	-310	-0.00600	-0.00530	34	0.00180	0.000240
2043	-320	-0.00630	-0.00560	33	0.00170	0.000220
2044	-330	-0.00660	-0.00580	31	0.00160	0.000200
2045	-340	-0.00680	-0.00600	29	0.00140	0.000180
2046	-360	-0.00710	-0.00620	26	0.00120	0.000150
2047	-360	-0.00730	-0.00640	24	0.00100	0.000120
2048	-370	-0.00750	-0.00660	21	0.00080	0.000092
2049	-380	-0.00770	-0.00670	17	0.00058	0.000060
2050	-390	-0.00780	-0.00680	14	0.00034	0.000026
2051	-390	-0.00790	-0.00690	14	0.00034	0.000026
2052	-390	-0.00800	-0.00700	14	0.00034	0.000026
2053	-390	-0.00800	-0.00710	14	0.00034	0.000026
2054	-390	-0.00810	-0.00710	14	0.00035	0.000027
2055	-400	-0.00810	-0.00720	14	0.00035	0.000027
Sum	-7,200	-0.14000	-0.13000	630	0.03200	0.004000

*GHG emission rates were not available for calculating GHG inventories from refineries.

Table 9-24 Greenhouse gas emission inventory impacts, Alternative 3 standards, light-duty and medium-duty (million metric tons) *

Calendar Year	Vehicle			EGU		
	CO2	CH4	N2O	CO2	CH4	N2O
2027	-5	-0.00010	-0.00010	1.3	0.00008	0.000011
2028	-12	-0.00025	-0.00022	3.0	0.00019	0.000025
2029	-21	-0.00043	-0.00038	5	0.00031	0.000042
2030	-35	-0.00068	-0.00061	8	0.00048	0.000065
2031	-56	-0.00110	-0.00098	12	0.00074	0.000100
2032	-84	-0.00150	-0.00140	17	0.00100	0.000140
2033	-110	-0.00210	-0.00190	22	0.00130	0.000180
2034	-140	-0.00260	-0.00240	26	0.00160	0.000210
2035	-170	-0.00320	-0.00290	30	0.00180	0.000240
2036	-190	-0.00360	-0.00330	32	0.00190	0.000250
2037	-220	-0.00410	-0.00370	34	0.00200	0.000270
2038	-250	-0.00460	-0.00420	36	0.00210	0.000280
2039	-270	-0.00510	-0.00460	37	0.00210	0.000280
2040	-290	-0.00560	-0.00500	38	0.00210	0.000280
2041	-310	-0.00600	-0.00530	38	0.00210	0.000270
2042	-330	-0.00640	-0.00560	37	0.00200	0.000260
2043	-350	-0.00680	-0.00600	36	0.00190	0.000240
2044	-360	-0.00710	-0.00620	34	0.00170	0.000220
2045	-370	-0.00730	-0.00640	31	0.00150	0.000190
2046	-390	-0.00760	-0.00670	29	0.00130	0.000170
2047	-400	-0.00780	-0.00680	26	0.00110	0.000130
2048	-410	-0.00810	-0.00700	23	0.00088	0.000100
2049	-420	-0.00830	-0.00720	19	0.00063	0.000066
2050	-420	-0.00840	-0.00740	16	0.00038	0.000029
2051	-430	-0.00850	-0.00750	16	0.00038	0.000029
2052	-430	-0.00860	-0.00760	16	0.00038	0.000030
2053	-430	-0.00870	-0.00760	16	0.00038	0.000030
2054	-440	-0.00880	-0.00770	16	0.00038	0.000030
2055	-440	-0.00880	-0.00780	16	0.00039	0.000030
Sum	-7,800	-0.15000	-0.13000	670	0.03300	0.004200
*GHG emission rates were not available for calculating GHG inventories from refineries.						

Table 9-25 Net Greenhouse gas emission inventory impacts, Proposed standards, light-duty and medium-duty *

Calendar Year	Vehicle, EGU (Million metric tons per year)			% Change		
	CO2	CH4	N2O	CO2	CH4	N2O
2027	-5.8	-0.000025	-0.00013	-0.4%	-0.1%	-0.6%
2028	-15	-0.000076	-0.00029	-1.2%	-0.2%	-1.3%
2029	-27	-0.00017	-0.00052	-2.3%	-0.4%	-2.4%
2030	-42	-0.00028	-0.00078	-3.6%	-0.8%	-3.8%
2031	-60	-0.00043	-0.0011	-5.4%	-1.2%	-5.7%
2032	-82	-0.00062	-0.0015	-7.6%	-1.9%	-7.9%
2033	-110	-0.00087	-0.002	-10.1%	-2.9%	-10.4%
2034	-130	-0.0012	-0.0024	-13%	-4.1%	-13%
2035	-150	-0.0015	-0.0028	-16%	-5.6%	-16%
2036	-170	-0.0018	-0.0032	-18%	-7.1%	-18%
2037	-200	-0.0022	-0.0036	-21%	-9.0%	-20%
2038	-220	-0.0027	-0.004	-24%	-11%	-23%
2039	-240	-0.0031	-0.0044	-26%	-14%	-25%
2040	-260	-0.0036	-0.0048	-29%	-16%	-27%
2041	-280	-0.0041	-0.0052	-31%	-19%	-29%
2042	-300	-0.0045	-0.0055	-34%	-21%	-31%
2043	-320	-0.005	-0.0058	-36%	-24%	-33%
2044	-330	-0.0054	-0.006	-38%	-27%	-34%
2045	-350	-0.0059	-0.0063	-39%	-30%	-35%
2046	-360	-0.0063	-0.0065	-41%	-32%	-37%
2047	-370	-0.0067	-0.0067	-42%	-35%	-38%
2048	-390	-0.0072	-0.0069	-44%	-38%	-39%
2049	-400	-0.0076	-0.0071	-45%	-40%	-39%
2050	-410	-0.008	-0.0073	-46%	-43%	-40%
2051	-410	-0.0081	-0.0074	-46%	-44%	-40%
2052	-420	-0.0082	-0.0075	-47%	-44%	-41%
2053	-420	-0.0083	-0.0076	-47%	-45%	-41%
2054	-420	-0.0084	-0.0077	-47%	-45%	-41%
2055	-420	-0.0084	-0.0077	-47%	-45%	-41%
Sum	-7,300	-0.12	-0.13	-26%	-17%	-25%

*GHG emission rates were not available for calculating GHG inventories from refineries.

Table 9-26 Net Greenhouse gas emission inventory impacts, Alternative 1 standards, light-duty and medium-duty *

Calendar Year	Vehicle, EGU, Refinery (Million metric tons per year)			% Change		
	CO2	CH4	N2O	CO2	CH4	N2O
2027	-6.1	-0.000027	-0.00014	-0.5%	-0.1%	-0.6%
2028	-17	-0.000073	-0.00031	-1.3%	-0.2%	-1.4%
2029	-31	-0.00015	-0.00053	-2.5%	-0.4%	-2.5%
2030	-49	-0.00026	-0.00084	-4.2%	-0.7%	-4.1%
2031	-69	-0.00042	-0.0012	-6.2%	-1.2%	-6.0%
2032	-93	-0.00062	-0.0016	-8.6%	-1.9%	-8.3%
2033	-120	-0.00089	-0.0021	-11.5%	-2.9%	-11.0%
2034	-150	-0.0012	-0.0026	-14%	-4.2%	-14%
2035	-170	-0.0016	-0.003	-17%	-5.8%	-17%
2036	-200	-0.002	-0.0034	-20%	-7.5%	-19%
2037	-220	-0.0024	-0.0039	-23%	-9.6%	-22%
2038	-250	-0.0028	-0.0043	-26%	-12%	-24%
2039	-270	-0.0033	-0.0048	-29%	-14%	-27%
2040	-290	-0.0038	-0.0052	-32%	-17%	-29%
2041	-320	-0.0043	-0.0056	-35%	-20%	-32%
2042	-330	-0.0048	-0.0059	-37%	-23%	-33%
2043	-360	-0.0054	-0.0062	-40%	-26%	-35%
2044	-370	-0.0059	-0.0065	-42%	-29%	-37%
2045	-390	-0.0064	-0.0068	-43%	-32%	-38%
2046	-400	-0.0069	-0.0071	-45%	-35%	-40%
2047	-410	-0.0073	-0.0073	-47%	-38%	-41%
2048	-430	-0.0078	-0.0075	-48%	-41%	-42%
2049	-440	-0.0083	-0.0077	-50%	-44%	-43%
2050	-450	-0.0088	-0.0079	-51%	-47%	-43%
2051	-450	-0.0089	-0.008	-51%	-48%	-44%
2052	-460	-0.009	-0.0081	-51%	-48%	-44%
2053	-460	-0.0091	-0.0082	-52%	-49%	-44%
2054	-460	-0.0091	-0.0083	-52%	-49%	-44%
2055	-460	-0.0092	-0.0083	-52%	-49%	-44%
Sum	-8,100	-0.13	-0.14	-29%	-18%	-27%

*GHG emission rates were not available for calculating GHG inventories from refineries.

Table 9-27 Net Greenhouse gas emission inventory impacts, Alternative 2 standards, light-duty and medium-duty *

Calendar Year	Vehicle, EGU, Refinery (Million metric tons per year)			% Change		
	CO2	CH4	N2O	CO2	CH4	N2O
2027	-4.2	-0.000021	-0.0001	-0.3%	0.0%	-0.4%
2028	-11	-0.000058	-0.00021	-0.9%	-0.1%	-1.0%
2029	-22	-0.00014	-0.00042	-1.8%	-0.4%	-2.0%
2030	-34	-0.00023	-0.00064	-2.9%	-0.6%	-3.1%
2031	-49	-0.00036	-0.00094	-4.4%	-1.0%	-4.8%
2032	-69	-0.00054	-0.0013	-6.4%	-1.7%	-6.8%
2033	-92	-0.00077	-0.0017	-8.8%	-2.5%	-9.2%
2034	-120	-0.0011	-0.0022	-11%	-3.7%	-12%
2035	-140	-0.0014	-0.0026	-14%	-5.0%	-14%
2036	-150	-0.0017	-0.0029	-16%	-6.4%	-16%
2037	-180	-0.002	-0.0033	-19%	-8.2%	-19%
2038	-200	-0.0024	-0.0037	-21%	-10%	-21%
2039	-220	-0.0028	-0.0041	-24%	-12%	-23%
2040	-240	-0.0033	-0.0044	-26%	-15%	-25%
2041	-260	-0.0037	-0.0048	-28%	-17%	-27%
2042	-270	-0.0041	-0.0051	-30%	-20%	-29%
2043	-290	-0.0046	-0.0054	-32%	-22%	-31%
2044	-300	-0.005	-0.0056	-34%	-25%	-32%
2045	-310	-0.0054	-0.0058	-35%	-27%	-33%
2046	-330	-0.0059	-0.0061	-37%	-30%	-34%
2047	-340	-0.0063	-0.0063	-38%	-32%	-35%
2048	-350	-0.0067	-0.0065	-40%	-35%	-36%
2049	-360	-0.0071	-0.0066	-41%	-38%	-37%
2050	-370	-0.0075	-0.0068	-42%	-40%	-37%
2051	-370	-0.0076	-0.0069	-42%	-40%	-38%
2052	-380	-0.0076	-0.007	-42%	-41%	-38%
2053	-380	-0.0077	-0.0071	-42%	-41%	-38%
2054	-380	-0.0077	-0.0071	-43%	-41%	-38%
2055	-380	-0.0078	-0.0072	-43%	-42%	-38%
Sum	-6,600	-0.11	-0.12	-23%	-15%	-23%

*GHG emission rates were not available for calculating GHG inventories from refineries.

Table 9-28 Net Greenhouse gas emission inventory impacts, Alternative 3 standards, light-duty and medium-duty *

Calendar Year	Vehicle, EGU, Refinery (Million metric tons per year)			% Change		
	CO2	CH4	N2O	CO2	CH4	N2O
2027	-3.4	-0.000023	-0.00009	-0.3%	-0.1%	-0.4%
2028	-8.9	-0.000062	-0.00019	-0.7%	-0.1%	-0.9%
2029	-16	-0.00012	-0.00033	-1.3%	-0.3%	-1.6%
2030	-27	-0.0002	-0.00054	-2.3%	-0.5%	-2.6%
2031	-44	-0.00033	-0.00088	-4.0%	-1.0%	-4.4%
2032	-66	-0.00051	-0.0013	-6.2%	-1.6%	-6.7%
2033	-91	-0.00075	-0.0017	-8.7%	-2.5%	-9.2%
2034	-120	-0.001	-0.0022	-11%	-3.7%	-12%
2035	-140	-0.0014	-0.0027	-14%	-5.1%	-15%
2036	-160	-0.0017	-0.003	-17%	-6.6%	-17%
2037	-190	-0.0021	-0.0035	-20%	-8.5%	-19%
2038	-210	-0.0026	-0.0039	-22%	-11%	-22%
2039	-230	-0.003	-0.0043	-25%	-13%	-24%
2040	-250	-0.0035	-0.0047	-28%	-15%	-27%
2041	-280	-0.0039	-0.0051	-31%	-18%	-29%
2042	-290	-0.0044	-0.0054	-33%	-21%	-31%
2043	-310	-0.0049	-0.0057	-35%	-24%	-32%
2044	-330	-0.0053	-0.006	-37%	-26%	-34%
2045	-340	-0.0058	-0.0062	-39%	-29%	-35%
2046	-360	-0.0063	-0.0065	-41%	-32%	-37%
2047	-370	-0.0067	-0.0067	-42%	-35%	-38%
2048	-390	-0.0072	-0.0069	-43%	-38%	-39%
2049	-400	-0.0076	-0.0071	-45%	-40%	-39%
2050	-410	-0.0081	-0.0073	-46%	-43%	-40%
2051	-410	-0.0082	-0.0074	-46%	-44%	-41%
2052	-420	-0.0083	-0.0075	-47%	-44%	-41%
2053	-420	-0.0083	-0.0076	-47%	-45%	-41%
2054	-420	-0.0084	-0.0077	-47%	-45%	-41%
2055	-420	-0.0084	-0.0077	-47%	-45%	-41%
Sum	-7,100	-0.12	-0.13	-25%	-16%	-24%
*GHG emission rates were not available for calculating GHG inventories from refineries.						

9.6.6.2 Criteria Air Pollutant Inventory Impacts

Table 9-29 Criteria air pollutant impacts from vehicles, Proposed standards, light-duty and medium-duty
(US tons per year)

Calendar Year	PM2.5	NOx	NMOG	SOx	CO
2027	-68	-720	-1,100	-50	-24,000
2028	-170	-1,700	-3,400	-130	-61,000
2029	-310	-3,200	-7,200	-230	-110,000
2030	-790	-4,800	-12,000	-350	-180,000
2031	-1,300	-6,800	-18,000	-490	-250,000
2032	-1,800	-9,100	-25,000	-650	-330,000
2033	-2,300	-12,000	-33,000	-830	-430,000
2034	-2,900	-14,000	-42,000	-1,000	-530,000
2035	-3,400	-17,000	-52,000	-1,200	-640,000
2036	-4,000	-19,000	-62,000	-1,300	-720,000
2037	-4,500	-21,000	-73,000	-1,500	-820,000
2038	-5,100	-24,000	-85,000	-1,600	-930,000
2039	-5,600	-26,000	-96,000	-1,800	-1,000,000
2040	-6,100	-28,000	-110,000	-1,900	-1,100,000
2041	-6,600	-30,000	-120,000	-2,000	-1,200,000
2042	-7,000	-32,000	-130,000	-2,100	-1,300,000
2043	-7,500	-33,000	-140,000	-2,300	-1,400,000
2044	-7,900	-35,000	-150,000	-2,300	-1,400,000
2045	-8,200	-36,000	-160,000	-2,400	-1,500,000
2046	-8,500	-37,000	-170,000	-2,500	-1,600,000
2047	-8,800	-38,000	-180,000	-2,500	-1,600,000
2048	-9,000	-39,000	-180,000	-2,600	-1,700,000
2049	-9,200	-40,000	-190,000	-2,600	-1,700,000
2050	-9,400	-41,000	-190,000	-2,700	-1,700,000
2051	-9,500	-42,000	-200,000	-2,700	-1,800,000
2052	-9,600	-43,000	-200,000	-2,700	-1,800,000
2053	-9,700	-43,000	-200,000	-2,700	-1,800,000
2054	-9,800	-44,000	-200,000	-2,800	-1,800,000
2055	-9,800	-44,000	-200,000	-2,800	-1,800,000

Table 9-30 Criteria air pollutant impacts from vehicles, Alternative 1 standards, light-duty and medium-duty (US tons per year)

Calendar Year	PM2.5	NOx	NMOG	SOx	CO
2027	-70	-750	-1,200	-53	-25,000
2028	-180	-1,800	-3,600	-140	-65,000
2029	-320	-3,100	-7,200	-250	-110,000
2030	-790	-4,900	-12,000	-400	-180,000
2031	-1,300	-6,900	-19,000	-550	-260,000
2032	-1,800	-9,300	-26,000	-730	-350,000
2033	-2,300	-12,000	-35,000	-940	-450,000
2034	-2,900	-15,000	-46,000	-1,100	-570,000
2035	-3,400	-18,000	-57,000	-1,300	-680,000
2036	-4,000	-20,000	-69,000	-1,500	-780,000
2037	-4,500	-23,000	-81,000	-1,700	-900,000
2038	-5,100	-25,000	-94,000	-1,800	-1,000,000
2039	-5,600	-27,000	-110,000	-2,000	-1,100,000
2040	-6,100	-30,000	-120,000	-2,100	-1,200,000
2041	-6,600	-32,000	-130,000	-2,300	-1,300,000
2042	-7,100	-34,000	-140,000	-2,400	-1,400,000
2043	-7,500	-36,000	-160,000	-2,500	-1,500,000
2044	-7,900	-37,000	-170,000	-2,600	-1,600,000
2045	-8,200	-39,000	-180,000	-2,700	-1,700,000
2046	-8,600	-40,000	-190,000	-2,800	-1,700,000
2047	-8,800	-41,000	-190,000	-2,800	-1,800,000
2048	-9,100	-42,000	-200,000	-2,900	-1,800,000
2049	-9,300	-43,000	-210,000	-2,900	-1,900,000
2050	-9,500	-44,000	-210,000	-3,000	-1,900,000
2051	-9,600	-45,000	-220,000	-3,000	-1,900,000
2052	-9,700	-46,000	-220,000	-3,000	-2,000,000
2053	-9,700	-46,000	-220,000	-3,000	-2,000,000
2054	-9,800	-47,000	-220,000	-3,000	-2,000,000
2055	-9,800	-47,000	-230,000	-3,000	-2,000,000

Table 9-31 Criteria air pollutant impacts from vehicles, Alternative 2 standards, light-duty and medium-duty (US tons per year)

Calendar Year	PM2.5	NOx	NMOG	SOx	CO
2027	-49	-570	-810	-36	-17,000
2028	-120	-1,300	-2,400	-91	-42,000
2029	-250	-2,600	-5,600	-180	-88,000
2030	-730	-3,900	-9,400	-280	-140,000
2031	-1,200	-5,800	-14,000	-400	-200,000
2032	-1,700	-7,900	-20,000	-540	-270,000
2033	-2,300	-10,000	-28,000	-720	-360,000
2034	-2,800	-13,000	-36,000	-890	-460,000
2035	-3,400	-15,000	-45,000	-1,000	-560,000
2036	-3,900	-17,000	-54,000	-1,200	-640,000
2037	-4,500	-20,000	-64,000	-1,300	-730,000
2038	-5,000	-22,000	-74,000	-1,500	-830,000
2039	-5,500	-24,000	-85,000	-1,600	-920,000
2040	-6,100	-26,000	-96,000	-1,700	-1,000,000
2041	-6,500	-28,000	-110,000	-1,800	-1,100,000
2042	-7,000	-29,000	-120,000	-1,900	-1,200,000
2043	-7,400	-31,000	-130,000	-2,000	-1,300,000
2044	-7,800	-32,000	-130,000	-2,100	-1,300,000
2045	-8,200	-34,000	-140,000	-2,200	-1,400,000
2046	-8,500	-35,000	-150,000	-2,200	-1,400,000
2047	-8,800	-36,000	-160,000	-2,300	-1,500,000
2048	-9,000	-37,000	-160,000	-2,300	-1,500,000
2049	-9,200	-38,000	-170,000	-2,400	-1,600,000
2050	-9,400	-39,000	-170,000	-2,400	-1,600,000
2051	-9,500	-39,000	-180,000	-2,500	-1,600,000
2052	-9,600	-40,000	-180,000	-2,500	-1,600,000
2053	-9,700	-40,000	-180,000	-2,500	-1,600,000
2054	-9,700	-41,000	-180,000	-2,500	-1,600,000
2055	-9,800	-41,000	-190,000	-2,500	-1,600,000

Table 9-32 Criteria air pollutant impacts from vehicles, Alternative 3 standards, light-duty and medium-duty (US tons per year)

Calendar Year	PM2.5	NOx	NMOG	SOx	CO
2027	-43	-550	-800	-30	-15,000
2028	-110	-1,200	-2,300	-75	-39,000
2029	-190	-2,100	-4,500	-130	-68,000
2030	-670	-3,400	-7,800	-220	-110,000
2031	-1,200	-5,400	-12,000	-360	-180,000
2032	-1,600	-7,700	-19,000	-530	-260,000
2033	-2,200	-10,000	-26,000	-710	-360,000
2034	-2,800	-13,000	-35,000	-910	-470,000
2035	-3,300	-16,000	-44,000	-1,100	-570,000
2036	-3,800	-18,000	-54,000	-1,200	-660,000
2037	-4,400	-20,000	-65,000	-1,400	-770,000
2038	-5,000	-23,000	-76,000	-1,600	-870,000
2039	-5,500	-25,000	-88,000	-1,700	-980,000
2040	-6,000	-27,000	-100,000	-1,900	-1,100,000
2041	-6,500	-29,000	-110,000	-2,000	-1,200,000
2042	-7,000	-31,000	-120,000	-2,100	-1,300,000
2043	-7,400	-33,000	-130,000	-2,200	-1,400,000
2044	-7,800	-34,000	-140,000	-2,300	-1,400,000
2045	-8,100	-36,000	-150,000	-2,400	-1,500,000
2046	-8,500	-37,000	-160,000	-2,500	-1,600,000
2047	-8,700	-38,000	-170,000	-2,500	-1,600,000
2048	-9,000	-39,000	-180,000	-2,600	-1,700,000
2049	-9,200	-40,000	-190,000	-2,600	-1,700,000
2050	-9,400	-41,000	-190,000	-2,700	-1,700,000
2051	-9,500	-42,000	-200,000	-2,700	-1,800,000
2052	-9,600	-43,000	-200,000	-2,700	-1,800,000
2053	-9,700	-43,000	-200,000	-2,700	-1,800,000
2054	-9,800	-44,000	-200,000	-2,800	-1,800,000
2055	-9,800	-44,000	-200,000	-2,800	-1,800,000

Table 9-33 Criteria air pollutant impacts from EGUs and refineries, Proposed standards, light-duty and medium-duty (US tons per year)*

Calendar Year	EGU				Refinery			
	PM2.5	NOx	NMOG	SOx	PM2.5	NOx	NMOG	SOx
2027	140	800	68	660	-130	-510	-440	-200
2028	310	1,800	150	1,500	-330	-1,200	-1,100	-490
2029	540	3,100	260	2,500	-590	-2,300	-1,900	-890
2030	790	4,400	380	3,600	-900	-3,400	-2,900	-1,400
2031	1,100	5,900	510	4,800	-1,300	-4,800	-4,100	-1,900
2032	1,300	7,500	660	6,000	-1,700	-6,400	-5,500	-2,600
2033	1,600	9,000	800	7,100	-2,100	-8,100	-7,000	-3,300
2034	1,900	10,000	940	8,100	-2,600	-9,900	-8,500	-4,000
2035	2,100	11,000	1,100	8,800	-3,100	-12,000	-9,900	-4,700
2036	2,300	12,000	1,100	9,000	-3,400	-13,000	-11,000	-5,200
2037	2,400	12,000	1,200	9,300	-3,800	-14,000	-12,000	-5,800
2038	2,500	13,000	1,300	9,300	-4,200	-16,000	-13,000	-6,400
2039	2,600	13,000	1,300	9,100	-4,500	-17,000	-14,000	-6,900
2040	2,600	13,000	1,400	8,700	-4,900	-18,000	-16,000	-7,400
2041	2,600	12,000	1,400	8,100	-5,200	-19,000	-16,000	-7,900
2042	2,600	12,000	1,400	7,300	-5,500	-20,000	-17,000	-8,300
2043	2,600	11,000	1,400	6,500	-5,700	-21,000	-18,000	-8,700
2044	2,400	10,000	1,400	5,400	-5,900	-22,000	-19,000	-9,000
2045	2,300	9,200	1,300	4,200	-6,100	-22,000	-19,000	-9,300
2046	2,200	8,100	1,300	2,900	-6,300	-23,000	-20,000	-9,600
2047	2,000	6,700	1,200	1,500	-6,400	-23,000	-20,000	-9,700
2048	1,900	5,400	1,100	1,500	-6,500	-24,000	-20,000	-10,000
2049	1,700	4,000	1,100	1,600	-6,600	-24,000	-21,000	-10,000
2050	1,500	2,500	1,000	1,600	-6,700	-24,000	-21,000	-10,000
2051	1,500	2,500	1,000	1,600	-6,800	-25,000	-21,000	-10,000
2052	1,500	2,500	1,000	1,600	-6,800	-25,000	-21,000	-10,000
2053	1,500	2,600	1,000	1,600	-6,900	-25,000	-21,000	-10,000
2054	1,500	2,600	1,000	1,600	-6,900	-25,000	-21,000	-11,000
2055	1,500	2,600	1,000	1,600	-6,900	-25,000	-21,000	-11,000

*CO emission rates were not available for calculating CO inventories from EGUs or refineries.

Table 9-34 Criteria air pollutant impacts from EGUs and refineries, Alternative 1 standards, light-duty and medium-duty (US tons per year)*

Calendar Year	EGU				Refinery			
	PM2.5	NOx	NMOG	SOx	PM2.5	NOx	NMOG	SOx
2027	140	830	71	680	-140	-530	-450	-210
2028	350	2,000	170	1,600	-370	-1,400	-1,200	-560
2029	570	3,300	280	2,700	-660	-2,500	-2,200	-990
2030	860	4,900	420	4,000	-1,000	-3,900	-3,400	-1,600
2031	1,100	6,300	550	5,100	-1,400	-5,400	-4,700	-2,200
2032	1,400	7,900	700	6,300	-1,900	-7,200	-6,200	-2,900
2033	1,800	9,700	860	7,700	-2,400	-9,200	-7,900	-3,700
2034	2,100	11,000	1,000	8,800	-2,900	-11,000	-9,500	-4,500
2035	2,300	12,000	1,100	9,500	-3,400	-13,000	-11,000	-5,200
2036	2,500	13,000	1,200	9,900	-3,800	-14,000	-12,000	-5,800
2037	2,600	14,000	1,300	10,000	-4,300	-16,000	-14,000	-6,500
2038	2,800	14,000	1,400	10,000	-4,700	-17,000	-15,000	-7,100
2039	2,800	14,000	1,500	10,000	-5,100	-19,000	-16,000	-7,700
2040	2,900	14,000	1,500	9,600	-5,400	-20,000	-17,000	-8,300
2041	2,900	14,000	1,500	9,000	-5,800	-21,000	-18,000	-8,800
2042	2,900	13,000	1,500	8,100	-6,100	-22,000	-19,000	-9,200
2043	2,800	12,000	1,500	7,200	-6,400	-23,000	-20,000	-9,700
2044	2,700	11,000	1,500	6,000	-6,600	-24,000	-21,000	-10,000
2045	2,600	10,000	1,500	4,600	-6,700	-25,000	-21,000	-10,000
2046	2,400	8,900	1,400	3,200	-7,000	-25,000	-22,000	-11,000
2047	2,200	7,500	1,300	1,700	-7,100	-26,000	-22,000	-11,000
2048	2,100	6,000	1,300	1,700	-7,200	-26,000	-22,000	-11,000
2049	1,900	4,400	1,200	1,800	-7,300	-27,000	-23,000	-11,000
2050	1,600	2,800	1,100	1,800	-7,400	-27,000	-23,000	-11,000
2051	1,700	2,800	1,100	1,800	-7,500	-27,000	-23,000	-11,000
2052	1,700	2,800	1,100	1,800	-7,500	-27,000	-23,000	-12,000
2053	1,700	2,800	1,100	1,800	-7,500	-27,000	-23,000	-12,000
2054	1,700	2,800	1,100	1,800	-7,600	-27,000	-23,000	-12,000
2055	1,700	2,800	1,100	1,900	-7,600	-27,000	-23,000	-12,000

*CO emission rates were not available for calculating CO inventories from EGUs or refineries.

Table 9-35 Criteria air pollutant impacts from EGUs and refineries, Alternative 2 standards, light-duty and medium-duty (US tons per year)*

Calendar	EGU				Refinery			
Year	PM2.5	NOx	NMOG	SOx	PM2.5	NOx	NMOG	SOx
2027	100	580	49	470	-96	-370	-320	-150
2028	220	1,300	110	1,000	-240	-900	-780	-360
2029	420	2,400	210	2,000	-470	-1,800	-1,500	-710
2030	620	3,500	300	2,800	-710	-2,700	-2,300	-1,100
2031	860	4,800	420	3,900	-1,000	-3,900	-3,400	-1,600
2032	1,100	6,200	540	4,900	-1,400	-5,300	-4,600	-2,100
2033	1,400	7,800	700	6,100	-1,900	-7,100	-6,100	-2,800
2034	1,700	9,100	830	7,100	-2,300	-8,700	-7,500	-3,500
2035	1,900	10,000	940	7,800	-2,700	-10,000	-8,700	-4,100
2036	2,000	11,000	1,000	8,000	-3,000	-11,000	-9,700	-4,600
2037	2,200	11,000	1,100	8,400	-3,400	-13,000	-11,000	-5,200
2038	2,300	12,000	1,200	8,400	-3,800	-14,000	-12,000	-5,700
2039	2,400	12,000	1,200	8,300	-4,100	-15,000	-13,000	-6,200
2040	2,400	12,000	1,300	8,000	-4,400	-16,000	-14,000	-6,700
2041	2,400	12,000	1,300	7,500	-4,700	-17,000	-15,000	-7,200
2042	2,400	11,000	1,300	6,800	-4,900	-18,000	-16,000	-7,500
2043	2,400	10,000	1,300	6,000	-5,200	-19,000	-16,000	-7,900
2044	2,300	9,500	1,300	4,900	-5,300	-20,000	-17,000	-8,100
2045	2,100	8,500	1,200	3,800	-5,500	-20,000	-17,000	-8,400
2046	2,000	7,400	1,200	2,700	-5,700	-21,000	-18,000	-8,700
2047	1,900	6,200	1,100	1,400	-5,800	-21,000	-18,000	-8,800
2048	1,700	5,000	1,100	1,400	-5,900	-22,000	-18,000	-9,000
2049	1,500	3,700	1,000	1,400	-6,000	-22,000	-19,000	-9,200
2050	1,400	2,300	930	1,500	-6,100	-22,000	-19,000	-9,300
2051	1,400	2,300	940	1,500	-6,200	-22,000	-19,000	-9,400
2052	1,400	2,300	940	1,500	-6,200	-22,000	-19,000	-9,500
2053	1,400	2,300	950	1,500	-6,200	-22,000	-19,000	-9,500
2054	1,400	2,400	950	1,500	-6,200	-22,000	-19,000	-9,500
2055	1,400	2,400	950	1,500	-6,200	-22,000	-19,000	-9,500

*CO emission rates were not available for calculating CO inventories from EGUs or refineries.

Table 9-36 Criteria air pollutant impacts from EGUs and refineries, Alternative 3 standards, light-duty and medium-duty (US tons per year)*

Calendar Year	EGU				Refinery			
	PM2.5	NOx	NMOG	SOx	PM2.5	NOx	NMOG	SOx
2027	84	490	42	400	-78	-300	-260	-120
2028	190	1,100	95	910	-200	-750	-650	-300
2029	320	1,800	160	1,500	-350	-1,300	-1,100	-520
2030	500	2,900	250	2,300	-570	-2,200	-1,900	-870
2031	780	4,400	380	3,500	-930	-3,500	-3,000	-1,400
2032	1,100	6,100	540	4,900	-1,400	-5,200	-4,500	-2,100
2033	1,400	7,700	690	6,100	-1,800	-7,000	-6,000	-2,800
2034	1,700	9,300	850	7,300	-2,400	-8,900	-7,600	-3,600
2035	2,000	10,000	970	8,100	-2,800	-11,000	-9,100	-4,300
2036	2,100	11,000	1,100	8,400	-3,200	-12,000	-10,000	-4,800
2037	2,300	12,000	1,200	8,800	-3,600	-13,000	-12,000	-5,500
2038	2,400	12,000	1,200	8,900	-4,000	-15,000	-13,000	-6,100
2039	2,500	12,000	1,300	8,800	-4,400	-16,000	-14,000	-6,600
2040	2,600	12,000	1,300	8,500	-4,700	-18,000	-15,000	-7,200
2041	2,600	12,000	1,400	8,000	-5,100	-19,000	-16,000	-7,700
2042	2,600	12,000	1,400	7,200	-5,300	-20,000	-17,000	-8,100
2043	2,500	11,000	1,400	6,400	-5,600	-21,000	-18,000	-8,600
2044	2,400	10,000	1,300	5,300	-5,800	-21,000	-18,000	-8,900
2045	2,300	9,200	1,300	4,100	-6,000	-22,000	-19,000	-9,200
2046	2,200	8,100	1,300	2,900	-6,200	-23,000	-19,000	-9,500
2047	2,000	6,800	1,200	1,500	-6,300	-23,000	-20,000	-9,700
2048	1,900	5,400	1,200	1,600	-6,500	-24,000	-20,000	-9,900
2049	1,700	4,000	1,100	1,600	-6,600	-24,000	-20,000	-10,000
2050	1,500	2,500	1,000	1,600	-6,700	-24,000	-21,000	-10,000
2051	1,500	2,500	1,000	1,600	-6,800	-25,000	-21,000	-10,000
2052	1,500	2,600	1,000	1,600	-6,800	-25,000	-21,000	-10,000
2053	1,500	2,600	1,000	1,600	-6,900	-25,000	-21,000	-10,000
2054	1,500	2,600	1,000	1,700	-6,900	-25,000	-21,000	-11,000
2055	1,500	2,600	1,000	1,700	-6,900	-25,000	-21,000	-11,000

*CO emission rates were not available for calculating CO inventories from EGUs or refineries.

Table 9-37 Net criteria air pollutant impacts from vehicles, EGUs and refineries, Proposed standards, light-duty and medium-duty *

Calendar Year	Vehicle, EGU, Refinery (US tons per year)					% Change				
	PM2.5	NOx	NMOG	SOx	CO*	PM2.5	NOx	NMOG	SOx	CO
2027	-62	-430	-1,500	410	-24,000	-0.11%	-0.070%	-0.13%	0.89%	-0.22%
2028	-180	-1,100	-4,300	860	-61,000	-0.33%	-0.21%	-0.42%	1.9%	-0.60%
2029	-360	-2,300	-8,900	1,400	-110,000	-0.68%	-0.49%	-0.91%	3.1%	-1.2%
2030	-900	-3,700	-15,000	1,900	-180,000	-1.8%	-0.9%	-1.6%	4.2%	-2.0%
2031	-1,500	-5,700	-21,000	2,400	-250,000	-3.0%	-1.5%	-2.5%	5.3%	-3.1%
2032	-2,100	-8,100	-30,000	2,800	-330,000	-4.4%	-2.4%	-3.6%	6.3%	-4.5%
2033	-2,800	-11,000	-39,000	3,000	-430,000	-6.0%	-3.5%	-5.1%	7.0%	-6.2%
2034	-3,600	-14,000	-50,000	3,100	-530,000	-7.7%	-4.9%	-6.9%	7.3%	-8.3%
2035	-4,400	-17,000	-61,000	3,000	-640,000	-9.5%	-6.5%	-8.9%	7.2%	-11%
2036	-5,100	-20,000	-72,000	2,600	-720,000	-11%	-8.2%	-11%	6.3%	-13%
2037	-5,900	-23,000	-84,000	2,000	-820,000	-13%	-10%	-14%	5.1%	-16%
2038	-6,700	-26,000	-97,000	1,300	-930,000	-15%	-13%	-17%	3.4%	-19%
2039	-7,500	-30,000	-110,000	400	-1,000,000	-17%	-15%	-20%	1.1%	-22%
2040	-8,400	-33,000	-120,000	-650	-1,100,000	-19%	-17%	-23%	-1.8%	-25%
2041	-9,200	-37,000	-130,000	-1,800	-1,200,000	-21%	-20%	-26%	-5.2%	-28%
2042	-9,900	-40,000	-150,000	-3,100	-1,300,000	-23%	-22%	-29%	-9%	-31%
2043	-11,000	-43,000	-160,000	-4,500	-1,400,000	-25%	-25%	-32%	-14%	-34%
2044	-11,000	-46,000	-170,000	-6,000	-1,400,000	-26%	-27%	-35%	-19%	-37%
2045	-12,000	-49,000	-180,000	-7,500	-1,500,000	-28%	-29%	-37%	-25%	-39%
2046	-13,000	-52,000	-190,000	-9,200	-1,600,000	-30%	-31%	-40%	-32%	-41%
2047	-13,000	-55,000	-190,000	-11,000	-1,600,000	-31%	-34%	-42%	-39%	-43%
2048	-14,000	-58,000	-200,000	-11,000	-1,700,000	-32%	-36%	-44%	-40%	-44%
2049	-14,000	-61,000	-210,000	-11,000	-1,700,000	-33%	-38%	-45%	-40%	-46%
2050	-15,000	-63,000	-210,000	-11,000	-1,700,000	-34%	-40%	-46%	-41%	-47%
2051	-15,000	-64,000	-220,000	-11,000	-1,800,000	-35%	-40%	-47%	-41%	-47%
2052	-15,000	-65,000	-220,000	-12,000	-1,800,000	-35%	-40%	-48%	-41%	-48%
2053	-15,000	-65,000	-220,000	-12,000	-1,800,000	-35%	-41%	-49%	-42%	-49%
2054	-15,000	-66,000	-220,000	-12,000	-1,800,000	-35%	-41%	-49%	-42%	-49%
2055	-15,000	-66,000	-220,000	-12,000	-1,800,000	-35%	-41%	-50%	-42%	-49%

*CO emission rates were not available for calculating CO inventories from EGUs or refineries.

Table 9-38 Net criteria air pollutant impacts from vehicles, EGUs and refineries, Alternative 1 standards, light-duty and medium-duty *

Calendar Year	Vehicle, EGU, Refinery (US tons per year)					% Change				
	PM2.5	NOx	NMOG	SOx	CO*	PM2.5	NOx	NMOG	SOx	CO
2027	-65	-440	-1,500	420	-25,000	-0.11%	-0.072%	-0.14%	0.92%	-0.23%
2028	-200	-1,200	-4,600	940	-65,000	-0.37%	-0.22%	-0.45%	2.1%	-0.65%
2029	-400	-2,400	-9,000	1,400	-110,000	-0.76%	-0.49%	-0.93%	3.1%	-1.2%
2030	-970	-3,900	-15,000	2,000	-180,000	-1.9%	-0.9%	-1.7%	4.4%	-2.1%
2031	-1,600	-6,000	-23,000	2,400	-260,000	-3.2%	-1.6%	-2.6%	5.3%	-3.2%
2032	-2,200	-8,600	-32,000	2,700	-350,000	-4.6%	-2.5%	-3.9%	6.2%	-4.7%
2033	-3,000	-12,000	-42,000	3,100	-450,000	-6.2%	-3.8%	-5.5%	7.0%	-6.6%
2034	-3,800	-15,000	-54,000	3,100	-570,000	-8.0%	-5.3%	-7.5%	7.4%	-8.8%
2035	-4,500	-18,000	-67,000	3,000	-680,000	-9.9%	-7.0%	-9.8%	7.2%	-11%
2036	-5,300	-21,000	-80,000	2,600	-780,000	-12%	-8.9%	-12%	6.4%	-14%
2037	-6,100	-25,000	-93,000	2,100	-900,000	-14%	-11%	-15%	5.2%	-17%
2038	-7,000	-29,000	-110,000	1,300	-1,000,000	-16%	-14%	-18%	3.4%	-20%
2039	-7,800	-32,000	-120,000	340	-1,100,000	-18%	-16%	-22%	0.9%	-24%
2040	-8,700	-36,000	-140,000	-780	-1,200,000	-20%	-19%	-25%	-2.2%	-27%
2041	-9,500	-40,000	-150,000	-2,100	-1,300,000	-22%	-21%	-29%	-5.9%	-31%
2042	-10,000	-43,000	-160,000	-3,500	-1,400,000	-24%	-24%	-32%	-10%	-34%
2043	-11,000	-47,000	-180,000	-5,000	-1,500,000	-26%	-27%	-35%	-15%	-37%
2044	-12,000	-50,000	-190,000	-6,600	-1,600,000	-27%	-29%	-38%	-21%	-40%
2045	-12,000	-53,000	-200,000	-8,300	-1,700,000	-29%	-32%	-41%	-28%	-43%
2046	-13,000	-57,000	-210,000	-10,000	-1,700,000	-31%	-34%	-44%	-35%	-45%
2047	-14,000	-59,000	-210,000	-12,000	-1,800,000	-32%	-36%	-46%	-43%	-47%
2048	-14,000	-63,000	-220,000	-12,000	-1,800,000	-33%	-39%	-48%	-44%	-49%
2049	-15,000	-66,000	-230,000	-12,000	-1,900,000	-35%	-41%	-50%	-45%	-50%
2050	-15,000	-69,000	-230,000	-13,000	-1,900,000	-36%	-43%	-51%	-45%	-52%
2051	-15,000	-69,000	-240,000	-13,000	-1,900,000	-36%	-43%	-52%	-45%	-52%
2052	-16,000	-70,000	-240,000	-13,000	-2,000,000	-36%	-44%	-53%	-45%	-53%
2053	-16,000	-71,000	-240,000	-13,000	-2,000,000	-37%	-44%	-54%	-46%	-54%
2054	-16,000	-71,000	-250,000	-13,000	-2,000,000	-37%	-44%	-54%	-46%	-54%
2055	-16,000	-71,000	-250,000	-13,000	-2,000,000	-37%	-44%	-55%	-46%	-55%

*CO emission rates were not available for calculating CO inventories from EGUs or refineries.

Table 9-39 Net criteria air pollutant impacts from vehicles, EGUs and refineries, Alternative 2 standards, light-duty and medium-duty *

Calendar Year	Vehicle, EGU, Refinery (US tons per year)					% Change				
	PM2.5	NOx	NMOG	SOx	CO*	PM2.5	NOx	NMOG	SOx	CO
2027	-45	-360	-1,100	290	-17,000	-0.08%	-0.058%	-0.10%	0.64%	-0.16%
2028	-130	-910	-3,100	600	-42,000	-0.25%	-0.17%	-0.30%	1.3%	-0.42%
2029	-290	-2,000	-6,900	1,100	-88,000	-0.55%	-0.41%	-0.71%	2.4%	-0.9%
2030	-820	-3,100	-11,000	1,500	-140,000	-1.6%	-0.7%	-1.2%	3.3%	-1.6%
2031	-1,400	-4,900	-17,000	1,900	-200,000	-2.8%	-1.3%	-2.0%	4.2%	-2.5%
2032	-2,000	-7,000	-24,000	2,200	-270,000	-4.1%	-2.1%	-3.0%	5.1%	-3.7%
2033	-2,700	-9,600	-33,000	2,600	-360,000	-5.7%	-3.2%	-4.3%	5.9%	-5.3%
2034	-3,400	-12,000	-43,000	2,700	-460,000	-7.4%	-4.5%	-5.9%	6.3%	-7.2%
2035	-4,200	-15,000	-53,000	2,600	-560,000	-9.1%	-5.9%	-7.7%	6.3%	-9%
2036	-4,900	-18,000	-63,000	2,300	-640,000	-11%	-7.5%	-10%	5.6%	-11%
2037	-5,700	-21,000	-74,000	1,900	-730,000	-13%	-9%	-12%	4.8%	-14%
2038	-6,500	-24,000	-85,000	1,300	-830,000	-15%	-11%	-15%	3.3%	-17%
2039	-7,300	-27,000	-97,000	500	-920,000	-17%	-14%	-17%	1.3%	-20%
2040	-8,000	-31,000	-110,000	-430	-1,000,000	-18%	-16%	-20%	-1.2%	-23%
2041	-8,800	-34,000	-120,000	-1,500	-1,100,000	-20%	-18%	-23%	-4.3%	-25%
2042	-9,500	-37,000	-130,000	-2,700	-1,200,000	-22%	-21%	-26%	-8%	-28%
2043	-10,000	-40,000	-140,000	-4,000	-1,300,000	-24%	-23%	-29%	-12%	-31%
2044	-11,000	-43,000	-150,000	-5,300	-1,300,000	-25%	-25%	-31%	-17%	-33%
2045	-12,000	-45,000	-160,000	-6,700	-1,400,000	-27%	-27%	-33%	-22%	-35%
2046	-12,000	-48,000	-170,000	-8,300	-1,400,000	-28%	-29%	-36%	-29%	-37%
2047	-13,000	-51,000	-170,000	-9,700	-1,500,000	-30%	-31%	-38%	-35%	-39%
2048	-13,000	-54,000	-180,000	-10,000	-1,500,000	-31%	-33%	-39%	-36%	-40%
2049	-14,000	-56,000	-190,000	-10,000	-1,600,000	-32%	-35%	-41%	-37%	-42%
2050	-14,000	-59,000	-190,000	-10,000	-1,600,000	-33%	-37%	-42%	-37%	-43%
2051	-14,000	-59,000	-200,000	-10,000	-1,600,000	-34%	-37%	-43%	-37%	-43%
2052	-14,000	-60,000	-200,000	-10,000	-1,600,000	-34%	-37%	-44%	-38%	-44%
2053	-15,000	-60,000	-200,000	-11,000	-1,600,000	-34%	-38%	-44%	-38%	-44%
2054	-15,000	-61,000	-200,000	-11,000	-1,600,000	-34%	-38%	-45%	-38%	-45%
2055	-15,000	-61,000	-200,000	-11,000	-1,600,000	-34%	-38%	-45%	-38%	-45%
*CO emission rates were not available for calculating CO inventories from EGUs or refineries.										

Table 9-40 Net criteria air pollutant impacts from vehicles, EGUs and refineries, Alternative 3 standards, light-duty and medium-duty *

Calendar Year	Vehicle, EGU, Refinery (US tons per year)					% Change				
	PM2.5	NOx	NMOG	SOx	CO*	PM2.5	NOx	NMOG	SOx	CO
2027	-37	-360	-1,000	250	-15,000	-0.07%	-0.058%	-0.09%	0.55%	-0.14%
2028	-110	-870	-2,900	530	-39,000	-0.21%	-0.16%	-0.28%	1.2%	-0.39%
2029	-220	-1,600	-5,500	830	-68,000	-0.42%	-0.34%	-0.56%	1.8%	-0.7%
2030	-740	-2,700	-9,400	1,200	-110,000	-1.4%	-0.6%	-1.0%	2.7%	-1.3%
2031	-1,300	-4,500	-15,000	1,700	-180,000	-2.6%	-1.2%	-1.7%	3.9%	-2.2%
2032	-1,900	-6,800	-23,000	2,300	-260,000	-4.0%	-2.0%	-2.8%	5.1%	-3.6%
2033	-2,600	-9,500	-31,000	2,600	-360,000	-5.5%	-3.1%	-4.1%	6.0%	-5.2%
2034	-3,400	-13,000	-41,000	2,800	-470,000	-7.2%	-4.5%	-5.7%	6.5%	-7.3%
2035	-4,200	-16,000	-52,000	2,700	-570,000	-9.0%	-6.1%	-7.7%	6.5%	-10%
2036	-4,900	-19,000	-63,000	2,400	-660,000	-11%	-7.8%	-10%	5.9%	-12%
2037	-5,700	-22,000	-75,000	1,900	-770,000	-13%	-10%	-12%	4.9%	-15%
2038	-6,500	-25,000	-88,000	1,300	-870,000	-15%	-12%	-15%	3.3%	-18%
2039	-7,300	-29,000	-100,000	440	-980,000	-17%	-14%	-18%	1.2%	-21%
2040	-8,200	-32,000	-110,000	-550	-1,100,000	-19%	-17%	-21%	-1.5%	-24%
2041	-9,000	-36,000	-130,000	-1,700	-1,200,000	-21%	-19%	-24%	-4.9%	-27%
2042	-9,700	-39,000	-140,000	-3,000	-1,300,000	-23%	-22%	-27%	-9%	-30%
2043	-11,000	-43,000	-150,000	-4,400	-1,400,000	-24%	-24%	-31%	-13%	-33%
2044	-11,000	-46,000	-160,000	-5,800	-1,400,000	-26%	-27%	-33%	-19%	-36%
2045	-12,000	-49,000	-170,000	-7,400	-1,500,000	-28%	-29%	-36%	-25%	-38%
2046	-13,000	-52,000	-180,000	-9,100	-1,600,000	-29%	-31%	-39%	-31%	-41%
2047	-13,000	-55,000	-190,000	-11,000	-1,600,000	-31%	-33%	-41%	-39%	-42%
2048	-14,000	-58,000	-200,000	-11,000	-1,700,000	-32%	-36%	-43%	-40%	-44%
2049	-14,000	-60,000	-210,000	-11,000	-1,700,000	-33%	-38%	-45%	-40%	-45%
2050	-15,000	-63,000	-210,000	-11,000	-1,700,000	-34%	-40%	-46%	-41%	-47%
2051	-15,000	-64,000	-210,000	-11,000	-1,800,000	-35%	-40%	-47%	-41%	-47%
2052	-15,000	-65,000	-220,000	-12,000	-1,800,000	-35%	-40%	-48%	-41%	-48%
2053	-15,000	-65,000	-220,000	-12,000	-1,800,000	-35%	-41%	-49%	-42%	-49%
2054	-15,000	-66,000	-220,000	-12,000	-1,800,000	-35%	-41%	-49%	-42%	-49%
2055	-15,000	-66,000	-220,000	-12,000	-1,800,000	-35%	-41%	-50%	-42%	-50%

*CO emission rates were not available for calculating CO inventories from EGUs or refineries.

9.7 Estimating Energy Security Effects

The energy security premia (the energy security savings, in dollars, per barrel of reduced imported oil) and the process used to estimate those values are described in Chapter 12. The discussion here focuses on how OMEGA estimates the oil consumption impacts to which the energy security premia can be multiplied to estimate monetized benefits.

9.7.1 Calculating Oil Consumption from Fuel Consumption

Chapter 9.5.3 describes how OMEGA estimates liquid-fuel consumption. This is done for every vehicle that operates any miles on a liquid-fuel, whether that fuel be gasoline or diesel. Chapter 0 presents the estimated impacts of the proposal on overall fuel consumption.

9.7.2 Calculating Oil Imports from Oil Consumption

To estimate energy security benefits, OMEGA converts fuel consumption impacts to oil import impacts. This is done using the values shown in Table 9-41 Parameters used in Estimating Oil Import Impacts.

Table 9-41 Parameters used in estimating oil import impacts

Item	Value
Share of pure gasoline in retail gasoline	0.9
Share of pure diesel in retail diesel	1.0
Energy density ratio of pure gasoline to crude oil	0.881
Energy density ratio of diesel to crude oil	0.998
Gallons per barrel of crude oil	42
Oil import reduction as percent of total oil demand reduction	0.907

The barrels of oil consumed in a given scenario are estimated as shown below.

$$Barrels = FuelConsumption_{vehicle;liquid} \times Share \times \frac{EnergyDensityRatio}{GallonsPerBarrel}$$

Where,

Barrels = the barrels of oil associated with the fuel consumption value

$FuelConsumption_{\mathrm{vehicle;liquid}}$ = the liquid-fuel consumption of the given vehicle (see Chapter 9.5.3)

Share = the applicable "pure share" shown in Table 9-41

EnergyDensityRatio = the applicable energy density ratio shown in Table 9-41

GallonsPerBarrel = 42 as shown in Table 9-41

The barrels of imported oil are then calculated as shown below.

$$Barrels_{imported} = Barrels \times (Oil\ import\ reduction\ as\ percent\ of\ total\ oil\ demand\ reduction)$$

9.7.3 Summary of Energy Security Effects

Table 9-42 Impacts on oil consumption and oil imports, Proposed standards, light-duty and medium-duty (millions)

Calendar Year	Barrels	Barrels Imported	Barrels Imported per Day
2027	-17	-15	-0.042
2028	-42	-38	-0.1
2029	-76	-69	-0.19
2030	-120	-100	-0.29
2031	-160	-150	-0.41
2032	-220	-200	-0.54
2033	-280	-250	-0.69
2034	-340	-310	-0.85
2035	-400	-360	-0.99
2036	-450	-400	-1.1
2037	-500	-450	-1.2
2038	-550	-500	-1.4
2039	-600	-540	-1.5
2040	-640	-580	-1.6
2041	-690	-620	-1.7
2042	-720	-650	-1.8
2043	-760	-690	-1.9
2044	-780	-710	-1.9
2045	-810	-730	-2
2046	-840	-760	-2.1
2047	-850	-770	-2.1
2048	-870	-790	-2.2
2049	-890	-810	-2.2
2050	-910	-820	-2.3
2051	-910	-830	-2.3
2052	-920	-840	-2.3
2053	-930	-840	-2.3
2054	-930	-840	-2.3
2055	-930	-850	-2.3
Sum	-17,000	-16,000	

Table 9-43 Impacts on oil consumption and oil imports, Alternative 1 standards, light-duty and medium-duty (millions)

Calendar Year	Barrels	Barrels Imported	Barrels Imported per Day
2027	-18	-16	-0.044
2028	-47	-43	-0.12
2029	-84	-76	-0.21
2030	-130	-120	-0.33
2031	-190	-170	-0.46
2032	-240	-220	-0.61
2033	-320	-290	-0.78
2034	-380	-350	-0.95
2035	-440	-400	-1.1
2036	-500	-450	-1.2
2037	-560	-500	-1.4
2038	-610	-560	-1.5
2039	-670	-600	-1.7
2040	-720	-650	-1.8
2041	-760	-690	-1.9
2042	-800	-730	-2
2043	-840	-760	-2.1
2044	-870	-790	-2.2
2045	-900	-810	-2.2
2046	-930	-840	-2.3
2047	-940	-850	-2.3
2048	-960	-870	-2.4
2049	-980	-890	-2.4
2050	-1000	-910	-2.5
2051	-1000	-910	-2.5
2052	-1000	-920	-2.5
2053	-1000	-920	-2.5
2054	-1000	-930	-2.5
2055	-1000	-930	-2.5
Sum	-19,000	-17,000	

Table 9-44 Impacts on oil consumption and oil imports, Alternative 2 standards, light-duty and medium-duty (millions)

Calendar Year	Barrels	Barrels Imported	Barrels Imported per Day
2027	-12	-11	-0.031
2028	-30	-28	-0.076
2029	-60	-55	-0.15
2030	-92	-84	-0.23
2031	-130	-120	-0.33
2032	-180	-170	-0.45
2033	-240	-220	-0.6
2034	-300	-270	-0.75
2035	-350	-320	-0.88
2036	-390	-360	-0.98
2037	-440	-400	-1.1
2038	-490	-450	-1.2
2039	-540	-490	-1.3
2040	-580	-530	-1.4
2041	-620	-560	-1.5
2042	-650	-590	-1.6
2043	-690	-620	-1.7
2044	-710	-640	-1.8
2045	-730	-660	-1.8
2046	-760	-690	-1.9
2047	-770	-700	-1.9
2048	-790	-720	-2
2049	-810	-730	-2
2050	-820	-750	-2
2051	-830	-750	-2.1
2052	-830	-760	-2.1
2053	-840	-760	-2.1
2054	-840	-760	-2.1
2055	-840	-770	-2.1
Sum	-15,000	-14,000	

Table 9-45 Impacts on oil consumption and oil imports, Alternative 3 standards, light-duty and medium-duty (millions)

Calendar Year	Barrels	Barrels Imported	Barrels Imported per Day
2027	-10	-9.2	-0.025
2028	-25	-23	-0.063
2029	-45	-41	-0.11
2030	-74	-67	-0.18
2031	-120	-110	-0.3
2032	-180	-160	-0.44
2033	-240	-220	-0.6
2034	-310	-280	-0.76
2035	-370	-330	-0.91
2036	-410	-380	-1
2037	-470	-430	-1.2
2038	-520	-480	-1.3
2039	-570	-520	-1.4
2040	-620	-570	-1.6
2041	-670	-610	-1.7
2042	-710	-640	-1.8
2043	-750	-680	-1.9
2044	-770	-700	-1.9
2045	-800	-720	-2
2046	-830	-750	-2.1
2047	-850	-770	-2.1
2048	-870	-790	-2.2
2049	-890	-810	-2.2
2050	-910	-820	-2.2
2051	-910	-830	-2.3
2052	-920	-840	-2.3
2053	-930	-840	-2.3
2054	-930	-840	-2.3
2055	-930	-850	-2.3
Sum	-17,000	-15,000	

Chapter 9 References

2022. "2022 CAFE FRIA." Final Regulatory Impact Analysis: Final Rulemaking for Model Years 2024-2026 Light-Duty Vehicle Corporate Average Fuel Economy Standards. U.S. Department of Transportation, National Highway Traffic Safety Administration, March.

2022. "2022 CAFE TSD." Technical Support Document: Final Rulemaking for Model Years 2024-2026 Light-Duty Vehicle Corporate Average Fuel Economy Standards. U.S. Department Of Transportation, National Highway Traffic Safety Administration, March.

86 FR 74434. 2021.

Beardsley, Megan. 2023. "Updates to MOVES for the Multi-Pollutant Emissions Standards for Model Years 2027 and Later Light-Duty and Medium-Duty Vehicles." January.

U.S. EIA. 2021. Annual Energy Outlook. Energy Information Administration.

U.S. EPA. 2021. Dose-Response Assessment for Assessing Health Risks Associated With Exposure to Hazardous Air Pollutants. September 29. Accessed November 15, 2022. https://www.epa.gov/fera/dose-response-assessment-assessing-health-risks-associated-exposure-hazardous-air-pollutants.

Chapter 10: Costs and Benefits of the Proposed Standards in OMEGA

This chapter presents the costs and benefits calculated within OMEGA. The results presented here show the estimated annual costs, fuel savings and benefits of the program for the indicated calendar years (CY). The results also show the present-values (PV) of those costs and the equivalent annualized values (EAV) for the calendar years 2027–2055 using both 3 percent and 7 percent discount rates. For the estimation of the stream of costs and benefits, we assume that after implementation of the MY 2027 and later standards, the MY 2032 standards apply to each year thereafter.

10.1 Costs

Vehicle technology costs are estimated in OMEGA using the technology cost inputs presented in Chapter 2 of this DRIA. Repair, maintenance, congestion, and noise costs are estimated in OMEGA using the approaches described in Chapter 4 of this DRIA. The resultant costs associated with the proposed standards are presented in Table 10-1.

Table 10-1 Costs associated with the Proposed standards, light-duty and medium-duty (billions of 2020 dollars)

Calendar Year	Vehicle Technology Costs	Repair Costs	Maintenance Costs	Congestion Costs	Noise Costs	Sum
2027	7.5	0.057	-0.048	-0.00023	-0.000014	7.5
2028	6.8	0.078	-0.34	0.01	0.00014	6.6
2029	6.6	0.017	-0.91	0.022	0.00033	5.8
2030	8.7	-0.15	-1.7	0.038	0.00059	6.9
2031	13	-0.43	-2.7	0.055	0.00087	9.8
2032	17	-0.84	-4	0.074	0.0012	12
2035	22	-2.8	-9.7	0.12	0.0019	10
2040	19	-9	-23	0.19	0.0029	-13
2045	13	-16	-37	0.17	0.0027	-40
2050	12	-21	-47	0.17	0.0027	-56
2055	10	-24	-51	0.16	0.0025	-65
PV3	280	-170	-410	2.3	0.037	-290
PV7	180	-79	-200	1.3	0.021	-96
EAV3	15	-8.9	-21	0.12	0.0019	-15
EAV7	15	-6.5	-16	0.11	0.0017	-7.8

As shown, estimated repair and maintenance costs, or reductions in those costs, are significant. BEVs have considerably less maintenance needs than do ICE vehicles (see Chapter 4.3 of this draft RIA which shows BEVs having 30 to 40 percent less maintenance than ICE vehicles).

Table 10-2, Table 10-3 and Table 10-4 show costs associated with Alternatives 1, 2 and 3, respectively.

Table 10-2 Costs associated with Alternative 1, light-duty and medium-duty (billions of 2020 dollars)

Calendar Year	Vehicle Technology Costs	Repair Costs	Maintenance Costs	Congestion Costs	Noise Costs	Sum
2027	7.9	0.06	-0.048	0.00063	-0.0000017	7.9
2028	10	0.11	-0.32	0.025	0.00037	9.9
2029	14	0.13	-0.8	0.071	0.0011	13
2030	17	0.032	-1.6	0.11	0.0018	15
2031	20	-0.17	-2.7	0.17	0.0026	17
2032	23	-0.51	-4.1	0.21	0.0033	19
2035	24	-2.4	-10	0.28	0.0043	12
2040	20	-9	-26	0.27	0.0043	-14
2045	13	-17	-42	0.2	0.0031	-46
2050	13	-23	-52	0.14	0.0022	-63
2055	11	-26	-57	0.11	0.0017	-71
PV3	330	-180	-450	3.5	0.055	-300
PV7	220	-82	-220	2.2	0.034	-82
EAV3	17	-9.3	-24	0.18	0.0028	-15
EAV7	18	-6.7	-18	0.18	0.0027	-6.7

Table 10-3 Costs associated with Alternative 2, light-duty and medium-duty (billions of 2020 dollars)

Calendar Year	Vehicle Technology Costs	Repair Costs	Maintenance Costs	Congestion Costs	Noise Costs	Sum
2027	5.5	0.043	-0.032	0.00072	0.0000041	5.6
2028	5	0.058	-0.24	0.012	0.00018	4.8
2029	5.8	0.0065	-0.68	0.02	0.00031	5.2
2030	6.1	-0.13	-1.3	0.03	0.00047	4.7
2031	11	-0.36	-2.1	0.046	0.00073	8.3
2032	15	-0.7	-3.2	0.065	0.001	11
2035	17	-2.5	-8.2	0.082	0.0013	6.6
2040	15	-8.4	-21	0.037	0.00064	-14
2045	10	-15	-34	0.0096	0.00021	-39
2050	10	-20	-43	0.028	0.00048	-53
2055	8.8	-22	-47	0.064	0.001	-60
PV3	230	-160	-370	0.74	0.012	-300
PV7	140	-74	-180	0.48	0.0078	-110
EAV3	12	-8.3	-19	0.039	0.00064	-16
EAV7	12	-6	-14	0.039	0.00064	-8.7

Table 10-4 Costs associated with Alternative 3, light-duty and medium-duty (billions of 2020 dollars)

Calendar Year	Vehicle Technology Costs	Repair Costs	Maintenance Costs	Congestion Costs	Noise Costs	Sum
2027	2.6	0.016	-0.044	-0.0039	-0.000059	2.6
2028	2.3	0.012	-0.22	-0.00089	-0.000006	2.1
2029	1.8	-0.049	-0.54	0.0042	0.000076	1.3
2030	4.9	-0.19	-1	0.012	0.0002	3.7
2031	12	-0.39	-1.7	0.023	0.00038	9.7
2032	18	-0.66	-2.7	0.039	0.00064	15
2035	24	-2.3	-7.7	0.088	0.0015	14
2040	18	-8.5	-21	0.12	0.002	-12
2045	13	-16	-36	0.11	0.0017	-39
2050	12	-21	-47	0.11	0.0017	-56
2055	11	-24	-51	0.11	0.0016	-64
PV3	270	-170	-390	1.5	0.024	-290
PV7	170	-77	-190	0.82	0.013	-95
EAV3	14	-8.6	-20	0.078	0.0012	-15
EAV7	14	-6.3	-15	0.066	0.0011	-7.8

10.2 Fuel Savings

The proposed standards are projected to reduce liquid fuel consumption (e.g., gasoline) while simultaneously increasing electricity consumption. The estimated impacts on fuel consumption are shown in Chapter 9.5 of this DRIA.

The net effect of these changes in consumption for consumers is decreased liquid-fuel expenditures or fuel savings and increased electricity expenditures. For more information of fuel consumption, including other considerations like rebound, see DRIA Chapter 4. Table 10-2 shows the undiscounted annual monetized fuel savings associated with the proposed standards as well as the present value (PV) of those costs and equivalent annualized value (EAV) for the calendar years 2027–2055 using both 3 percent and 7 percent discount rates. We include here the social costs associated with EVSE ports, as discussed in detail in Chapter 5.3. These reflect the upfront costs associated with procuring and installing PEV charging infrastructure needed to meet the anticipated electricity demand in the proposal relative to the no action case. We include these EVSE port costs in the net benefits presented in Chapter 10.6. Net benefits are determined using pre-tax fuel savings since fuel taxes do not contribute to the value of the fuel and the EVSE port costs. We present fuel taxes and other transfers below in Chapter 10.7.

Table 10-5 Pretax fuel savings and EVSE port costs associated with the Proposed standards, light-duty and medium-duty (billions of 2020 dollars) *

Calendar Year	Gasoline	Diesel	Electricity	EVSE Port Costs	Sum
2027	1.7	0.074	-0.92	-1.3	-0.4
2028	4.5	0.12	-2.2	-0.66	1.8
2029	8.3	0.19	-3.9	-1.1	3.5
2030	13	0.34	-5.8	-1.1	6.6
2031	19	0.55	-8.1	-8.3	2.8
2032	25	0.9	-11	-8.3	7.4
2035	48	1.9	-19	-6.7	24
2040	83	3.3	-30	-7.1	49
2045	110	4.3	-38	-7.3	67
2050	120	5.2	-41	-7.1	81
2055	130	5.8	-41	-7.1	86
PV3	1300	52	-460	-120	770
PV7	670	27	-240	-68	380
EAV3	68	2.7	-24	-6.2	40
EAV7	54	2.2	-20	-5.6	31
* Positive values represent savings, negative values represent increased costs.					

Table 10-6 Pretax fuel savings and EVSE port costs associated with Alternative 1, light-duty and medium-duty (billions of 2020 dollars) *

Calendar Year	Gasoline	Diesel	Electricity	EVSE Port Costs	Sum
2027	1.8	0.074	-0.96	-1.3	-0.35
2028	5.1	0.12	-2.4	-0.66	2.2
2029	9.3	0.2	-4.1	-1.1	4.3
2030	15	0.34	-6.3	-1.1	8.1
2031	21	0.55	-8.6	-8.3	4.8
2032	29	0.9	-11	-8.3	9.9
2035	54	1.9	-21	-6.7	28
2040	93	3.3	-33	-7.1	56
2045	120	4.4	-42	-7.3	75
2050	140	5.3	-46	-7.1	89
2055	140	5.9	-45	-7.1	95
PV3	1400	53	-510	-120	870
PV7	750	27	-270	-68	440
EAV3	75	2.8	-26	-6.2	45
EAV7	61	2.2	-22	-5.6	36
* Positive values represent savings, negative values represent increased costs.					

Table 10-7 Pretax fuel savings and EVSE port costs associated with Alternative 2, light-duty and medium-duty (billions of 2020 dollars) *

Calendar Year	Gasoline	Diesel	Electricity	EVSE Port Costs	Sum
2027	1.2	0.074	-0.66	-1.3	-0.63
2028	3.2	0.11	-1.5	-0.66	1.2
2029	6.6	0.19	-3	-1.1	2.6
2030	10	0.34	-4.6	-1.1	5.1
2031	15	0.55	-6.5	-8.3	0.86
2032	21	0.9	-8.8	-8.3	4.9
2035	42	1.9	-17	-6.7	20
2040	75	3.3	-28	-7.1	43
2045	97	4.4	-35	-7.3	59
2050	110	5.3	-38	-7.1	72
2055	120	5.8	-37	-7.1	77
PV3	1200	53	-420	-120	680
PV7	590	27	-220	-68	330
EAV3	60	2.7	-22	-6.2	35
EAV7	48	2.2	-18	-5.6	27
* Positive values represent savings, negative values represent increased costs.					

Table 10-8 Pretax fuel savings and EVSE port costs associated with Alternative 3, light-duty and medium-duty (billions of 2020 dollars) *

Calendar Year	Gasoline	Diesel	Electricity	EVSE Port Costs	Sum
2027	1	0.072	-0.56	-1.3	-0.77
2028	2.7	0.11	-1.3	-0.66	0.81
2029	4.8	0.18	-2.3	-1.1	1.6
2030	8.3	0.33	-3.7	-1.1	3.8
2031	14	0.54	-6	-8.3	-0.13
2032	21	0.89	-8.7	-8.3	4.4
2035	44	1.9	-18	-6.7	21
2040	81	3.3	-30	-7.1	47
2045	110	4.4	-38	-7.3	66
2050	120	5.3	-42	-7.1	80
2055	130	5.9	-41	-7.1	86
PV3	1200	53	-450	-120	740
PV7	630	27	-230	-68	360
EAV3	65	2.7	-23	-6.2	38
EAV7	52	2.2	-19	-5.6	29
* Positive values represent savings, negative values represent increased costs.					

10.3 Non-Emission Benefits

Non-emission benefits are shown in Table 10-9 through Table 10-12 for the Proposed standards, Alternative 1, Alternative 2 and Alternative 3, respectively. The drive value represents the value that consumers place on the additional driving they may do resulting from the rebound effect. The value is positive here which represents a benefit to consumers because we have estimated a small amount of rebound driving relative to the no action case. The value of time spent refueling is shown as a negative benefit, or disbenefit, because we estimate additional time spent refueling relative to the no-action scenario. This is due to the additional BEV stock in the fleet and the additional time required, using current estimates, to refuel a BEV relative to the refueling time involved for an ICE vehicle. Energy security benefits are shown as positive because we estimate reductions in liquid-fuel consumption and corresponding reductions in imported oil.

Table 10-9 Non-emission benefits associated with the Proposed standards, light-duty and medium-duty (billions of 2020 dollars) *

Calendar Year	Drive Value	Value of Time Spent Refueling	Energy Security	Total
2027	0.0011	-0.14	0.052	-0.089
2028	0.024	-0.36	0.13	-0.21
2029	0.049	-0.67	0.24	-0.38
2030	0.086	-1	0.37	-0.59
2031	0.12	-1.5	0.54	-0.8
2032	0.16	-1.9	0.73	-0.99
2035	0.26	-3.4	1.4	-1.7
2040	0.37	-5.5	2.6	-2.5
2045	0.34	-6.9	3.5	-3.1
2050	0.34	-7.9	4.2	-3.3
2055	0.31	-8.2	4.4	-3.6
PV3	4.8	-85	41	-39
PV7	2.7	-45	21	-21
EAV3	0.25	-4.4	2.2	-2
EAV7	0.22	-3.6	1.7	-1.7
* Positive values represent benefits while negative values represent disbenefits.				

Table 10-10 Non-emission benefits associated with Alternative 1, light-duty and medium-duty (billions of 2020 dollars) *

Calendar Year	Drive Value	Value of Time Spent Refueling	Energy Security	Total
2027	0.0019	-0.15	0.055	-0.091
2028	0.045	-0.38	0.15	-0.19
2029	0.12	-0.67	0.27	-0.29
2030	0.2	-1.1	0.43	-0.45
2031	0.28	-1.5	0.61	-0.6
2032	0.37	-1.9	0.82	-0.75
2035	0.5	-3.5	1.6	-1.4
2040	0.51	-5.8	2.9	-2.4
2045	0.37	-7.4	3.8	-3.2
2050	0.29	-8.4	4.7	-3.4
2055	0.22	-8.8	4.8	-3.8
PV3	6.5	-90	46	-38
PV7	3.9	-47	23	-20
EAV3	0.34	-4.7	2.4	-2
EAV7	0.32	-3.8	1.9	-1.6
* Positive values represent benefits while negative values represent disbenefits.				

Table 10-11 Non-emission benefits associated with Alternative 2, light-duty and medium-duty (billions of 2020 dollars) *

Calendar Year	Drive Value	Value of Time Spent Refueling	Energy Security	Total
2027	0.0026	-0.1	0.038	-0.063
2028	0.028	-0.27	0.095	-0.15
2029	0.049	-0.55	0.19	-0.31
2030	0.077	-0.88	0.3	-0.5
2031	0.11	-1.2	0.44	-0.69
2032	0.16	-1.6	0.61	-0.88
2035	0.22	-3.1	1.3	-1.6
2040	0.15	-5.1	2.3	-2.6
2045	0.087	-6.5	3.1	-3.2
2050	0.11	-7.3	3.8	-3.3
2055	0.17	-7.6	3.9	-3.5
PV3	2.4	-79	37	-39
PV7	1.5	-41	19	-21
EAV3	0.12	-4.1	1.9	-2
EAV7	0.12	-3.3	1.5	-1.7
* Positive values represent benefits while negative values represent disbenefits.				

Table 10-12 Non-emission benefits associated with Alternative 3, light-duty and medium-duty (billions of 2020 dollars) *

Calendar Year	Drive Value	Value of Time Spent Refueling	Energy Security	Total
2027	-0.0036	-0.093	0.031	-0.065
2028	0.0068	-0.25	0.08	-0.17
2029	0.02	-0.47	0.14	-0.3
2030	0.041	-0.78	0.24	-0.5
2031	0.063	-1.2	0.4	-0.72
2032	0.1	-1.6	0.6	-0.93
2035	0.21	-3.2	1.3	-1.7
2040	0.26	-5.4	2.5	-2.6
2045	0.22	-6.9	3.4	-3.2
2050	0.21	-7.8	4.2	-3.4
2055	0.21	-8.2	4.4	-3.6
PV3	3.2	-83	40	-39
PV7	1.8	-43	20	-21
EAV3	0.17	-4.3	2.1	-2.1
EAV7	0.15	-3.5	1.6	-1.7
* Positive values represent benefits while negative values represent disbenefits.				

10.4 Climate Benefits

We estimate the social benefits of GHG reductions expected to occur as a result of the proposed and alternative standards using estimates of the social cost of greenhouse gases (SC-GHG),[161] The SC-GHG is the monetary value of the net harm to society associated with a marginal increase in emissions of that GHG in a given year. In principle, the 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 naturally restrain the ability of SC-GHG estimates to include all the important physical, ecological, and economic impacts of climate change, such that the estimates are a partial accounting of climate change impacts and will therefore, tend to be underestimates of the marginal benefits of abatement. EPA and other Federal agencies began regularly incorporating SC-GHG estimates in their benefit-cost analyses conducted under Executive Order (E.O.) 12866[162] since 2008, following a Ninth Circuit Court of Appeals remand of a rule for failing to monetize the benefits of reducing CO2 emissions in a rulemaking process.

In 2017, the National Academies of Sciences, Engineering, and Medicine published a report that provides a roadmap for how to update SC-GHG estimates used in Federal analyses going forward to ensure that they reflect advances in the scientific literature (National Academies 2017). The National Academies' report recommended specific criteria for future SC-GHG updates, 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. The research community has made considerable progress in developing new data and methods that help to advance various components of the SC-GHG estimation process in response to the National Academies' recommendations.

In a first-day executive order (E.O. 13990), Protecting Public Health and the Environment and Restoring Science To Tackle the Climate Crisis, President Biden called for a renewed focus on updating estimates of the social cost of greenhouse gases (SC-GHG) to reflect the latest science, noting that "it is essential that agencies capture the full benefits of reducing greenhouse gas emissions as accurately as possible." Important steps have been taken to begin to fulfill this directive of E.O. 13990. In February 2021, the Interagency Working Group on the SC-GHG (IWG) released a technical support document (hereinafter the "February 2021 TSD") that

[161] Estimates of the social cost of greenhouse gases are gas- specific (e.g., social cost of carbon (SC-CO2), social cost of methane (SC-CH4), social cost of nitrous oxide (SC-N2O)), but collectively they are referenced as the social cost of greenhouse gases (SC-GHG).

[162] Benefit-cost analyses have been an integral part of executive branch rulemaking for decades. Presidents since the 1970s have issued executive orders requiring agencies to conduct analysis of the economic consequences of regulations as part of the rulemaking development process. E.O. 12866, released in 1993 and still in effect today, requires that for all regulatory actions that are significant under 3(f)(1), an agency provide an assessment of the potential costs and benefits of the regulatory action, and that this assessment include a quantification of benefits and costs to the extent feasible.

provided a set of IWG recommended SC-GHG estimates while work on a more comprehensive update is underway to reflect recent scientific advances relevant to SC-GHG estimation (IWG 2021). In addition, as discussed further below, EPA has developed a draft updated SC-GHG methodology within a sensitivity analysis in the regulatory impact analysis of EPA's November 2022 supplemental proposal for oil and gas standards that is currently undergoing external peer review and a public comment process (U.S. EPA 2022).

The EPA has applied the IWG's recommended interim SC-GHG estimates in the Agency's regulatory benefit-cost analyses published since the release of the February 2021 TSD and is likewise using them in this draft RIA. We have evaluated the SC-GHG estimates in the February 2021 TSD and have determined that these estimates are appropriate for use in estimating the social benefits of GHG reductions expected to occur as a result of the proposed and alternative standards. These SC-GHG estimates are interim values developed for use in benefit-cost analyses until updated estimates of the impacts of climate change can be developed based on the best available science and economics. After considering the TSD, and the issues and studies discussed therein, EPA finds that these estimates, while likely an underestimate, are the best currently available SC-GHG estimates until revised estimates have been developed reflecting the latest, peer-reviewed science.

The SC-GHG estimates presented in the February 2021 SC-GHG TSD and used in this draft RIA were developed over many years, using a transparent process, peer-reviewed methodologies, the best science available at the time of that process, and with input from the public. Specifically, in 2009, an interagency working group (IWG) that included the EPA and other executive branch agencies and offices was established to develop estimates relying on the best available science for agencies to use. The IWG published SC-CO_2 estimates in 2010 that were developed from an ensemble of three widely cited integrated assessment models (IAMs) that estimate global climate damages using highly aggregated representations of climate processes and the global economy combined into a single modeling framework. The three IAMs were run using a common set of input assumptions in each model for future population, economic, and CO_2 emissions growth, as well as equilibrium climate sensitivity (ECS)—a measure of the globally averaged temperature response to increased atmospheric CO_2 concentrations. These estimates were updated in 2013 based on new versions of each IAM.[163] In August 2016 the IWG published estimates of the social cost of methane (SC-CH_4) and nitrous oxide (SC-N_2O) using methodologies that are consistent with the methodology underlying the SC-CO_2 estimates. The modeling approach that extends the IWG SC-CO_2 methodology to non-CO_2 GHGs has undergone multiple stages of peer review. The SC-CH_4 and SC-N_2O estimates were developed by Marten, Kopits, Griffiths, Newbold, and Wolverton (2015) and underwent a standard double-blind peer review process prior to journal publication. These estimates were applied in regulatory impact analyses of EPA proposed rulemakings with CH_4 and N_2O emissions impacts (U.S. EPA 2015a).[164] The EPA also sought additional external peer review of

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[163] Dynamic Integrated Climate and Economy (DICE) (Nordhaus 2010), Climate Framework for Uncertainty, Negotiation, and Distribution (FUND) 3.8 (Anthoff 2013b) (Anthoff 2013a), and Policy Analysis of the Greenhouse Gas Effect (PAGE) 2009 (Hope 2013).

[164] The SC-CH4 and SC-N2O estimates were first used in sensitivity analysis for the Proposed Rulemaking for Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles–Phase 2.

technical issues associated with its application to regulatory analysis. Following the completion of the independent external peer review of the application of the Marten et al. (2015) estimates, the EPA began using the estimates in the primary benefit-cost analysis calculations and tables for a number of proposed rulemakings in 2015 (U.S. EPA 2015b) (U.S. EPA 2015c). The EPA considered and responded to public comments received for the proposed rulemakings before using the estimates in final regulatory analyses in 2016. The IWG TSD (2016b) provides discussion of the SC-CH_4 and SC-N_2O and the peer review and public comment processes accompanying their development. In 2015, as part of the response to public comments received to a 2013 solicitation for comments on the SC-CO_2 estimates, the IWG announced a National Academies of Sciences, Engineering, and Medicine review of the SC-CO_2 estimates to offer advice on how to approach future updates to ensure that the estimates continue to reflect the best available science and methodologies. In January 2017, the National Academies released their final report, Valuing Climate Damages: Updating Estimation of the Social Cost of Carbon Dioxide, and recommended specific criteria for future updates to the SC-GHG 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. Shortly thereafter, in March 2017, President Trump issued Executive Order 13783, which disbanded the IWG, withdrew the previous TSDs, and directed agencies to ensure SC-GHG estimates used in regulatory analyses are consistent with the guidance contained in OMB's Circular A-4, "including with respect to the consideration of domestic versus international impacts and the consideration of appropriate discount rates" (E.O. 13783, Section 5(c)). Benefit-cost analyses following E.O. 13783 used SC-GHG estimates that attempted to focus on the specific share of climate change damages in the U.S. as captured by the models (which did not reflect many pathways by which climate impacts affect the welfare of U.S. citizens and residents) and were calculated using two default discount rates recommended by Circular A-4, 3 percent and 7 percent.[165] All other methodological decisions and model versions used in SC-GHG calculations remained the same as those used by the IWG in 2010 and 2013, respectively.

On January 20, 2021, President Biden issued Executive Order 13990, which established an IWG and directed it to develop an update of the SC-GHG estimates that reflect the best available science and the recommendations of the National Academies. In February 2021, the IWG recommended the interim use of the most recent SC-GHG estimates developed by the IWG prior to the group being disbanded in 2017, adjusted for inflation (IWG 2021). As discussed in the February 2021 TSD, the IWG's selection of these interim estimates reflected the immediate need to have SC-GHG estimates available for agencies to use in regulatory benefit-cost analyses and other applications that were developed using a transparent process, peer reviewed methodologies, and the science available at the time of that process.

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[165] EPA regulatory analyses under E.O. 13783 included sensitivity analyses based on global SC-GHG values and using a lower discount rate of 2.5%. OMB Circular A-4 (OMB, 2003) recognizes that special considerations arise when applying discount rates if intergenerational effects are important. In the IWG's 2015 Response to Comments, OMB—as a co-chair of the IWG—made clear that "Circular A-4 is a living document," that "the use of 7 percent is not considered appropriate for intergenerational discounting," and that "[t]here is wide support for this view in the academic literature, and it is recognized in Circular A-4 itself." OMB, as part of the IWG, similarly repeatedly confirmed that "a focus on global SCC estimates in [regulatory impact analyses] is appropriate" (IWG 2015).

As noted above, EPA participated in the IWG but has also independently evaluated the interim SC-GHG estimates published in the February 2021 TSD and determined they are appropriate to use here to estimate climate benefits. EPA and other agencies intend to undertake a fuller update of the SC-GHG estimates that takes into consideration the advice of the National Academies (2017) and other recent scientific literature. The EPA has also evaluated the supporting rationale of the February 2021 TSD, including the studies and methodological issues discussed therein, and concludes that it agrees with the rationale for these estimates presented in the TSD and summarized below.

In particular, the IWG found that the SC-GHG estimates used under E.O. 13783 fail to reflect the full impact of GHG emissions in multiple ways. First, the IWG concluded that those estimates fail to capture many climate impacts that can affect the welfare of U.S. citizens and residents. 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 are better captured within global measures of the social cost of greenhouse gases.

In addition, 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. A wide range of scientific and economic experts have emphasized the issue of reciprocity as support for considering global damages of GHG emissions. 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 take significant steps to reduce emissions. 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—is for all countries to base their policies on global estimates of damages.

As a member of the IWG involved in the development of the February 2021 SC-GHG TSD, EPA agrees with this assessment and, therefore, in this proposed rule the EPA centers attention on a global measure of SC-GHG. This approach is the same as that taken in EPA regulatory analyses over 2009 through 2016. A robust estimate of climate damages only to U.S. citizens and residents that accounts for the myriad of ways that global climate change reduces the net welfare of U.S. populations does not currently exist in the literature. As explained in the February 2021 TSD, existing estimates are both incomplete and an underestimate of total damages that accrue to the citizens and residents of the U.S. because they do not fully capture the regional interactions and spillovers discussed above, nor do they include all of the important physical, ecological, and economic impacts of climate change recognized in the climate change literature, as discussed further below. EPA, as a member of the IWG, 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 carbon impacts.

Second, the IWG concluded that the use of the social rate of return on capital (7 percent under current OMB Circular A-4 guidance) to discount the future benefits of reducing GHG emissions inappropriately underestimates the impacts of climate change for the purposes of estimating the SC-GHG. Consistent with the findings of the National Academies (2017) and the economic literature, the IWG continued to conclude that the consumption rate of interest is the theoretically appropriate discount rate in an intergenerational context, and recommended that discount rate uncertainty and relevant aspects of intergenerational ethical considerations be accounted for in selecting future discount rates (IWG 2010) (IWG 2013) (IWG 2016a) (IWG 2016b).[166] Furthermore, the damage estimates developed for use in the SC-GHG are estimated in consumption-equivalent terms, and so an application of OMB Circular A-4's guidance for regulatory analysis would then use the consumption discount rate to calculate the SC-GHG. EPA agrees with this assessment and will continue to follow developments in the literature pertaining to this issue. EPA also notes that while OMB Circular A-4, as published in 2003, recommends using 3 percent and 7 percent discount rates as "default" values, Circular A-4 also reminds agencies that "different regulations may call for different emphases in the analysis, depending on the nature and complexity of the regulatory issues and the sensitivity of the benefit and cost estimates to the key assumptions." On discounting, Circular A-4 recognizes that "special ethical considerations arise when comparing benefits and costs across generations," and Circular A-4 acknowledges that analyses may appropriately "discount future costs and consumption benefits…at a lower rate than for intragenerational analysis." In the 2015 Response to Comments on the Social Cost of Carbon for Regulatory Impact Analysis, OMB, EPA, and the other IWG members recognized that "Circular A-4 is a living document" and "the use of 7 percent is not considered appropriate for intergenerational discounting. There is wide support for this view in the academic literature, and it is recognized in Circular A-4 itself." Thus, EPA concludes that a 7 percent discount rate is not appropriate to apply to value the social cost of greenhouse gases in the analysis presented in this analysis. In this analysis, to calculate the present and annualized values of climate benefits, EPA uses the same discount rate as the rate used to discount the value of damages from future GHG emissions, for internal consistency. That approach to discounting follows the same approach that the February 2021 TSD recommends "to ensure internal consistency—i.e., future damages from climate change using the SC-GHG at 2.5 percent should be discounted to the base year of the analysis using the same 2.5 percent rate." EPA has also consulted the National Academies' 2017 recommendations on how SC-GHG estimates can "be combined in RIAs with other cost and benefits estimates that may use different discount rates." The National Academies reviewed "several options," including "presenting all discount rate combinations of other costs and benefits with [SC-GHG] estimates."

While the IWG works to assess how best to incorporate the latest, peer reviewed science to develop an updated set of SC-GHG estimates, it recommended the interim estimates to be the most recent estimates developed by the IWG prior to the group being disbanded in 2017. The estimates rely on the same models and harmonized inputs and are calculated using a range of discount rates. As explained in the February 2021 TSD, the IWG has concluded that it is appropriate for agencies to revert to the same set of four values drawn from the SC-GHG

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[166] GHG emissions are stock pollutants, where damages are associated with what has accumulated in the atmosphere over time, and they are long lived such that subsequent damages resulting from emissions today occur over many decades or centuries depending on the specific greenhouse gas under consideration. In calculating the SC-GHG, the stream of future damages to agriculture, human health, and other market and non-market sectors from an additional unit of emissions are estimated in terms of reduced consumption (or consumption equivalents). Then that stream of future damages is discounted 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.

distributions based on three discount rates as were used in regulatory analyses between 2010 and 2016 and subject to public comment. For each discount rate, the IWG combined the distributions across models and socioeconomic emissions scenarios (applying equal weight to each) and then selected a set of four values for use in agency analyses: an average value resulting from the model runs for each of three discount rates (2.5 percent, 3 percent, and 5 percent), plus a fourth value, selected as the 95th percentile of estimates based on a 3 percent discount rate. The fourth value was included to provide information on potentially higher-than-expected economic impacts from climate change, conditional on the 3 percent estimate of the discount rate. As explained in the February 2021 TSD, this update reflects the immediate need to have an operational SC-GHG that was developed using a transparent process, peer-reviewed methodologies, and the science available at the time of that process. Those estimates were subject to public comment in the context of dozens of proposed rulemakings as well as in a dedicated public comment period in 2013.

Table 10-13, Table 10-14, and Table 10-15 summarize the interim SC-CO_2, SC-CH_4, and SC-N_2O estimates for the years 2027–2055[167]. These estimates are reported in 2020 dollars in the IWG's 2021 TSD but are otherwise identical to those presented in the IWG's 2016 TSD (IWG 2021). For purposes of capturing uncertainty around the SC-CO_2 estimates in analyses, the February 2021 TSD emphasizes the importance of considering all four of the SC-CO_2 values. The SC-CO_2 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 2025) 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.

[167] The February 2021 TSD provides SC-GHG estimates through emissions year 2050. Estimates were extended for the period 2051 to 2055 using the IWG methods, assumptions, and parameters identical to the 2020-2050 estimates. Specifically, 2051-2055 SC-GHG estimates were calculated in Mimi.jl, an open-source modular computing platform used for creating, running, and performing analyses on IAMs (www.mimiframework.org). For CO_2, the 2051-2054 SC-GHG values were calculated by linearly interpolating between the 2050 TSD values and the 2055 Mimi-based values.

Table 10-13 Interim Social Cost of Carbon Values, 2027-2055 (2020$/Metric Ton CO_2)

Calendar Year	Discount Rate and Statistic			
	5% Average	3% Average	2.5% Average	3%, 95th percentile
2027	$18	$59	$86	$176
2028	$18	$60	$87	$180
2029	$19	$61	$88	$183
2030	$19	$62	$89	$187
2031	$20	$63	$91	$191
2032	$21	$64	$92	$194
2033	$21	$65	$94	$198
2034	$22	$66	$95	$202
2035	$22	$67	$96	$206
2036	$23	$69	$98	$210
2037	$23	$70	$99	$213
2038	$24	$71	$100	$217
2039	$25	$72	$102	$221
2040	$25	$73	$103	$225
2041	$26	$74	$104	$228
2042	$26	$75	$106	$232
2043	$27	$77	$107	$235
2044	$28	$78	$108	$239
2045	$28	$79	$110	$242
2046	$29	$80	$111	$246
2047	$30	$81	$112	$249
2048	$30	$82	$114	$253
2049	$31	$84	$115	$256
2050	$32	$85	$116	$260
2051	$33	$85	$118	$261
2052	$33	$86	$119	$262
2053	$34	$87	$120	$263
2054	$34	$88	$121	$263
2055	$35	$89	$122	$266

Note: The 2027-2055 SC-CO2 values are identical to those reported in the 2016 TSD (IWG 2016a) adjusted to 2017 dollars using the annual GDP Implicit Price Deflator values in the U.S. Bureau of Economic Analysis' (BEA) NIPA Table 1.1.9 (U.S. BEA 2022). 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 CO2 and vary depending on the year of CO2 emissions.

Table 10-14 Interim Social Cost of Carbon Values, 2027-2055 (2020$/Metric Ton CH_4)

Calendar Year	Discount Rate and Statistic			
	5% Average	3% Average	2.5% Average	3%, 95th percentile
2027	$860	$1,800	$2,300	$4,800
2028	$880	$1,900	$2,400	$4,900
2029	$910	$1,900	$2,500	$5,100
2030	$940	$2,000	$2,500	$5,200
2031	$970	$2,000	$2,600	$5,300
2032	$1,000	$2,100	$2,600	$5,500
2033	$1,000	$2,100	$2,700	$5,700
2034	$1,100	$2,200	$2,800	$5,800
2035	$1,100	$2,200	$2,800	$6,000
2036	$1,100	$2,300	$2,900	$6,100
2037	$1,200	$2,300	$3,000	$6,300
2038	$1,200	$2,400	$3,000	$6,400
2039	$1,200	$2,500	$3,100	$6,600
2040	$1,300	$2,500	$3,100	$6,700
2041	$1,300	$2,600	$3,200	$6,900
2042	$1,400	$2,600	$3,300	$7,000
2043	$1,400	$2,700	$3,300	$7,200
2044	$1,400	$2,700	$3,400	$7,300
2045	$1,500	$2,800	$3,500	$7,500
2046	$1,500	$2,800	$3,500	$7,600
2047	$1,500	$2,900	$3,600	$7,700
2048	$1,600	$3,000	$3,700	$7,900
2049	$1,600	$3,000	$3,700	$8,000
2050	$1,700	$3,100	$3,800	$8,200
2051	$1,700	$3,100	$3,800	$8,200
2052	$1,700	$3,100	$3,900	$8,300
2053	$1,700	$3,200	$3,900	$8,300
2054	$1,800	$3,200	$3,900	$8,300
2055	$1,800	$3,200	$4,000	$8,400

Note: The 2027-2055 SC-CH4 values are identical to those reported in the 2016 TSD (IWG 2016a) adjusted to 2017 dollars using the annual GDP Implicit Price Deflator values in the U.S. Bureau of Economic Analysis' (BEA) NIPA Table 1.1.9 (U.S. BEA 2022). 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 2054 using methods, assumptions, and parameters identical to the 2020-2050 estimates. The values are stated in $/metric ton CH4 and vary depending on the year of CH4 emissions.

Table 10-15 Interim Social Cost of Carbon Values, 2027-2055 (2020$/Metric Ton N_2O)

Calendar Year	Discount Rate and Statistic			
	5% Average	3% Average	2.5% Average	3%, 95th percentile
2027	$7,200	$21,000	$31,000	$57,000
2028	$7,400	$22,000	$32,000	$58,000
2029	$7,600	$22,000	$32,000	$59,000
2030	$7,800	$23,000	$33,000	$60,000
2031	$8,000	$23,000	$33,000	$62,000
2032	$8,300	$24,000	$34,000	$63,000
2033	$8,500	$24,000	$35,000	$64,000
2034	$8,800	$25,000	$35,000	$66,000
2035	$9,000	$25,000	$36,000	$67,000
2036	$9,300	$26,000	$36,000	$68,000
2037	$9,500	$26,000	$37,000	$70,000
2038	$9,800	$27,000	$38,000	$71,000
2039	$10,000	$27,000	$38,000	$73,000
2040	$10,000	$28,000	$39,000	$74,000
2041	$11,000	$28,000	$39,000	$75,000
2042	$11,000	$29,000	$40,000	$77,000
2043	$11,000	$29,000	$41,000	$78,000
2044	$11,000	$30,000	$41,000	$80,000
2045	$12,000	$30,000	$42,000	$81,000
2046	$12,000	$31,000	$43,000	$82,000
2047	$12,000	$31,000	$43,000	$84,000
2048	$13,000	$32,000	$44,000	$85,000
2049	$13,000	$32,000	$45,000	$87,000
2050	$13,000	$33,000	$45,000	$88,000
2051	$14,000	$34,000	$46,000	$89,000
2052	$14,000	$34,000	$47,000	$90,000
2053	$14,000	$35,000	$47,000	$92,000
2054	$14,000	$35,000	$48,000	$93,000
2055	$15,000	$36,000	$48,000	$94,000

Note: The 2027-2055 SC-N2O values are identical to those reported in the 2016 TSD (IWG 2016a) adjusted to 2017 dollars using the annual GDP Implicit Price Deflator values in the U.S. Bureau of Economic Analysis' (BEA) NIPA Table 1.1.9 (U.S. BEA 2022). 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 2054 using methods, assumptions, and parameters identical to the 2020-2050 estimates. The values are stated in $/metric ton N2O and vary depending on the year of N2O emissions.

There are a number of limitations and uncertainties associated with the SC-GHG estimates presented in Table 10-13, Table 10-14, and Table 10-15. Some uncertainties are captured within the analysis, while other areas of uncertainty have not yet been quantified in a way that can be modeled. Figure 10-1, Figure 10-2, and Figure 10-3 present the quantified sources of uncertainty in the form of frequency distributions for the SC-CO_2, SC-CH_4, and SC-N_2O estimates for emissions in 2030 (in 2020$). The distribution of the SC-CO_2 estimate reflects uncertainty in key model parameters such as the equilibrium climate sensitivity, as well as uncertainty in other parameters set by the original model developers. To highlight the difference between the impact of the discount rate and other quantified sources of uncertainty, the bars below the frequency distributions provide a symmetric representation of quantified variability in the SC-CO_2 estimates for each discount rate. As illustrated by the figure, the assumed discount rate plays a critical role in the ultimate estimate of the SC-CO_2. This is because CO_2 emissions today continue to impact society far out into the future, so with a higher discount rate, costs that accrue to future generations are weighted less, resulting in a lower estimate. As discussed in the February 2021 TSD, there are other sources of uncertainty that have not yet been quantified and are thus not reflected in these estimates.

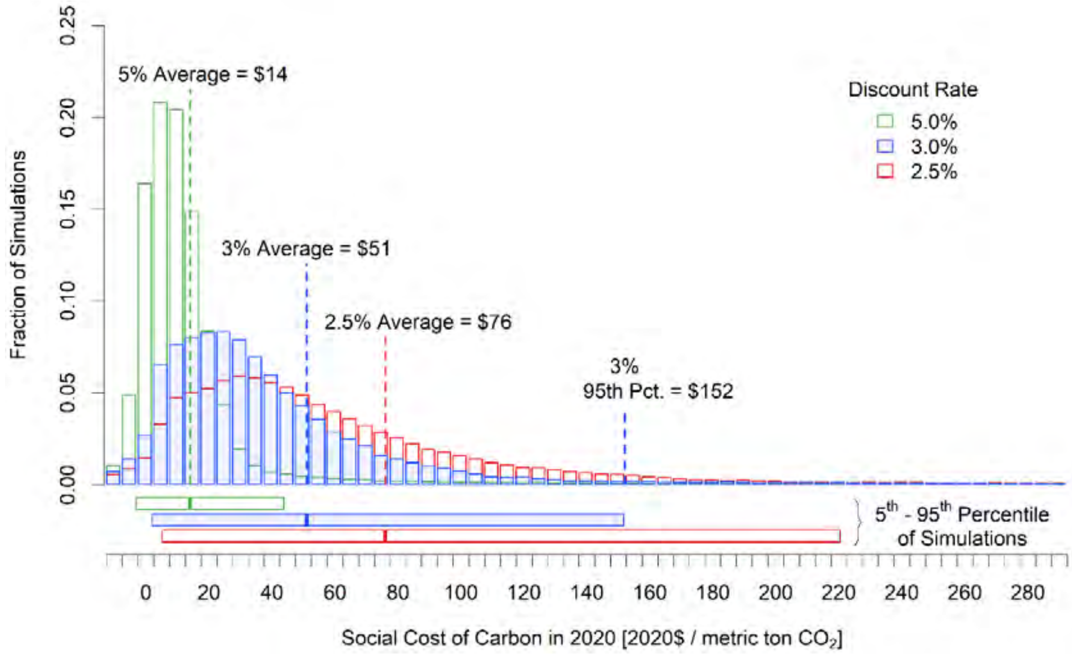

Figure 10-1: Frequency Distribution of SC-CO_2 Estimates for 2030[168]

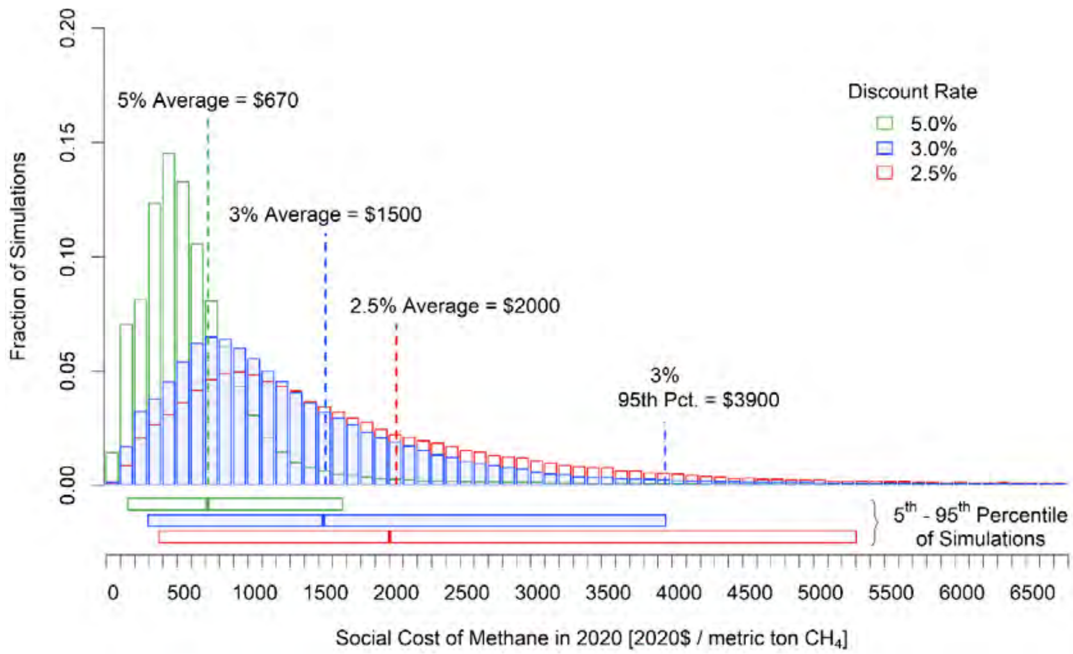

Figure 10-2: Frequency Distribution of SC-CH4 Estimates for 2030[168]

[168] Although the distributions and numbers are based on the full set of model results (150,000 estimates for each discount rate and gas), for display purposes the horizontal axis is truncated with 0.02 to 0.68 percent of the estimates falling below the lowest bin displayed and 0.12 to 3.11 percent of the estimates falling above the highest bin displayed, depending on the discount rate and GHG.

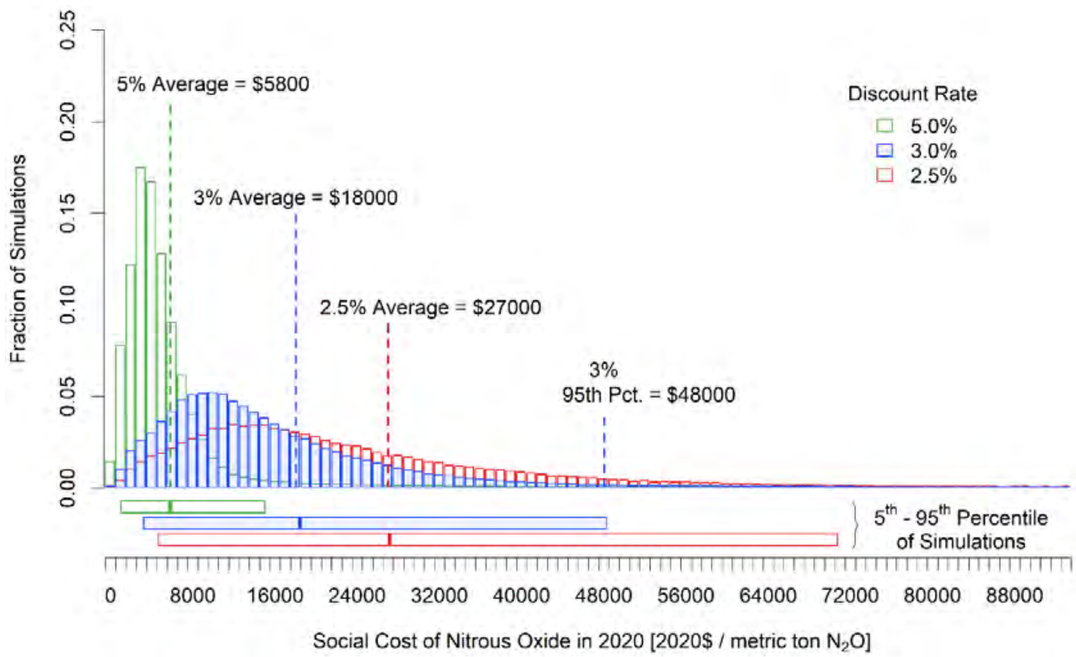

Figure 10-3: Frequency Distribution of SC-N2O Estimates for 2030[168]

The interim SC-GHG estimates presented in Table 10-13 through Table 10-15 have a number of other limitations. First, the current scientific and economic understanding of discounting approaches suggests discount rates appropriate for intergenerational analysis in the context of climate change are likely to be less than 3 percent, near 2 percent or lower (IPCC 2007). Second, the IAMs used to produce these interim estimates do not include all of the important physical, ecological, and economic impacts of climate change recognized in the climate change literature and the science underlying their "damage functions" – i.e., the core parts of the IAMs that map global mean temperature changes and other physical impacts of climate change into economic (both market and nonmarket) damages–lags behind the most recent research. For example, limitations include the incomplete treatment of catastrophic and non-catastrophic impacts in the integrated assessment models, their incomplete treatment of adaptation and technological change, the incomplete way in which inter-regional and intersectoral linkages are modeled, uncertainty in the extrapolation of damages to high temperatures, and inadequate representation of the relationship between the discount rate and uncertainty in economic growth over long time horizons. Likewise, the socioeconomic and emissions scenarios used as inputs to the models do not reflect new information from the last decade of scenario generation or the full range of projections.

The modeling limitations do not all work in the same direction in terms of their influence on the SC-GHG estimates. However, as discussed in the February 2021 TSD, the IWG has recommended that, taken together, the limitations suggest that the SC-GHG estimates used in this final rule likely underestimate the damages from GHG emissions. EPA concurs that the values used in this rulemaking conservatively underestimate the rule's climate benefits. In particular, the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report, which was the most current IPCC assessment available at the time when the IWG decision over the ECS input was made, concluded that SC-CO_2 estimates "very likely…underestimate the damage costs" due to omitted impacts. Since then, the peer-reviewed literature has continued to support this conclusion, as noted in the IPCC's Fifth Assessment report and other recent scientific assessments (IPCC 2014) (IPCC 2018) (IPCC 2019a) (IPCC 2019b) (USGCRP 2016) (USGCRP 2018) (National Academies 2016b) (National Academies 2019). These assessments confirm and strengthen the science, updating projections of future climate change and documenting and attributing ongoing changes. For example, sea level rise projections from the IPCC's Fourth Assessment report ranged from 18 to 59 centimeters by the 2090s relative to 1980-1999, while excluding any dynamic changes in ice sheets due to the limited understanding of those processes at the time (IPCC 2007). A decade later, the Fourth National Climate Assessment projected a substantially larger sea level rise of 30 to 130 centimeters by the end of the century relative to 2000, while not ruling out even more extreme outcomes (USGCRP 2018). EPA has reviewed and considered the limitations of the models used to estimate the interim SC-GHG estimates, and concurs with the February 2021 SC-GHG TSD's assessment that, taken together, the limitations suggest that the interim SC-GHG estimates likely underestimate the damages from GHG emissions.

The February 2021 TSD briefly previews some of the recent advances in the scientific and economic literature that the IWG is actively following and that could provide guidance on, or methodologies for, addressing some of the limitations with the interim SC-GHG estimates. The IWG is currently working on a comprehensive update of the SC-GHG estimates taking into consideration recommendations from the National Academies of Sciences, Engineering and Medicine, recent scientific literature, public comments received on the February 2021 TSD and other input from experts and diverse stakeholder groups (National Academies 2017). While that process continues, 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 going forward. Most recently, EPA presented a draft set of updated SC-GHG estimates within a sensitivity analysis in the regulatory impact analysis of EPA's November 2022 supplemental proposal for oil and gas standards that that aims to incorporate recent advances in the climate science and economics literature. Specifically, the draft updated methodology incorporates new literature and research consistent with the National Academies near-term recommendations on socioeconomic and emissions inputs, climate modeling components, discounting approaches, and treatment of uncertainty, and an enhanced representation of how physical impacts of climate change translate to economic damages in the modeling framework based on the best and readily adaptable damage functions available in the peer reviewed literature. EPA solicited public comment on the sensitivity analysis and the accompanying draft technical report, which explains the methodology underlying the new set of estimates, in the docket for the proposed Oil and Gas rule. EPA is also embarking on an external peer review of this technical report. More information about this process and public comment opportunities is available on EPA's website (U.S. EPA 2022). EPA's draft technical report will be among the many technical inputs available to the IWG as it continues its work.

EPA estimated the dollar value of the GHG-related effects for each analysis year between 2027 through 2055 by applying the SC-GHG estimates, shown in Table 10-13 through Table 10-15, to the net inventory impacts calculated within OMEGA (vehicle and EGU). EPA then calculated the present value and annualized benefits from the perspective of 2027 by discounting each year-specific value to the year 2027 using the same discount rate used to calculate the SC-

GHG. Climate benefits are shown in Table 10-16 through Table 10-19 for the proposed standards and each of the alternatives.[169]

[169] According to OMB's Circular A-4 (OMB 2003), an "analysis should focus on benefits and costs that accrue to citizens and residents of the United States", and international effects should be reported, but separately. Circular A-4 also reminds analysts that "[d]ifferent regulations may call for different emphases in the analysis, depending on the nature and complexity of the regulatory issues." To correctly assess the total climate damages to U.S. citizens and residents, an analysis should account for all the ways climate impacts affect the welfare of U.S. citizens and residents, including how U.S. GHG mitigation activities affect mitigation activities by other countries, and spillover effects from climate action elsewhere. The SC-GHG estimates used in regulatory analysis under revoked EO 13783 were a limited approximation of some of the U.S. specific climate damages from GHG emissions. These estimates range from $8 per metric ton CO2, $231 per metric ton CH4, $2,649 per metric ton N20 (2020 dollars) using a 3 percent discount rate for emissions occurring in 2027 to $12 per metric ton CO2, $382 per metric ton CH4, $4,281 per metric ton N20 using a 3 percent discount rate for emissions occurring in 2055. Applying these estimates (based on a 3 percent discount rate) to the CO2, CH4, and N2O emissions reduction expected under the proposed rule would yield benefits from climate impacts of $57 million in 2027, increasing to $5.2 billion in 2055. However, as discussed at length in the IWG's February 2021 SC-GHG TSD, these estimates are an underestimate of the benefits of GHG mitigation accruing to U.S. citizens and residents, as well as being subject to a considerable degree of uncertainty due to the manner in which they are derived. In particular, as discussed in this analysis, EPA concurs with the assessment in the February 2021 SC-GHG TSD that the estimates developed under revoked E.O. 13783 did not capture significant regional interactions, spillovers, and other effects and so are incomplete underestimates. As the U.S. Government Accountability Office (GAO) concluded in a June 2020 report examining the SC-GHG estimates developed under E.O. 13783, the models "were not premised or calibrated to provide estimates of the social cost of carbon based on domestic damages" p.29 (U.S. GAO 2020). Further, the report noted that the National Academies found that country-specific social costs of carbon estimates were "limited by existing methodologies, which focus primarily on global estimates and do not model all relevant interactions among regions" p.26 (U.S. GAO 2020). It is also important to note that the SC-GHG estimates developed under E.O. 13783 were never peer reviewed, and when their use in a specific regulatory action was challenged, the U.S. District Court for the Northern District of California determined that use of those values had been "soundly rejected by economists as improper and unsupported by science," and that the values themselves omitted key damages to U.S. citizens and residents including to supply chains, U.S. assets and companies, and geopolitical security. The Court found that by omitting such impacts, those estimates "fail[ed] to consider…important aspect[s] of the problem" and departed from the "best science available" as reflected in the global estimates. California v. Bernhardt, 472 F. Supp. 3d 573, 613-14 (N.D. Cal. 2020). EPA continues to center attention in this analysis on the global measures of the SC-GHG as the appropriate estimates given the flaws in the U.S. specific estimates, and as necessary for all countries to use to achieve an efficient allocation of resources for emissions reduction on a global basis, and so benefit the U.S. and its citizens.

Table 10-16 Climate benefits from reductions in GHG emissions associated with the Proposed standards, light-duty and medium-duty (billions of 2020 dollars)

Calendar Year	5% Average SC-GHG	3% Average SC-GHG	2.5% Average SC-GHG	3%, 95th percentile SC-GHG
2027	0.1	0.34	0.5	1
2028	0.27	0.88	1.3	2.7
2029	0.52	1.7	2.4	5
2030	0.82	2.6	3.8	7.9
2031	1.2	3.8	5.5	12
2032	1.7	5.3	7.6	16
2033	2.3	6.9	10	21
2034	2.9	8.8	13	27
2035	3.5	11	15	32
2036	4	12	17	37
2037	4.7	14	20	42
2038	5.3	16	22	48
2039	6	18	25	54
2040	6.7	19	27	60
2041	7.4	21	30	65
2042	8	23	32	70
2043	8.8	25	35	76
2044	9.4	26	37	80
2045	10	28	38	85
2046	11	29	41	90
2047	11	31	42	94
2048	12	32	44	98
2049	12	34	46	100
2050	13	35	48	110
2051	14	35	49	110
2052	14	36	50	110
2053	14	37	51	110
2054	15	37	51	110
2055	15	38	52	110
PV	82	330	500	1000
EAV	5.4	17	25	52

Notes: Climate benefits are based on changes (reductions) in CO2, CH4, and N2O emissions and are calculated using four different estimates of the SC-CO2, SC-CH4, and SC-N2O CH4 (model average at 2.5 percent, 3 percent, and 5 percent discount rates; and 95th percentile at 3 percent discount rate). The IWG emphasized the importance and value of considering the benefits calculated using all four estimates. As discussed in the Technical Support Document: Social Cost of Carbon, Methane, and Nitrous Oxide Interim Estimates under EO 13990 (IWG, 2021), a consideration of climate benefits calculated using discount rates below 3 percent, including 2 percent and lower, are also warranted when discounting intergenerational impacts. The same discount rate used to discount the value of damages from future emissions (SC-GHGs at 5, 3, 2.5 percent) is used to calculate the present value of SC-GHGs for internal consistency. Annual benefits shown are undiscounted values.

Table 10-17 Climate benefits from reductions in GHG emissions associated with Alternative 1, light-duty and medium-duty (billions of 2020 dollars)

Calendar Year	5% Average SC-GHG	3% Average SC-GHG	2.5% Average SC-GHG	3%, 95th percentile SC-GHG
2027	0.11	0.36	0.52	1.1
2028	0.31	1	1.5	3
2029	0.58	1.9	2.7	5.6
2030	0.96	3.1	4.4	9.2
2031	1.4	4.4	6.3	13
2032	1.9	6	8.6	18
2033	2.6	7.9	11	24
2034	3.2	9.9	14	30
2035	3.9	12	17	36
2036	4.5	14	19	41
2037	5.2	16	22	48
2038	6	18	25	54
2039	6.7	20	28	60
2040	7.5	22	30	66
2041	8.2	24	33	73
2042	8.9	25	36	78
2043	9.7	27	38	84
2044	10	29	40	89
2045	11	31	43	94
2046	12	32	45	100
2047	12	34	47	100
2048	13	35	49	110
2049	14	37	51	110
2050	14	38	53	120
2051	15	39	54	120
2052	15	40	55	120
2053	16	40	56	120
2054	16	41	56	120
2055	16	41	57	120
PV	91	360	560	1100
EAV	6	19	27	58

Notes: Climate benefits are based on changes (reductions) in CO2, CH4, and N2O emissions and are calculated using four different estimates of the SC-CO2, SC-CH4, and SC-N2O CH4 (model average at 2.5 percent, 3 percent, and 5 percent discount rates; and 95th percentile at 3 percent discount rate). The IWG emphasized the importance and value of considering the benefits calculated using all four estimates. As discussed in the Technical Support Document: Social Cost of Carbon, Methane, and Nitrous Oxide Interim Estimates under EO 13990 (IWG, 2021), a consideration of climate benefits calculated using discount rates below 3 percent, including 2 percent and lower, are also warranted when discounting intergenerational impacts. The same discount rate used to discount the value of damages from future emissions (SC-GHGs at 5, 3, 2.5 percent) is used to calculate the present value of SC-GHGs for internal consistency. Annual benefits shown are undiscounted values.

Table 10-18 Climate benefits from reductions in GHG emissions associated with Alternative 2, light-duty and medium-duty (billions of 2020 dollars)

Calendar Year	5% Average SC-GHG	3% Average SC-GHG	2.5% Average SC-GHG	3%, 95th percentile SC-GHG
2027	0.076	0.25	0.36	0.75
2028	0.2	0.65	0.95	2
2029	0.41	1.3	1.9	4
2030	0.66	2.1	3	6.3
2031	0.99	3.1	4.5	9.5
2032	1.4	4.4	6.4	13
2033	2	6	8.7	18
2034	2.5	7.7	11	23
2035	3.1	9.3	13	28
2036	3.6	11	15	33
2037	4.2	12	18	38
2038	4.8	14	20	43
2039	5.4	16	22	48
2040	6	17	25	54
2041	6.7	19	27	59
2042	7.3	21	29	63
2043	7.9	22	31	69
2044	8.5	24	33	73
2045	9	25	35	77
2046	9.6	27	37	81
2047	10	28	38	85
2048	11	29	40	89
2049	11	30	42	93
2050	12	32	44	97
2051	12	32	45	98
2052	13	33	45	99
2053	13	33	46	100
2054	13	34	47	100
2055	13	34	47	100
PV	74	290	450	900
EAV	4.9	15	22	47

Notes: Climate benefits are based on changes (reductions) in CO2, CH4, and N2O emissions and are calculated using four different estimates of the SC-CO2, SC-CH4, and SC-N2O CH4 (model average at 2.5 percent, 3 percent, and 5 percent discount rates; and 95th percentile at 3 percent discount rate). The IWG emphasized the importance and value of considering the benefits calculated using all four estimates. As discussed in the Technical Support Document: Social Cost of Carbon, Methane, and Nitrous Oxide Interim Estimates under EO 13990 (IWG, 2021), a consideration of climate benefits calculated using discount rates below 3 percent, including 2 percent and lower, are also warranted when discounting intergenerational impacts. The same discount rate used to discount the value of damages from future emissions (SC-GHGs at 5, 3, 2.5 percent) is used to calculate the present value of SC-GHGs for internal consistency. Annual benefits shown are undiscounted values.

Table 10-19 Climate benefits from reductions in GHG emissions associated with Alternative 3, light-duty and medium-duty (billions of 2020 dollars)

Calendar Year	5% Average SC-GHG	3% Average SC-GHG	2.5% Average SC-GHG	3%, 95th percentile SC-GHG
2027	0.062	0.2	0.3	0.61
2028	0.17	0.54	0.78	1.6
2029	0.3	0.98	1.4	2.9
2030	0.53	1.7	2.4	5.1
2031	0.89	2.8	4.1	8.5
2032	1.4	4.3	6.2	13
2033	1.9	6	8.6	18
2034	2.6	7.8	11	24
2035	3.2	9.7	14	29
2036	3.7	11	16	34
2037	4.4	13	19	40
2038	5.1	15	21	46
2039	5.8	17	24	52
2040	6.5	19	26	58
2041	7.2	21	29	63
2042	7.9	22	31	69
2043	8.6	24	34	74
2044	9.2	26	36	79
2045	9.9	27	38	84
2046	11	29	40	89
2047	11	30	42	93
2048	12	32	44	98
2049	12	33	46	100
2050	13	35	48	110
2051	14	35	49	110
2052	14	36	50	110
2053	14	37	51	110
2054	15	37	51	110
2055	15	38	52	110
PV	80	320	490	970
EAV	5.3	17	24	51

Notes: Climate benefits are based on changes (reductions) in CO2, CH4, and N2O emissions and are calculated using four different estimates of the SC-CO2, SC-CH4, and SC-N2O CH4 (model average at 2.5 percent, 3 percent, and 5 percent discount rates; and 95th percentile at 3 percent discount rate). The IWG emphasized the importance and value of considering the benefits calculated using all four estimates. As discussed in the Technical Support Document: Social Cost of Carbon, Methane, and Nitrous Oxide Interim Estimates under EO 13990 (IWG, 2021), a consideration of climate benefits calculated using discount rates below 3 percent, including 2 percent and lower, are also warranted when discounting intergenerational impacts. The same discount rate used to discount the value of damages from future emissions (SC-GHGs at 5, 3, 2.5 percent) is used to calculate the present value of SC-GHGs for internal consistency. Annual benefits shown are undiscounted values.

10.5 Criteria Air Pollutant Benefits

For the analysis of the proposed standards, we use a reduced-form "benefit-per-ton" (BPT) approach to estimate the monetized $PM_{2.5}$-related health benefits of this proposal. As described in draft RIA Chapter 7.4, 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 attributable to the proposed standards. 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 proposal would be larger if we were able to monetize these unquantified benefits at this time.

Using the BPT approach, we estimate the present value of $PM_{2.5}$-related benefits of the proposed program to be $140 to $280 billion at a 3% discount rate and $63 to $130 billion at a 7% discount rate. Benefits are reported in year 2020 dollars and reflect the $PM_{2.5}$-related benefits associated with reductions in NO_X, SO_2, and direct $PM_{2.5}$ emissions. Because premature mortality typically constitutes the vast majority of monetized benefits in a $PM_{2.5}$ benefits assessment, we present a range of 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: 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).

Table 10-20 presents the annual, undiscounted $PM_{2.5}$-related health benefits estimated for the stream of years beginning with the first year of rule implementation, 2027, through 2055 for the proposed standards. Benefits are presented by source (onroad and upstream) and are estimated using either a 3 percent or 7 percent discount rate to account for a “cessation” lag between the change in PM exposures and the total realization of changes in mortality effects. Table 10-20 also shows the present and annualized values of $PM_{2.5}$-related benefits for the proposed program between 2027 and 2055 (discounted back to 2027). Table 10-21 through Table 10-23 present the results for each of the alternatives.

Table 10-20 Monetized $PM_{2.5}$ health benefits of onroad and upstream emissions reductions associated with the Proposed standards (billions of 2020 dollars)

	Total Onroad		Total Upstream		Total Benefits	
	3% Discount Rate	7% Discount Rate	3% Discount Rate	7% Discount Rate	3% Discount Rate	7% Discount Rate
2027	0.053 - 0.11	0.048 - 0.1	0.011 - 0.026	0.01 - 0.023	0.064 - 0.14	0.058 - 0.13
2028	0.13 - 0.28	0.12 - 0.25	0.039 - 0.088	0.035 - 0.08	0.17 - 0.37	0.15 - 0.33
2029	0.24 - 0.52	0.22 - 0.47	0.083 - 0.19	0.075 - 0.17	0.33 - 0.71	0.29 - 0.63
2030	0.65 - 1.3	0.58 - 1.2	0.15 - 0.33	0.14 - 0.29	0.8 - 1.7	0.72 - 1.5
2031	1 - 2.1	0.93 - 1.9	0.24 - 0.52	0.22 - 0.47	1.3 - 2.7	1.2 - 2.4
2032	1.4 - 3	1.3 - 2.7	0.36 - 0.77	0.33 - 0.69	1.8 - 3.7	1.6 - 3.4
2033	1.9 - 3.9	1.7 - 3.5	0.51 - 1.1	0.45 - 0.96	2.4 - 4.9	2.1 - 4.4
2034	2.3 - 4.8	2.1 - 4.3	0.67 - 1.4	0.6 - 1.3	3 - 6.2	2.7 - 5.6
2035	3.2 - 6.4	2.9 - 5.8	0.98 - 2	0.88 - 1.8	4.2 - 8.4	3.7 - 7.6
2036	3.7 - 7.4	3.3 - 6.6	1.2 - 2.4	1 - 2.2	4.8 - 9.8	4.3 - 8.8
2037	4.2 - 8.4	3.7 - 7.5	1.4 - 2.8	1.2 - 2.6	5.6 - 11	5 - 10
2038	4.7 - 9.4	4.2 - 8.5	1.6 - 3.3	1.5 - 3	6.3 - 13	5.6 - 11
2039	5.1 - 10	4.6 - 9.3	1.9 - 3.8	1.7 - 3.4	7 - 14	6.3 - 13
2040	6.3 - 13	5.7 - 11	2.4 - 4.8	2.1 - 4.3	8.7 - 17	7.8 - 16
2041	6.8 - 14	6.1 - 12	2.7 - 5.3	2.4 - 4.8	9.5 - 19	8.5 - 17
2042	7.3 - 14	6.6 - 13	2.9 - 5.8	2.6 - 5.2	10 - 20	9.2 - 18
2043	7.8 - 15	7 - 14	3.2 - 6.4	2.9 - 5.8	11 - 22	9.8 - 20
2044	8.1 - 16	7.3 - 14	3.4 - 6.9	3.1 - 6.2	12 - 23	10 - 21
2045	9.3 - 18	8.4 - 16	3.7 - 7.4	3.3 - 6.6	13 - 26	12 - 23
2046	9.7 - 19	8.7 - 17	4 - 7.9	3.6 - 7.1	14 - 27	12 - 24
2047	10 - 20	9 - 18	4.2 - 8.3	3.8 - 7.5	14 - 28	13 - 25
2048	10 - 20	9.2 - 18	4.3 - 8.6	3.9 - 7.7	15 - 29	13 - 26
2049	11 - 21	9.4 - 18	4.4 - 8.9	4 - 8	15 - 29	13 - 26
2050	12 - 22	10 - 20	4.6 - 9.1	4.1 - 8.2	16 - 31	14 - 28
2051	12 - 23	11 - 20	4.6 - 9.2	4.1 - 8.2	16 - 32	15 - 29
2052	12 - 23	11 - 21	4.6 - 9.2	4.1 - 8.3	16 - 32	15 - 29
2053	12 - 23	11 - 21	4.6 - 9.3	4.2 - 8.3	17 - 32	15 - 29
2054	12 - 23	11 - 21	4.6 - 9.3	4.2 - 8.3	17 - 32	15 - 29
2055	13 - 25	12 - 22	4.6 - 9.3	4.2 - 8.3	18 - 34	16 - 31
Present Value	100 - 200	46 - 91	39 - 79	17 - 35	140 - 280	63 - 130
Equivalent Annualized Value	5.4 - 11	3.7 - 7.4	2.1 - 4.1	1.4 - 2.8	7.5 - 15	5.1 - 10

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). 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 2020 dollars) using either a 3% or 7% discount rate. The benefits associated with the standards presented here do not include the full complement of health and environmental benefits that, if quantified and monetized, would increase the total monetized benefits.

Table 10-21 Monetized $PM_{2.5}$ health benefits of onroad and upstream emissions reductions associated with Alternative 1 (billions of 2020 dollars)

	Total Onroad		Total Upstream		Total Benefits	
	3% Discount Rate	7% Discount Rate	3% Discount Rate	7% Discount Rate	3% Discount Rate	7% Discount Rate
2027	0.055 - 0.12	0.05 - 0.11	0.012 - 0.027	0.011 - 0.025	0.067 - 0.15	0.06 - 0.13
2028	0.14 - 0.3	0.13 - 0.27	0.048 - 0.11	0.044 - 0.098	0.19 - 0.41	0.17 - 0.37
2029	0.25 - 0.53	0.22 - 0.48	0.11 - 0.23	0.095 - 0.21	0.35 - 0.76	0.32 - 0.69
2030	0.66 - 1.4	0.59 - 1.2	0.2 - 0.42	0.18 - 0.38	0.85 - 1.8	0.77 - 1.6
2031	1 - 2.2	0.93 - 1.9	0.31 - 0.65	0.28 - 0.59	1.3 - 2.8	1.2 - 2.5
2032	1.4 - 3	1.3 - 2.7	0.44 - 0.94	0.4 - 0.84	1.9 - 3.9	1.7 - 3.5
2033	1.9 - 3.9	1.7 - 3.5	0.61 - 1.3	0.55 - 1.2	2.5 - 5.2	2.2 - 4.6
2034	2.3 - 4.8	2.1 - 4.3	0.78 - 1.7	0.71 - 1.5	3.1 - 6.5	2.8 - 5.8
2035	3.2 - 6.5	2.9 - 5.8	1.1 - 2.3	1 - 2.1	4.3 - 8.8	3.9 - 7.9
2036	3.7 - 7.4	3.3 - 6.7	1.3 - 2.7	1.2 - 2.5	5 - 10	4.5 - 9.1
2037	4.2 - 8.5	3.8 - 7.6	1.6 - 3.2	1.4 - 2.9	5.8 - 12	5.2 - 11
2038	4.7 - 9.5	4.2 - 8.6	1.8 - 3.7	1.6 - 3.4	6.5 - 13	5.9 - 12
2039	5.2 - 10	4.7 - 9.4	2.1 - 4.2	1.9 - 3.8	7.3 - 15	6.5 - 13
2040	6.4 - 13	5.7 - 11	2.7 - 5.3	2.4 - 4.8	9.1 - 18	8.1 - 16
2041	6.9 - 14	6.2 - 12	3 - 5.9	2.7 - 5.3	9.9 - 20	8.9 - 18
2042	7.4 - 15	6.6 - 13	3.2 - 6.5	2.9 - 5.8	11 - 21	9.5 - 19
2043	7.8 - 15	7 - 14	3.5 - 7.1	3.2 - 6.4	11 - 23	10 - 20
2044	8.2 - 16	7.4 - 15	3.8 - 7.6	3.4 - 6.8	12 - 24	11 - 21
2045	9.4 - 18	8.5 - 17	4.1 - 8.2	3.7 - 7.3	14 - 27	12 - 24
2046	9.8 - 19	8.8 - 17	4.4 - 8.8	3.9 - 7.9	14 - 28	13 - 25
2047	10 - 20	9.1 - 18	4.6 - 9.2	4.1 - 8.3	15 - 29	13 - 26
2048	10 - 20	9.3 - 18	4.8 - 9.5	4.3 - 8.6	15 - 30	14 - 27
2049	11 - 21	9.5 - 19	4.9 - 9.8	4.4 - 8.8	16 - 31	14 - 27
2050	12 - 23	11 - 20	5 - 10	4.5 - 9	17 - 33	15 - 29
2051	12 - 23	11 - 21	5 - 10	4.5 - 9.1	17 - 33	15 - 30
2052	12 - 23	11 - 21	5.1 - 10	4.6 - 9.1	17 - 33	15 - 30
2053	12 - 23	11 - 21	5.1 - 10	4.6 - 9.1	17 - 33	15 - 30
2054	12 - 23	11 - 21	5.1 - 10	4.6 - 9.1	17 - 34	15 - 30
2055	13 - 25	12 - 23	5.1 - 10	4.6 - 9.1	18 - 35	16 - 32
Present Value	100 - 210	46 - 92	44 - 88	19 - 39	150 - 290	66 - 130
Equivalent Annualized Value	5.4 - 11	3.8 - 7.5	2.3 - 4.6	1.6 - 3.2	7.7 - 15	5.3 - 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 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 2020 dollars) using either a 3% or 7% discount rate. The benefits associated with the standards presented here do not include the full complement of health and environmental benefits that, if quantified and monetized, would increase the total monetized benefits.

Table 10-22 Monetized $PM_{2.5}$ health benefits of onroad and upstream emissions reductions associated with Alternative 2 (billions of 2020 dollars)

	Total Onroad		Total Upstream		Total Benefits	
	3% Discount Rate	7% Discount Rate	3% Discount Rate	7% Discount Rate	3% Discount Rate	7% Discount Rate
2027	0.039 - 0.083	0.035 - 0.075	0.0083 - 0.019	0.0075 - 0.017	0.047 - 0.1	0.042 - 0.092
2028	0.094 - 0.2	0.084 - 0.18	0.031 - 0.07	0.028 - 0.063	0.13 - 0.27	0.11 - 0.24
2029	0.19 - 0.41	0.17 - 0.37	0.069 - 0.15	0.062 - 0.14	0.26 - 0.56	0.23 - 0.51
2030	0.59 - 1.2	0.53 - 1.1	0.12 - 0.27	0.11 - 0.24	0.71 - 1.5	0.64 - 1.3
2031	0.97 - 2	0.87 - 1.8	0.2 - 0.43	0.18 - 0.39	1.2 - 2.4	1.1 - 2.2
2032	1.4 - 2.8	1.2 - 2.5	0.31 - 0.65	0.28 - 0.59	1.7 - 3.5	1.5 - 3.1
2033	1.8 - 3.7	1.6 - 3.3	0.44 - 0.94	0.4 - 0.85	2.2 - 4.6	2 - 4.2
2034	2.2 - 4.6	2 - 4.2	0.59 - 1.2	0.53 - 1.1	2.8 - 5.9	2.5 - 5.3
2035	3.1 - 6.2	2.8 - 5.6	0.87 - 1.8	0.78 - 1.6	4 - 8	3.6 - 7.2
2036	3.6 - 7.2	3.2 - 6.5	1 - 2.1	0.92 - 1.9	4.6 - 9.3	4.1 - 8.4
2037	4.1 - 8.2	3.7 - 7.4	1.2 - 2.5	1.1 - 2.3	5.3 - 11	4.8 - 9.6
2038	4.6 - 9.2	4.1 - 8.3	1.4 - 2.9	1.3 - 2.6	6 - 12	5.4 - 11
2039	5.1 - 10	4.5 - 9.2	1.6 - 3.4	1.5 - 3	6.7 - 14	6 - 12
2040	6.2 - 12	5.6 - 11	2.1 - 4.3	1.9 - 3.8	8.4 - 17	7.5 - 15
2041	6.7 - 13	6.1 - 12	2.4 - 4.8	2.1 - 4.3	9.1 - 18	8.2 - 16
2042	7.2 - 14	6.5 - 13	2.6 - 5.2	2.4 - 4.7	9.8 - 19	8.8 - 18
2043	7.7 - 15	6.9 - 14	2.9 - 5.8	2.6 - 5.2	11 - 21	9.5 - 19
2044	8 - 16	7.2 - 14	3.1 - 6.2	2.8 - 5.6	11 - 22	10 - 20
2045	9.2 - 18	8.3 - 16	3.3 - 6.6	3 - 6	13 - 25	11 - 22
2046	9.6 - 19	8.6 - 17	3.6 - 7.1	3.2 - 6.4	13 - 26	12 - 23
2047	9.9 - 19	8.9 - 17	3.8 - 7.5	3.4 - 6.8	14 - 27	12 - 24
2048	10 - 20	9.1 - 18	3.9 - 7.8	3.5 - 7	14 - 28	13 - 25
2049	10 - 20	9.4 - 18	4 - 8	3.6 - 7.2	14 - 28	13 - 26
2050	11 - 22	10 - 20	4.1 - 8.3	3.7 - 7.4	16 - 30	14 - 27
2051	12 - 22	10 - 20	4.2 - 8.3	3.7 - 7.5	16 - 31	14 - 28
2052	12 - 23	11 - 20	4.2 - 8.3	3.8 - 7.5	16 - 31	14 - 28
2053	12 - 23	11 - 20	4.2 - 8.4	3.8 - 7.5	16 - 31	14 - 28
2054	12 - 23	11 - 21	4.2 - 8.4	3.8 - 7.5	16 - 31	14 - 28
2055	13 - 25	12 - 22	4.2 - 8.4	3.8 - 7.5	17 - 33	15 - 30
Present Value	100 - 200	45 - 89	35 - 71	15 - 31	140 - 270	61 - 120
Equivalent Annualized Value	5.3 - 10	3.7 - 7.3	1.8 - 3.7	1.3 - 2.5	7.2 - 14	4.9 - 9.8

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). 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 2020 dollars) using either a 3% or 7% discount rate. The benefits associated with the standards presented here do not include the full complement of health and environmental benefits that, if quantified and monetized, would increase the total monetized benefits.

Table 10-23 Monetized $PM_{2.5}$ health benefits of onroad and upstream emissions reductions associated with Alternative 3 (billions of 2020 dollars)

	Total Onroad		Total Upstream		Total Benefits	
	3% Discount Rate	7% Discount Rate	3% Discount Rate	7% Discount Rate	3% Discount Rate	7% Discount Rate
2027	0.034 - 0.073	0.031 - 0.066	0.0057 - 0.013	0.0051 - 0.012	0.04 - 0.086	0.036 - 0.078
2028	0.085 - 0.18	0.076 - 0.16	0.023 - 0.052	0.021 - 0.047	0.11 - 0.23	0.097 - 0.21
2029	0.15 - 0.32	0.14 - 0.29	0.049 - 0.11	0.044 - 0.098	0.2 - 0.43	0.18 - 0.39
2030	0.54 - 1.1	0.48 - 1	0.098 - 0.21	0.088 - 0.19	0.63 - 1.3	0.57 - 1.2
2031	0.92 - 1.9	0.83 - 1.7	0.18 - 0.38	0.16 - 0.34	1.1 - 2.3	0.99 - 2.1
2032	1.3 - 2.7	1.2 - 2.4	0.29 - 0.62	0.26 - 0.56	1.6 - 3.3	1.4 - 3
2033	1.7 - 3.6	1.6 - 3.3	0.43 - 0.92	0.39 - 0.83	2.2 - 4.5	2 - 4.1
2034	2.2 - 4.6	2 - 4.1	0.6 - 1.3	0.54 - 1.1	2.8 - 5.8	2.5 - 5.2
2035	3 - 6.1	2.7 - 5.5	0.9 - 1.8	0.81 - 1.7	3.9 - 8	3.5 - 7.2
2036	3.5 - 7.1	3.2 - 6.4	1.1 - 2.2	0.97 - 2	4.6 - 9.3	4.1 - 8.4
2037	4 - 8.1	3.6 - 7.3	1.3 - 2.7	1.2 - 2.4	5.3 - 11	4.8 - 9.7
2038	4.6 - 9.2	4.1 - 8.3	1.5 - 3.1	1.4 - 2.8	6.1 - 12	5.5 - 11
2039	5 - 10	4.5 - 9.1	1.8 - 3.6	1.6 - 3.3	6.8 - 14	6.1 - 12
2040	6.2 - 12	5.6 - 11	2.3 - 4.6	2.1 - 4.1	8.5 - 17	7.7 - 15
2041	6.7 - 13	6 - 12	2.6 - 5.2	2.3 - 4.6	9.3 - 18	8.4 - 17
2042	7.2 - 14	6.5 - 13	2.8 - 5.7	2.6 - 5.1	10 - 20	9 - 18
2043	7.7 - 15	6.9 - 14	3.1 - 6.3	2.8 - 5.6	11 - 21	9.7 - 19
2044	8 - 16	7.2 - 14	3.4 - 6.8	3 - 6.1	11 - 23	10 - 20
2045	9.3 - 18	8.3 - 16	3.6 - 7.3	3.3 - 6.5	13 - 25	12 - 23
2046	9.7 - 19	8.7 - 17	3.9 - 7.8	3.5 - 7	14 - 27	12 - 24
2047	9.9 - 19	8.9 - 17	4.1 - 8.3	3.7 - 7.4	14 - 28	13 - 25
2048	10 - 20	9.2 - 18	4.3 - 8.6	3.9 - 7.7	15 - 29	13 - 26
2049	10 - 20	9.4 - 18	4.4 - 8.9	4 - 8	15 - 29	13 - 26
2050	12 - 22	10 - 20	4.6 - 9.1	4.1 - 8.2	16 - 31	14 - 28
2051	12 - 23	10 - 20	4.6 - 9.2	4.1 - 8.2	16 - 32	15 - 29
2052	12 - 23	11 - 21	4.6 - 9.2	4.1 - 8.3	16 - 32	15 - 29
2053	12 - 23	11 - 21	4.6 - 9.2	4.2 - 8.3	16 - 32	15 - 29
2054	12 - 23	11 - 21	4.6 - 9.3	4.2 - 8.3	17 - 32	15 - 29
2055	13 - 25	12 - 22	4.6 - 9.3	4.2 - 8.3	18 - 34	16 - 31
Present Value	100 - 200	45 - 89	38 - 77	17 - 33	140 - 280	62 - 120
Equivalent Annualized Value	5.3 - 10	3.7 - 7.3	2 - 4	1.4 - 2.7	7.3 - 14	5 - 10

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). 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 2020 dollars) using either a 3% or 7% discount rate. The benefits associated with the standards presented here do not include the full complement of health and environmental benefits that, if quantified and monetized, would increase the total monetized benefits.

10.6 Summary and Net Benefits

The above costs, savings and benefits are summarized for the proposed standards in Table 10-24 along with net benefits. Table 10-25, Table 10-26 and Table 10-27 present this information for Alternatives 1, 2 and 3, respectively.

Table 10-24 Summary of costs, fuel savings and benefits of the Proposal standards, light-duty and medium-duty (billions of 2020 dollars)[a,b,c]

	CY 2055	PV, 3%	PV, 7%	EAV, 3%	EAV, 7%
Non-Emission Costs					
Vehicle Technology Costs	10	280	180	15	15
Repair Costs	-24	-170	-79	-8.9	-6.5
Maintenance Costs	-51	-410	-200	-21	-16
Congestion Costs	0.16	2.3	1.3	0.12	0.11
Noise Costs	0.0025	0.037	0.021	0.0019	0.0017
Sum of Non-Emission Costs	-65	-290	-96	-15	-7.8
Fueling Impacts					
Pre-tax Fuel Savings	93	890	450	46	37
EVSE Port Costs	7.1	120	68	6.2	5.6
Sum of Fuel Savings less EVSE Port Costs	86	770	380	40	31
Non-Emission Benefits					
Drive Value Benefits	0.31	4.8	2.7	0.25	0.22
Refueling Time	-8.2	-85	-45	-4.4	-3.6
Energy Security	4.4	41	21	2.2	1.7
Sum of Non-Emission Benefits	-3.6	-39	-21	-2	-1.7
Climate Benefits					
5% Average	15	82	82	5.4	5.4
3% Average	38	330	330	17	17
2.5% Average	52	500	500	25	25
3% 95th Percentile	110	1,000	1,000	52	52
Criteria Air Pollutant Benefits					
$PM_{2.5}$ Health Benefits – Wu et al., 2020	16 - 18	140	63	7.5	5.1
$PM_{2.5}$ Health Benefits – Pope III et al., 2019	31 - 34	280	130	15	10
Net Benefits					
With Climate 5% Average	180 - 200	1,400	610	74	48
With Climate 3% Average	200 - 220	1,600	850	85	60
With Climate 2.5% Average	210 - 230	1,800	1,000	93	67
With Climate 3% 95th Percentile	280 - 290	2,300	1,500	120	95

[a] The same discount rate used to discount the value of damages from future emissions (SC-GHG at 5, 3, 2.5 percent) is used to calculate present and equivalent annualized values of SC-GHGs for internal consistency, while all other costs and benefits are discounted at either 3 percent or 7 percent.

[b] $PM_{2.5}$-related health benefits are presented based on two different long-term exposure studies of mortality risk: a Medicare study (Wu et al., 2020) and a National Health Interview Survey study (Pope III et al., 2019). The criteria pollutant benefits associated with the standards presented here do not include the full complement of health and environmental benefits that, if quantified and monetized, would increase the total monetized benefits.

[c] For net benefits, the range in 2055 uses the low end of the Wu range and the high end of the Pope III et al. range. The present and equivalent annualized value of net benefits for a 3 percent discount rate reflect benefits based on the Pope III et al. study while the present and equivalent annualized value of net benefits for a 7 percent discount rate reflect benefits based on the Wu et al. study.

Table 10-25 Summary of costs, fuel savings and benefits of Alternative 1, light-duty and medium-duty (billions of 2020 dollars)[a,b,c]

	CY 2055	PV, 3%	PV, 7%	EAV, 3%	EAV, 7%
Non-Emission Costs					
Vehicle Technology Costs	11	330	220	17	18
Repair Costs	-26	-180	-82	-9.3	-6.7
Maintenance Costs	-57	-450	-220	-24	-18
Congestion Costs	0.11	3.5	2.2	0.18	0.18
Noise Costs	0.0017	0.055	0.034	0.0028	0.0027
Sum of Non-Emission Costs	-71	-300	-82	-15	-6.7
Fueling Impacts					
Pre-tax Fuel Savings	100	990	510	51	41
EVSE Port Costs	7.1	120	68	6.2	5.6
Sum of Fuel Savings less EVSE Port Costs	95	870	440	45	36
Non-Emission Benefits					
Drive Value Benefits	0.22	6.5	3.9	0.34	0.32
Refueling Time	-8.8	-90	-47	-4.7	-3.8
Energy Security	4.8	46	23	2.4	1.9
Sum of Non-Emission Benefits	-3.8	-38	-20	-2	-1.6
Climate Benefits					
5% Average	16	91	91	6	6
3% Average	41	360	360	19	19
2.5% Average	57	560	560	27	27
3% 95th Percentile	120	1,100	1,100	58	58
Criteria Air Pollutant Benefits					
$PM_{2.5}$ Health Benefits – Wu et al., 2020	16 - 18	150	66	7.7	5.3
$PM_{2.5}$ Health Benefits – Pope III et al., 2019	32 - 35	290	130	15	11
Net Benefits					
With Climate 5% Average	200 - 210	1,500	660	80	52
With Climate 3% Average	220 - 240	1,800	930	93	65
With Climate 2.5% Average	240 - 260	2,000	1,100	100	73
With Climate 3% 95th Percentile	300 - 320	2,500	1,700	130	100

[a] The same discount rate used to discount the value of damages from future emissions (SC-GHG at 5, 3, 2.5 percent) is used to calculate present and equivalent annualized values of SC-GHGs for internal consistency, while all other costs and benefits are discounted at either 3 percent or 7 percent.

[b] $PM_{2.5}$-related health benefits are presented based on two different long-term exposure studies of mortality risk: a Medicare study (Wu et al., 2020) and a National Health Interview Survey study (Pope III et al., 2019). The criteria pollutant benefits associated with the standards presented here do not include the full complement of health and environmental benefits that, if quantified and monetized, would increase the total monetized benefits.

[c] For net benefits, the range in 2055 uses the low end of the Wu range and the high end of the Pope III et al. range. The present and equivalent annualized value of net benefits for a 3 percent discount rate reflect benefits based on the Pope III et al. study while the present and equivalent annualized value of net benefits for a 7 percent discount rate reflect benefits based on the Wu et al. study.

Table 10-26 Summary of costs, fuel savings and benefits of Alternative 2, light-duty and medium-duty (billions of 2020 dollars)[a,b,c]

	CY 2055	PV, 3%	PV, 7%	EAV, 3%	EAV, 7%
Non-Emission Costs					
Vehicle Technology Costs	8.8	230	140	12	12
Repair Costs	-22	-160	-74	-8.3	-6
Maintenance Costs	-47	-370	-180	-19	-14
Congestion Costs	0.064	0.74	0.48	0.039	0.039
Noise Costs	0.001	0.012	0.0078	0.00064	0.00064
Sum of Non-Emission Costs	-60	-300	-110	-16	-8.7
Fueling Impacts					
Pre-tax Fuel Savings	84	790	400	41	33
EVSE Port Costs	7.1	120	68	6.2	5.6
Sum of Fuel Savings less EVSE Port Costs	77	680	330	35	27
Non-Emission Benefits					
Drive Value Benefits	0.17	2.4	1.5	0.12	0.12
Refueling Time	-7.6	-79	-41	-4.1	-3.3
Energy Security	3.9	37	19	1.9	1.5
Sum of Non-Emission Benefits	-3.5	-39	-21	-2	-1.7
Climate Benefits					
5% Average	13	74	74	4.9	4.9
3% Average	34	290	290	15	15
2.5% Average	47	450	450	22	22
3% 95th Percentile	100	900	900	47	47
Criteria Air Pollutant Benefits					
$PM_{2.5}$ Health Benefits – Wu et al., 2020	15 - 17	140	61	7.2	4.9
$PM_{2.5}$ Health Benefits – Pope III et al., 2019	30 - 33	270	120	14	10
Net Benefits					
With Climate 5% Average	160 - 180	1,300	550	68	44
With Climate 3% Average	180 - 200	1,500	780	78	54
With Climate 2.5% Average	200 - 210	1,700	930	85	61
With Climate 3% 95th Percentile	250 - 270	2,100	1,400	110	86

[a] The same discount rate used to discount the value of damages from future emissions (SC-GHG at 5, 3, 2.5 percent) is used to calculate present and equivalent annualized values of SC-GHGs for internal consistency, while all other costs and benefits are discounted at either 3 percent or 7 percent.

[b] $PM_{2.5}$-related health benefits are presented based on two different long-term exposure studies of mortality risk: a Medicare study (Wu et al., 2020) and a National Health Interview Survey study (Pope III et al., 2019). The criteria pollutant benefits associated with the standards presented here do not include the full complement of health and environmental benefits that, if quantified and monetized, would increase the total monetized benefits.

[c] For net benefits, the range in 2055 uses the low end of the Wu range and the high end of the Pope III et al. range. The present and equivalent annualized value of net benefits for a 3 percent discount rate reflect benefits based on the Pope III et al. study while the present and equivalent annualized value of net benefits for a 7 percent discount rate reflect benefits based on the Wu et al. study.

Table 10-27 Summary of costs, fuel savings and benefits of Alternative 3, light-duty and medium-duty (billions of 2020 dollars)[a,b,c]

	CY 2055	PV, 3%	PV, 7%	EAV, 3%	EAV, 7%
Non-Emission Costs					
Vehicle Technology Costs	11	270	170	14	14
Repair Costs	-24	-170	-77	-8.6	-6.3
Maintenance Costs	-51	-390	-190	-20	-15
Congestion Costs	0.11	1.5	0.82	0.078	0.066
Noise Costs	0.0016	0.024	0.013	0.0012	0.0011
Sum of Non-Emission Costs	-64	-290	-95	-15	-7.8
Fueling Impacts					
Pre-tax Fuel Savings	93	850	430	45	35
EVSE Port Costs	7.1	120	68	6.2	5.6
Sum of Fuel Savings less EVSE Port Costs	86	740	360	38	29
Non-Emission Benefits					
Drive Value Benefits	0.21	3.2	1.8	0.17	0.15
Refueling Time	-8.2	-83	-43	-4.3	-3.5
Energy Security	4.4	40	20	2.1	1.6
Sum of Non-Emission Benefits	-3.6	-39	-21	-2.1	-1.7
Climate Benefits					
5% Average	15	80	80	5.3	5.3
3% Average	38	320	320	17	17
2.5% Average	52	490	490	24	24
3% 95th Percentile	110	970	970	51	51
Criteria Air Pollutant Benefits					
$PM_{2.5}$ Health Benefits – Wu et al., 2020	16 - 18	140	62	7.3	5.0
$PM_{2.5}$ Health Benefits – Pope III et al., 2019	31 - 34	280	120	14	10
Net Benefits					
With Climate 5% Average	180 - 190	1,300	580	71	46
With Climate 3% Average	200 - 220	1,600	820	82	57
With Climate 2.5% Average	210 - 230	1,800	990	90	64
With Climate 3% 95th Percentile	270 - 290	2,200	1,500	120	91

[a] The same discount rate used to discount the value of damages from future emissions (SC-GHG at 5, 3, 2.5 percent) is used to calculate present and equivalent annualized values of SC-GHGs for internal consistency, while all other costs and benefits are discounted at either 3 percent or 7 percent.

[b] $PM_{2.5}$-related health benefits are presented based on two different long-term exposure studies of mortality risk: a Medicare study (Wu et al., 2020) and a National Health Interview Survey study (Pope III et al., 2019). The criteria pollutant benefits associated with the standards presented here do not include the full complement of health and environmental benefits that, if quantified and monetized, would increase the total monetized benefits.

[c] For net benefits, the range in 2055 uses the low end of the Wu range and the high end of the Pope III et al. range. The present and equivalent annualized value of net benefits for a 3 percent discount rate reflect benefits based on the Pope III et al. study while the present and equivalent annualized value of net benefits for a 7 percent discount rate reflect benefits based on the Wu et al. study.

10.7 Transfers

There are three types of transfers included in our analysis. Two of these transfers come in the form of tax credits arising from the Inflation Reduction Act to encourage investment in battery technology and the purchase of electrified vehicles. These are transfers from the government to producers of vehicles (the battery tax credit) or purchasers of vehicles (the vehicle purchase tax credit). The third is fuel taxes which are transfers from purchasers of fuel to the government. The proposal results in less liquid-fuel consumed and, therefore, less money transferred from purchasers of fuel to the government.

Table 10-28 presents transfers associated with the proposed standards. Table 10-29, Table 10-30 and Table 10-31 present transfers associated with Alternatives 1, 2 and 3, respectively.

Table 10-28 Transfers associated with the Proposed standards, light-duty and medium-duty (billions of 2020 dollars)

Calendar Year	Battery Tax Credits	Purchase Tax Credits	Fuel Taxes	Sum
2027	6.8	6.7	0.31	14
2028	9.2	9.9	0.77	20
2029	13	14	1.4	29
2030	11	18	2.4	31
2031	9	22	3.3	34
2032	5.3	27	4.5	37
2035	0	0	8	8
2040	0	0	12	12
2045	0	0	15	15
2050	0	0	16	16
2055	0	0	15	15
PV3	49	86	180	320
PV7	43	74	97	210
EAV3	2.6	4.5	9.5	17
EAV7	3.5	6	7.9	17

Table 10-29 Transfers associated with Alternative 1, light-duty and medium-duty (billions of 2020 dollars)

Calendar Year	Battery Tax Credits	Purchase Tax Credits	Fuel Taxes	Sum
2027	7.1	7	0.32	14
2028	11	11	0.88	22
2029	13	14	1.6	28
2030	13	20	2.8	36
2031	9.3	23	3.9	36
2032	5.5	29	5.2	39
2035	0	0	9	9
2040	0	0	14	14
2045	0	0	16	16
2050	0	0	17	17
2055	0	0	17	17
PV3	52	92	200	350
PV7	46	79	110	230
EAV3	2.7	4.8	11	18
EAV7	3.8	6.4	8.8	19

Table 10-30 Transfers associated with Alternative 2, light-duty and medium-duty (billions of 2020 dollars)

Calendar Year	Battery Tax Credits	Purchase Tax Credits	Fuel Taxes	Sum
2027	4.8	4.8	0.22	9.8
2028	6.3	6.7	0.57	14
2029	11	13	1.1	25
2030	8.7	14	1.9	24
2031	7.6	19	2.7	29
2032	4.6	24	3.8	32
2035	0	0	7	7
2040	0	0	11	11
2045	0	0	13	13
2050	0	0	14	14
2055	0	0	14	14
PV3	39	71	160	270
PV7	34	60	85	180
EAV3	2	3.7	8.4	14
EAV7	2.8	4.9	7	15

Table 10-31 Transfers associated with Alternative 3, light-duty and medium-duty (billions of 2020 dollars)

Calendar Year	Battery Tax Credits	Purchase Tax Credits	Fuel Taxes	Sum
2027	4.1	4	0.18	8.3
2028	5.6	6.1	0.46	12
2029	6.9	7.7	0.81	15
2030	7.9	13	1.5	22
2031	8.4	21	2.4	31
2032	5.4	27	3.6	36
2035	0	0	7.3	7.3
2040	0	0	12	12
2045	0	0	14	14
2050	0	0	16	16
2055	0	0	15	15
PV3	34	68	170	280
PV7	30	58	91	180
EAV3	1.8	3.6	9	14
EAV7	2.4	4.7	7.4	15

Chapter 10 References

Alex L. Marten, et al. 2015. "Incremental CH4 and N2O mitigation benefits consistent with the US Government's SC-CO2 estimates." Climate Policy 15 (2): 272-298. doi:10.1080/14693062.201.

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. Edited by Core Writing Team, R.K. Pachauri and L.A. Meyer. Geneva.

—. 2019a. 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. Edited by P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmot, H.-O. Pörtner, D. C. Roberts, P. Zhai, et al.

—. 2007. Core WritingTeam; Pachauri, R.K; and Reisinger, A. (ed.) Climate Change 2007: Synthesis Report, Contribution of Working Groups I, II, and II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Vols. ISBN 92-9169-122-4. 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,. Edited by Masson-Delmotte, V., P. Zhai, H.-O Pörtner, D. Roberts, J. Skea, P.R. Shukla, et al.

—. 2019b. IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. Edited by H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, et al.

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.

—. 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.

—. 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.

—. 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.

—. 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.

National Academies. 2016b. Attribution of Extreme Weather Events in the Context of Climate Change. Washington, D.C.: The National Academies Press. doi:10.17226/21852.

—. 2019. Climate Change and Ecosystems. Washington, D.C.: The National Academies Press. doi:10.17226/25504.

—. 2017. Valuing Climate Damages: Updating Estimation of the Social Cost of Carbon Dioxide. Washington, D.C.: The National Academies Press.

Pope III et al., 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.

U.S. EPA. 2022. "EPA's Social Cost of Greenhouse Gases Web Area." Accessed January 10, 2022. https://www.epa.gov/environmental-economics/scghg.

—. 2015a. Proposed Rulemaking for Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium - and Heavy-Duty Engines and Vehicles-Phase 2. Vols. (EPA-420-D-15-900). Washington, D.C.: Office of Transportation and Air Quaility, Assessment and Standards Division. Accessed 2023. https://nepis.epa.gov/Exe/ZyPDF.cgi/P100MKYR.PDF?Dockey=P100MKYR.PDF.

—. 2015b. Regulatory Impact Analysis for the Proposed Revisions to the Emission Guidelines for Existing Sources and Supplemental Proposed New Source Performance Standards in the Municipal Solid Waste Landfills Sector. Accessed January 2023. https://www.regulations.gov/document?D=EPA-HQ-OAR-2014-0451-0086.

—. 2015c. Regulatory Impact Analysis of the Proposed Emission Standards for New and Modified Sources in the Oil and Natural Gas Sector. Accessed January 2023. https://www.regulations.gov/document/EPA-HQ-OAR-2010-0505-5258.

USGCRP. 2018. Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II. Edited by D.R. Reidmiller, C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock and B.C. Stewart. Washington, D.C.: U.S. Global Change Research Program. doi:10.7930/NCA4.2018.

—. 2016. The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment. Edited by A. Crimmins, J. Balbus, J.L. Gamble, C.B. Beard, J.E. Bell, D. Dodgen, R.J. Eisen, et al. U.S. Global Change Research Program.

Wu et al., 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.

Chapter 11: Energy Security Impacts

In this section of the DRIA, we evaluate the energy security impacts of this proposed light- and medium-duty vehicle (LMDV) (2027–2032) rule. Energy security is broadly defined as the uninterrupted availability of energy sources at affordable prices (IEA 2019). Most discussions of U.S. energy security revolve around the topic of the economic costs of U.S. dependence on oil imports.[170] Energy independence and energy security are distinct but related concepts, and an analysis of energy independence informs our assessment of energy security. The goal of U.S. energy independence is generally the elimination of all U.S. imports of petroleum and other foreign sources of energy, or more broadly, reducing the sensitivity of the U.S. economy to energy imports and foreign energy markets (Greene 2010).

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 (EIA 2022). By July 2021, U.S. oil consumption had returned to pre-pandemic levels and has remained fairly stable since then (EIA 2022). The U.S. has increased its production of oil, particularly "tight" (i.e., shale) oil, over the last decade (EIA 2022). 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 projected to be a net exporter of crude oil and refined petroleum products for the foreseeable future (EIA 2022). 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 (EIA 2022).

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 modest net exporter of crude oil and refined petroleum products for the time frame of this analysis (2027–2055), 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 the Organization of Petroleum Exporting Countries (OPEC) to alter oil supply relative to demand. These factors contribute to the vulnerability of the U.S. economy to episodic oil supply shocks and price spikes, even when the U.S. is projected to be an overall net exporter of crude oil and refined petroleum products. Reducing U.S. net oil imports and use reduces the U.S.'s exposure to oil price volatility.

EPA estimates that U.S. consumption and net imports of petroleum will be reduced as a result of this proposed rule, both from an increase in fuel efficiency of LMDVs using petroleum-based fuels and from the greater use of plug-in electric vehicles (PEVs), which are fueled with electricity. A reduction of U.S. net petroleum imports reduces both financial and strategic risks caused by potential sudden disruptions in the supply of petroleum to the U.S. and global market, 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.

[170] 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 (Sanger, Krauss and Perlroth 2021).

It is anticipated that manufacturers will choose to comply with this proposed standard with significant increases in PEVs in the LMDV fleet. The wider use of electricity to power vehicles in the U.S. will likely result in the use of a generally more affordable fuel that has less price volatility compared to the current widespread use of gasoline in LMDVs. Furthermore, the U.S. supply and demand of electricity is almost entirely domestic, and largely independent of electricity markets outside of North America. Over time, the wider penetration of PEVs into the U.S. vehicle fleet will likely provide significant energy security benefits, principally by reducing the overall U.S. demand for oil. As new PEVs enter the vehicle market and the stock of PEVs becomes an increasingly larger fraction of the total stock of vehicles on the road, high oil prices and oil price shocks will have a diminishing impact on the overall U.S. economy, leading to greater energy security. The wider use of electricity to power LMDVs will also move the U.S. towards energy independence, that is independence of foreign markets, since the electricity to power PEVs will almost exclusively be produced in the U.S.

This Chapter of the DRIA first reviews the historical and recent energy security literature relevant in the context of this proposed LMDV rule. This review provides a discussion of recent oil security literature, recent studies on tight oil and recent electricity security studies on the wider use of PEVs. Second, this Chapter also provides an assessment of the electricity security implications of this LMDV proposed rule. Third, in the last section of this Chapter, the agency's estimates of U.S. oil import reductions of the proposed LMDV GHG standards for model years 2027–2032 are presented. The military cost impacts of this proposed rule are discussed as well. However, due to methodological issues, we do not quantify the military costs savings from reduced U.S. oil imports.

11.1 Review of Historical Energy Security Literature

Energy security discussions are typically based around the concept of the oil import premium, sometimes also labeled the oil security premium. The oil import premium is the extra cost/impacts of importing oil beyond the price of the oil 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 shocks of the 1970s. (Bohi and Montgomery 1982), (EMF 1982), and (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. (Bohi and Montgomery 1982) detailed the theoretical foundations of the oil import premium and established many of the critical analytic relationships. Broadman and Hogan revised and extended the established analytical framework to estimate optimal oil import premia with a more detailed accounting of macroeconomic effects (Broadman and Hogan 1988) (Broadman 1986) (Hogan 1981). Since the original work on energy security was undertaken in the 1980s, there have been a couple of reviews on this topic: (Leiby, Jones, et al. 1997), (Parry and Darmstadter 2003).

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, (National Research Council 2010) argued that the non-environmental externalities associated with dependence on foreign oil are small, and potentially trivial. (Nordhaus 2007) and (Blanchard and Galí 2010) question the impact of oil price shocks on the economy in the early 2000s time frame. They were motivated by attempts to explain why the economy actually expanded during the oil shock in the early-2000s time frame, 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 movements are temporary and have noted that price impacts are not passed on as inflation in other parts of the economy.

(Hamilton 2012) reviews the empirical literature on oil shocks and suggests that the results are mixed, noting that some work (Rasmussen and Roitman 2011) finds less evidence for economic effects of oil shocks or declining effects of shocks (Blanchard and Galí 2010), while other work continues to find evidence regarding the economic importance of oil shocks. For example, (Baumeister and Peersman 2013) 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 meant 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." Hamilton observes that "a negative effect of oil prices on real output has also been reported for a number of other countries, particularly when non-linear functional forms have been employed" (citing as examples (Kim 2012) and (Engemann, Kliesen and Owyang 2011)). 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 rationing and shortages."

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 (Baumeister, Peersman and Van Robays 2010). (Kilian and Vigfusson 2014), for example, assigns a more prominent role to the effects of price increases that are unusual, in the sense of being beyond the range of recent experience. Kilian and Vigfusson also conclude 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 the U.S. economy in the short-run and some of which slow down U.S. growth (see Kilian 2009)" (Kilian 2009).

The general conclusion that oil supply-driven shocks reduce economic output is also reached in (Cashin, et al. 2014), which focused on 38 countries from 1979 to 2011. They state: "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 caused by an oil-demand disturbance.

Considering all of the recent energy security literature, EPA's assessment concludes that there are benefits to the U.S. from reductions in its oil imports. There is some debate as to the magnitude, and even the existence, of energy security benefits from U.S. oil import reductions.

However, differences in economic impacts from oil demand and oil supply shocks have been distinguished, with oil supply shocks resulting in economic losses in oil importing countries. The oil import premium calculations in this analysis (described in Chapter 11.4.2) are based on price shocks from potential future supply events. 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 1970s.

11.2 Review of Recent Energy Security Literature

There have also been a handful of recent studies that are relevant for the issue of oil 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 to world oil price changes. We provide a review and high-level summary of each of these studies below. In addition, we review the recent literature on electricity security in the context of the wider use of PEVs.

11.2.1 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). The RFF study (Krupnick, et al. 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 2018) summarized the RFF study results as well. The RFF work 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 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 2018). The second set of modeling frameworks use alternative structural vector autoregressive models of the global crude oil market (Kilian 2009), (Kilian and Murphy 2014), (Baumeister and Hamilton 2019). The last of the models utilized is the 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 –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 MMBD or about 7 percent of global crude oil production capacity (EIA 2019). On September 16th, the first full day of commodity trading after the attack, both Brent and 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 (EIA 2019). Tanker loading estimates from third-party data sources indicated that loadings at two Saudi Arabian export facilities were restored to the pre-attack levels (EIA 2019). 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 at the beginning of 2022. For example, as of January 3rd, 2022, the WTI crude oil price was roughly $76 per barrel (EIA 2022). The WTI oil price increased to roughly $123 per barrel on March 8th, 2022, a 62 percent increase (EIA 2022). High and volatile oil prices in the first part of 2022 were a result of supply concerns with Russia's invasion of Ukraine on February 24th contributing to crude oil price increases (EIA 2023). Russia's invasion of Ukraine came after eight consecutive quarters of global crude oil inventory decreases. The lower inventory of crude oil stocks were the result of rising economic activity after COVID-19 pandemic restrictions were eased. Oil prices have drifted downwards throughout the second half of 2022 and in the early part of 2023. It is not clear to what extent the current oil price volatility will continue, or even increase, or be transitory. Since both significant demand and supply factors are influencing world oil prices in 2022, it is not clear how to evaluate unfolding 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 2022 do not currently provide enough empirical evidence to undertake an updated estimate of the response of the U.S. economy to an oil supply shock of a significant magnitude.[171]

A second set of recent studies related to energy security are from ORNL. In the first study, (Uría-Martínez, et al. 2018) undertake 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, the authors undertake 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 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 (Oladosu, et al. 2018). 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.

11.2.2 **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.[172] 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 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. 18th, 2015). According to the GAO, the ban was lifted in part due to increases in tight (i.e., shale) oil (GAO 2020).[173] Second,

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[171] 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.

[172] The Union of Concerned Scientist define tight oil as follows: “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." (Union of Concerned Scientists 2016).

[173] 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”.

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 (Kemp 2021). Other factors such as cost inflation and supply chain constraints have contributed to the slow pace of tight oil production growth in the early 2020s, despite high world oil prices. Although some of those factors may be transitory, the muted production response of 2021–2022 suggests that tight oil producers (and their investors) are not likely to increase drilling in a quick, coordinated manner in response to future potential world oil price spikes. For that reason, the short-run price responsiveness assumed for U.S. tight oil for the estimation of the oil security benefits of this proposed rule is the same as for other non-OPEC oil supplies.

U.S. crude oil production increased from 5.0 Million Barrels a Day (MMBD) in 2008 to an all-time peak of 12.3 MMBD in 2019 and tight oil wells have been responsible for most of the increase (EIA 2022). Figure 11-1 below shows tight 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. As illustrated in Figure 11-1, the annual average U.S. tight oil production grew from 0.6 MMBD in 2008 to 7.8 MMBD in 2019 (EIA 2022). 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. U.S. tight oil production represents a relatively modest share (less than 10 percent in 2019) of global liquid fuel supply.[174]

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, tight oil wells require the additional step of fracking to complete the well and release the oil.[175] Tight oil producers keep a stock of drilled but uncompleted wells and can optimize the timing of the completion operation depending on oil price expectations. Combining this decoupling between 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 (Bjørnland, Nordvik and Rohrer 2020).

[174] The 2019 global crude oil production value used to compute the U.S. tight oil share is from (EIA 2022).
[175] 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.

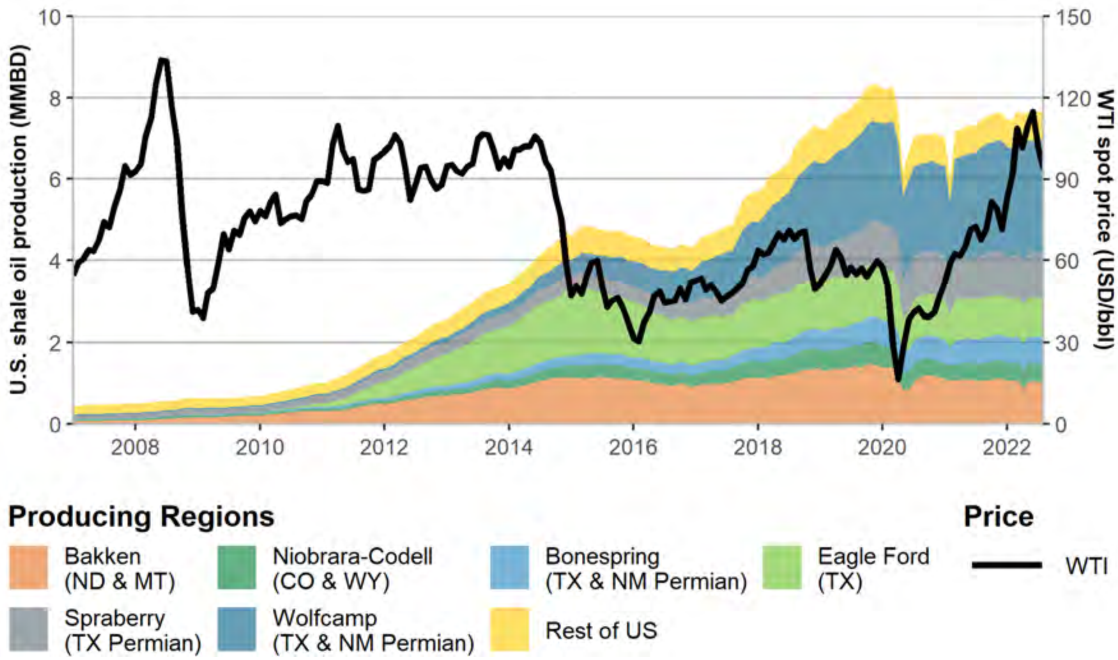


Figure 11-1. U.S. tight oil production by producing regions (in MMBD) and West Texas Intermediate (WTI) crude oil spot price (in U.S. Dollars per Barrel) Source: (EIA 2022) (EIA 2022)

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 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 affecting 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, 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 tight oil wells, using a detailed dataset of 150,000 oil wells, during the time frame of 2005–2017 in five major oil-producing states: Texas, North Dakota, California, Oklahoma, and Colorado. For both conventional oil wells and tight 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 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, (Bjørnland, Nordvik and Rohrer 2020), 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. 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 area 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 2019), (Bjørnland, Nordvik and Rohrer 2020), and (Walls and Zheng 2022) 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 11-1 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 tight oil production growth cycles were financed predominantly with debt, at very low interest rates (McLean 2018). Most U.S. tight oil producers did not generate positive cashflow (McLean 2018). As of 2021, U.S. tight oil producers have pledged to repay their debt and reward shareholders through dividends and stock buybacks (Crowley and Wethe 2021). These pledges translate into higher prices that need to be reached (or sustained for a longer period) than in the past decade to trigger large increases in drilling activity.

In its first quarter 2022 energy survey, the Dallas Fed (Federal Reserve Bank of Dallas 2022) asked oil exploration and production (E&P) 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 tight 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 was 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. Given the recent behavior of tight oil producers, we do not believe that tight oil will provide additional significant energy security benefits in the time frame of this analysis, 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 the oil 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 used in the energy security literature.

11.2.3 Recent Electricity Security Studies

The International Energy Agency (IEA) defines energy security as the uninterrupted availability of energy sources at affordable prices (IEA 2019). The energy security literature, first developed in response to the oil shocks of the 1970s, is extensive. This literature mainly focuses on the energy security benefits of reduced oil use, particularly oil imports. However, even though there is likely to be a substantial increase in the use of electricity from PEVs in the U.S., the literature on the topic of the energy security implications of wider use of PEVs is somewhat limited. We have not been able to identify any study that systematically quantifies the differential energy security risks of using electricity versus petroleum-based fuels to power vehicles in the U.S. Nonetheless, a review of existing, published studies provides information to help assess the implications of the use of electricity as transportation fuel in LMDVs in the U.S. across multiple dimensions of energy security–affordability, price stability, and resilience/reliability–as well as energy independence.[176]

Since the energy security literature has largely focused on the economic and national security risks associated with oil imports, early studies considering the energy security benefits of PEVs focus on the reduction in oil imports that result from widespread PEV adoption. (Michalek, et al.

[176] Our discussion of "affordability" in this Chapter only considers fuel costs, including gasoline prices and charging costs for PEVs. Vehicle purchase costs are not considered within the scope of our evaluation of energy security. More discussion of consumer impacts in the context of PEVs is presented in Chapter 4 of this DRIA.

2011) quantifies this aspect of the energy security impacts of PEVs. The study focuses on the benefits associated with a reduction in U.S. oil imports from the wider use of PEVs and provide a direct estimate of the energy security benefits of using PEVs in the U.S. based on the amount of oil PEV's displace over the lifetime of a typical PEV. They use a $0.34/gal (2010 dollars) estimate of the avoided macroeconomic disruption costs/ monopsony/ military cost savings for oil to calculate an energy security benefit of roughly $1,000 over the lifetime of a PEV. (Michalek, et al. 2011) is similar to the approach used by EPA in past vehicle rulemakings: estimate the displaced petroleum use and apply a security cost premium that draws on some of the same studies that EPA uses. But EPA does not include monopsony impacts or quantify military cost savings as benefits. The Michalek et al. study also does not account for electricity supply stability.

11.2.3.1 Fuel Costs

Most of the cost comparisons of PEVs versus gasoline-powered vehicles in the literature are total cost of ownership (TCO) studies, which compare the total cost of purchasing, owning, and operating each type of vehicle for a specified number of years. They include the vehicle purchase costs as well as annual operation (fees, fuel, and insurance) and maintenance costs.

Vehicles are refueled fairly frequently and increased fueling costs due to energy price spikes are felt almost immediately by consumers, whereas the impact of price changes in components and materials used to produce vehicles (e.g., alloys, batteries, etc.), which are also considered in a TCO analysis, only impact consumers when purchasing a vehicle. Our focus in this Chapter is on energy markets. Critical materials and the supply chains necessary for PEV production are, therefore, outside of our intended scope in this discussion of energy security. See Preamble IV.C.6 and Chapter 3.1.3 of the DRIA for a discussion of critical materials and PEV supply chains.

TCO studies of vehicles in the U.S. find that fuel costs are lower for PEVs than internal combustion engine (ICE) vehicles. See, for examples, (P. Slowik, A. Isenstadt, et al., Assessment of Light-duty Electric Vehicle Costs and Consumer Benefits in the United States in the 2022-2035 Time Frame 2022), (Liu, et al. 2021), (Lutsey and Nicholas 2019), and (Breetz and Salon 2018). TCO studies tend to not explore in great detail the heterogeneity in fuel costs for PEV owners depending on geography and charging location or strategy, but other studies focus on the sources of PEV fuel cost variability. For example, a 2017 brief by the Union of Concerned Scientists examines the rates offered by electric utilities in the 50 largest U.S. cities and finds that all of them offered at least one electricity rate that results in fuel savings for PEV owners compared to a gasoline-powered vehicle, with median annual savings of $770 (Union of Concerned Scientists 2017). Clearly these savings depend on the prevailing price of petroleum fuels, which varies widely over location and time, and the assumed efficiency of the comparable gasoline vehicle.

(Borlaug, Salisbury, et al., Levelized Cost of Charging Electric Vehicles in the United States 2020) perform a detailed analysis of PEV charging costs in the U.S. that takes into consideration the type of charging equipment, a range of real-world electricity rates, and frequency of charging at home versus workplace or public stations. They find that PEV fuel cost savings over a 15-year period ranged from $3,000 to $10,500 (2019 dollars) for average U.S. electricity and gasoline price projections, with additional variability across states and depending on PEV lifetimes. The percentage of battery charging done at home versus using public chargers is an important source of variability in the fuel costs of individual PEV owners. Extracting charging rate information from a commercial database that includes records for more than 30,000 U.S. public chargers, (Trinko, et al. 2021) reports mean rates of 28 cents/kWh for Level 2 chargers and 32 cents/kWh for faster Direct Current Fast Charging chargers; in contrast, the study reports a lower mean residential electric rate of 13 cents/kWh as of March 2021.

To date, residential charging access has been prevalent among PEV owners. (Y. Ge, C. Simeone, et al., There's No Place Like Home: Residential Parking, Electrical Access, and Implications for the Future of Electric Vehicle Charging Infrastructure 2021) find that the percentage of PEVs with residential charging access is likely to become more uncertain as the PEV market share of light-duty (LD) vehicles increases. They conduct a survey to gather detailed information on residential parking availability, parking behavior, and electrical access by parking location. Combining public data on housing stock and LD vehicle stock characteristics with the survey results, the authors develop estimates of residential charging access percentages for each housing type and a PEV adoption likelihood model using housing type, housing tenure (owning versus renting), income, population density, and presence/absence of zero emission vehicle incentives in the state of residence as explanatory variables. For PEV shares no greater than 10 percent of total LD vehicles, residential charging access is estimated to range from 78 percent to 98 percent. For a 90 percent PEV share, the estimated residential charging access percentage ranges from 35 percent to 75 percent. The higher end of the ranges represents a scenario that requires modifications in parking behavior (e.g., parking in garage rather than driveway) and installation of electrical access whenever possible, if not already available at the residential parking location.

In a study for the California Public Utility Commission, (Sieren-Smith, et al. 2021) projects future fuel costs of PEVs in California for the 2020–2030 time frame in comparison to gasoline-powered vehicles. This study finds that there is wide spatial variability in fuel costs for PEVs and there are substantial differences across individual electric utilities within California alone. The study also finds that for customers with Time of Use (TOU) tariffs, charging a PEV regularly at the off-peak rates (i.e., “managed charging” as opposed to “unmanaged charging”) results in significant fuel cost savings. With TOU tariffs or Time Variable Pricing, electricity prices depend on the time of use, and change at set times and amounts through the day–generally with higher prices in an afternoon peak period and lower prices in overnight off-peak hours (DOE 2022). The study also finds that PEV fuel costs are likely to be lower than gasoline-powered vehicles’ fuel costs across a variety of assumptions about projected gasoline and electricity prices and managed/unmanaged PEV charging rates in California over the time frame of the analysis.

In the U.S., according to (Hardman, et al. 2021), the lowest income households spend 11.2 percent of their annual income on fuel, maintenance, and repairs of vehicles compared to all other households that spend 4.5 percent of their annual income on these expenses. For the most common use case in terms of PEV charging equipment (i.e., at-home charging), fuel costs in the U.S. are lower for PEVs than gasoline-powered vehicles. Therefore, owning a PEV results in a lower percentage of household income going toward that expense category. However, (Hardman, et al. 2021) find that lower income households are less able to afford installation of residential charging equipment and more likely to live in multi-unit dwellings without a designated parking space and charging equipment. Thus, low-income households that purchase a PEV and have no residential charging and, thus, rely primarily on public chargers, could face higher fuel costs and a larger overall energy burden (i.e., fraction of household income directed toward energy costs) with a PEV than a gasoline-powered vehicle. The Inflation Reduction Act (IRA) signed into law on August 16, 2022, can help reduce the costs for deploying charging infrastructure (Inflation Reduction Act 2022). The IRA extends the Alternative Fuel Refueling Property Tax Credit (Section 13404) through Dec 31, 2032, with modifications. Under the new provisions, residents in low-income and rural areas would be eligible for a 30 percent credit for the cost of installing residential charging equipment up to a $1,000 cap.

11.2.3.2 Fuel Price Stability/Volatility

(Melodia and Karlsson 2022) show that the rate of inflation and volatility of U.S. retail electricity prices have been historically much lower than for gasoline. Using consumer price data from the Bureau of Labor Statistics from 1968 to 2022, the authors report that gasoline was almost four times more volatile than electricity during that period. The diversity of the fuel mix used to produce electricity and the stronger regulatory oversight of the U.S. electricity sector, where residential electricity rates must meet a “just and reasonable” standard, are among the reasons for the lower volatility of electricity prices versus gasoline prices. The authors also discuss how renewable electricity generation can contribute to electricity price stability. First, the cost profile of renewable resources such as wind and solar involves an initial large fixed-capital investment but have no fuel costs once they are in operation, removing a key source of the price volatility experienced by electricity generation plants that use fossil fuels. Moreover, wind and solar resources are available much more widely across the globe than oil and gas resulting in lower geopolitical supply risk–although some risk is still present through the critical materials needed to produce renewable energy infrastructure components such as wind turbines, solar panels, and electric batteries (Melodia and Karlsson 2022).

While (Melodia and Karlsson 2022) discuss the positive contribution that increased use of renewables can make to electricity price stability, other authors consider how the process of decarbonization in the energy sector might affect oil price stability. (Bordoff and O’Sullivan 2022) suggest that a smooth transition to clean energy in response to climate change may be challenging and may result in more price volatility in oil markets. In other words, they suggest that the transition to clean energy may be “jagged”. According to the authors, the combination of pressure on investors to divest from fossil fuels and uncertainty about the future of oil demand may raise concerns that oil investment levels may decrease in the future, leading to oil supplies declining at a faster rate than oil demand falls–or declining even as oil demand continues to rise. This outcome could produce more volatile oil prices. Also, in the early stages of the transition to clean energy before oil demand declines significantly, the power of OPEC and other non-competitive suppliers could be boosted by increasing their revenues, while giving OPEC extra clout as a “swing producer” when world oil markets are tight.

11.2.3.3 Electricity Reliability/Resiliency

Reliability and resilience of electricity service are needed to ensure the “continuous availability” of service that is required for a fuel to be considered secure. (DOE 2017) defines the two terms as follows. Reliability is “the ability of the electric power sector to provide a stable source of electricity to consumers, both households and businesses, under normal operating conditions”. Resilience is “the ability of the electric power sector to withstand and recover from any disruptions created by extreme weather, cyberattack, terrorism, or other unanticipated events.” A reliable and resilient electricity sector is crucial for the U.S.’s national security. The

Department of Defense is the largest customer of the electricity grid in the U.S. (DOE 2017). Also, the electricity sector is interconnected with many other types of critical infrastructure–water systems, oil, natural gas, communications, information technology, and financial services–crucial for the U.S. economy to function (DOE 2017). Standards and metrics to track reliability are better established than those for resilience, which is concerned with lower probability, high-consequence events (DOE 2017).

Electricity, while generally reliably provided in the U.S., is subject to periodic supply disruptions (i.e., "electricity outages") due to a variety of factors including (but not limited to): weather-related events such as hurricanes, heat waves/storms, wildfires; cybersecurity risks and system/equipment failures. On average, U.S. electricity customers experienced 8 hours of power outages in 2020, the most since the DOE's Energy Information Administration (EIA) began collecting electricity reliability data in 2013 (EIA 2021). The Fourth National Climate Assessment, released in 2018, concludes that "climate change will increasingly threaten the U.S. energy supply via more frequent and long-lasting power outages that will broadly affect critical energy infrastructure" (Zamuda, et al. 2018). It also states that extreme weather is already the most frequent cause of electricity grid outages in the U.S. Electricity in the U.S. is provided by a set of local and regional interconnected electric grids. Thus, electricity supply disruptions are likely to result in electricity outages that are more local or regional in their nature in comparison to petroleum disruptions, which commonly have national or, oftentimes, global impacts.

U.S. electric utilities follow long-term plans to ensure electricity reliability. These plans, typically known as integrated resource plans, set out an investment roadmap to ensure sufficient regional generation capacity and power purchases to meet the projected demand in their electricity service areas. According to (Bistline 2021), although these long-term plans contribute to electricity supply reliability, both resource planning and electric grid operation are becoming more difficult due to overlapping layers of increased variability in electricity supply and demand. For example, climate change is leading to an increase in the frequency and severity of extreme weather events which affects both supply (e.g., droughts reducing hydropower generation) and demand (e.g., record peak loads due to heat waves). Increased penetration of wind and solar also results in significant fluctuations in electricity production at different time scales that need to be managed by electric grid operators and planners. Maintaining reliability of supply and price stability under this new set of evolving conditions requires a range of technology, analysis, and policy solutions (Bistline 2021).

As auto manufacturers respond to this proposed rule with increased sales of PEVs, U.S. electricity demand is anticipated to increase. Overall, U.S. electricity demand is projected to increase by 2 Terawatt-hours (TWh) in 2028 (a 0.04 percent increase), 18 TWh in 2030 (a 0.39 percent increase), 114 TWh in 2035 (a 2.25 percent increase), 195 TWh in 2040 (a 3.52 percent increase) and 252 TWh in 2050 (a 3.92 percent increase). See Chapter 5 of this DRIA for more discussion of these estimates. Projections of PEV uptake will need to be accounted for by U.S. electric utilities and transmission system operators in their resource planning processes. It is difficult to assess the combined effects of higher demand for electricity from PEVs, increasing extreme weather events in the context of climate change, and the greater use of variable supply technologies, such as wind/solar power, on electricity grid reliability and resiliency issues in the U.S. In part, this is because there is little experience to assess the impacts of significant PEV use on U.S. electric grid reliability and resiliency.

At early levels of PEV adoption, the investments needed to shore up electric grid reliability might first appear at the local distribution level. Early PEV sales to date have often happened in clusters such that some neighborhoods have achieved large PEV penetrations even as PEV market share remained lower at the regional or national level. The extent of distribution level reliability impacts will depend on multiple factors: number of PEVs, PEV mix (BEVs/PHEVs), type of charger used (Level 1, Level 2), and most importantly, whether charging is managed or unmanaged. (Muratori 2018) evaluates the effect of uncoordinated PEV charging on residential demand. The author finds that uncoordinated PEV charging leads to more pronounced and abrupt load (i.e., electricity demand) peaks which shorten the life of distribution transformers. Using detailed datasets of charging events at homes and public chargers in California to simulate future PEV charging behavior (timing of charging and duration), (Jenn and Highleyman 2022) conclude that in a scenario with 6 million PEVs in California (compared to approximately 1 million in 2021), more than 20 percent of distribution feeder circuits would experience loads greater than their capacity, resulting in accelerated degradation of the distribution network equipment and requiring upgrades to maintain adequate electricity grid reliability.

(Powell, et al. 2022) explore electric grid impacts in the U.S. portion of the Western Interconnection grid in 2035 under scenarios with high penetration (greater or equal to 50 percent adoption) of LD PEVs. They find that the timing of the extra electricity demand brought about by PEVs depends on charging behavior and is crucial to the magnitude of the electric grid impacts. The authors develop a detailed model of charging behavior where drivers are assigned to clusters based on combinations of the battery capacity of their PEVs, number of miles driven per year, and access to charging infrastructure. The aggregated PEV charging demand is then used as an input in a generation dispatch model that represents the Western Interconnection 2035 grid by accounting for planned generation unit additions/retirements, increasing baseline demand to reflect electrification of other sectors, and multiplying solar generation by a factor of 3.5 and wind generation by a factor of 3 relative to 2019 levels.

The authors calculate the electric grid impacts for various scenarios regarding charging controls and access to home and workplace charging infrastructure. All charging scenarios assume unidirectional charging (i.e., no vehicle-to-grid flows). For the Western Interconnection, given the high level of penetration of solar generation expected by 2035, daytime charging leads to lower costs and emissions because it aligns better with the solar generation profile. Investing in widespread access to workplace charging leads to lower peak net demand (i.e., peak demand net of solar and wind generation), lower electricity grid storage capacity investment needs, less ramping-related costs from the operation of fossil fuel generators, and lower CO_2 emissions per mile driven by PEVs. Since the U.S. electricity grid is composed of a set of regional electricity grids with different fuel mixes, the charging infrastructure and charging schedules that will best match and balance the extra electricity demand from PEVs with electricity supply will vary on a region-by-region basis.

Large and abrupt electricity demand peaks due to PEV charging deserve special attention when they are linked to extreme weather events that can also disrupt the demand and supply of electricity. (Feng, et al. 2020) explore the mobility implications of vehicle fleets with high PEV penetration rates during extreme weather events triggering evacuation orders. They simulate the evacuation traffic flow during Hurricane Irma and compare electricity demand if all evacuating vehicles were PEVs with the transmission capacity in the Florida electric grid. They conclude that up to a fleet-wide PEV penetration rate of 45 percent could have been supported by the existing transmission network during that evacuation scenario. The more general insights from the analysis include: 1) fleetwide PEV penetration levels of up to 45 percent can be helpful during an evacuation scenario to alleviate gasoline shortages, 2) PHEVs are especially valuable during those events as drivers can start the evacuation trip using their battery and fill their gasoline tanks away from the population centers that experience gasoline shortages when an evacuation order is announced, and, 3) development of disaster-optimized charging schedules would be crucial to avoid surges of power during an extreme event such as a hurricane as PEV penetration increases.[177]

With PEVs becoming an increasingly significant portion of vehicles on the road in the U.S., some losses in overall U.S. output, measured in terms of a loss in U.S. gross domestic product (GDP), will likely result from electricity supply disruptions. The losses in U.S. output will be determined by the extent and duration of the future electricity supply disruptions, the flexibility of the additional electricity demand from PEVs, and whether PEVs can help avoid or ameliorate electricity supply disruptions. Given the local and regional nature of electricity supply disruptions and noting that the U.S. is projected to produce almost all of its own electricity (see discussion below), the losses in U.S. output from future electricity supply disruptions will likely be lower than output losses that have resulted from world oil supply disruptions with the widespread use of gasoline-powered vehicles. Higher electricity payments in the event of a U.S. electricity supply disruption will be transferred to other electricity producers in the U.S., not to foreign suppliers, as was the case in past oil supply disruptions, which will reduce the effective cost to the U.S. economy. However, more analysis is needed to make a definitive statement about the net effect of this proposed rule on expected GDP losses from future electricity and oil supply disruptions or price spikes. Estimates of disruption probabilities and associated U.S. macroeconomic disruption costs are available for oil but not for electricity. Without an estimate of electricity disruption probabilities and expected U.S. output losses, it is difficult to conduct assessments of the size and types of potential investments, or initiatives in the U.S. electricity sector, that could mitigate or adapt to those losses.

Although PEVs can pose challenges for electricity supply reliability if PEV charging is not coordinated, PEVs can also potentially provide an important source of electricity storage, which could help to improve the overall functioning of the U.S. electricity grid in terms of the reliability and availability of electricity over time. See Chapter 5.4 of the DRIA for more discussion on this topic. With a bidirectional connection to the electricity grid that enables vehicle-to-grid (V2G) flows, PEVs can act as a storage resource that provides energy during electric peak demand hours by discharging their batteries while parked. PEVs can also provide services to the electrical grid such as frequency and voltage regulation or act as electricity reserves, ready to supply energy in response to an outage at an electricity generation facility. In addition, PEVs can be used to provide electricity to home residences in the event of an electricity supply disruption. Managed bidirectional flows of energy from a large PEV fleet could also be particularly valuable to integrate higher levels of variable renewables (wind and solar) into the electricity generation mix (Yilmaz and Krein 2013).

[177] Under the proposed standards, the penetration rates of PEVs in the stock of U.S. light- and medium-duty vehicles are projected to remain below a 45 percent rate until the late 2030's. By the late 2030's, there should be sufficient lead time for the U.S. electricity grid to expand and accommodate increasingly higher penetration rates of PEVs.

The wider use of electricity in U.S. vehicles also provides both short- and long-run fuel substitution opportunities for vehicle owners facing high and volatile world oil prices. For example, drivers of PHEVs can switch to using more electricity during an oil price shock (Lemoine 2010). Also, during an oil shock, a wider penetration of PEVs will allow for a short-run reduction in oil use by multi-vehicle households that can drive their PEVs more, rather than using their gasoline-powered vehicles. Flexibility is achieved when drivers have options to shift to electricity, and the responsiveness of oil demand to the oil price (i.e., the elasticity of demand for oil) increases. These benefits occur because there is more substitutability between electricity and oil in end-use fuel use. With electricity supply disruptions, on the other hand, multi-vehicle households could also switch to driving their gasoline-powered vehicles more. Households with only one vehicle, dedicated to gasoline or electricity, are likely be the most affected by volatile oil prices and electricity outages, since they cannot substitute among vehicles or fuels in response to changing oil prices and the availability of electricity, as multi-vehicle households or owners of PHEVs can.

11.2.3.4 Energy Independence

The goal of U.S. energy independence is generally equated with the elimination of all U.S. imports of petroleum and other foreign sources of energy, but more broadly, it is the elimination of U.S. sensitivity to the variations in the price and supply of foreign sources of energy (Greene 2010). (Grove 2008) and (Stein 2013) promote the idea that the wider use of PEVs can bring about U.S. energy independence by substituting electricity for oil to power vehicles in the U.S. As Grove/Stein note, the physical characteristics of oil and electricity can have very different consequences for energy independence. Oil is a commodity that is globally traded. In comparison, Grove labels electricity as “sticky”: in other words, “it stays in the continent where it is produced.” As a result, global electricity markets are not nearly as linked or interconnected as global oil markets. The interconnectedness of the oil market means that price shocks are transmitted globally but it also contributes to its resilience. Oil tankers can be redirected to those destinations where price signals reveal that their value is highest. In contrast, the volume of electricity that can be rerouted across regions in response to an emergency is strictly limited by the number and configuration of electricity transmission interconnections.

The wider use of PEVs in U.S. LMDVs will likely result in the substitution of one fuel, oil, with significant imports and which is subject to global price shocks, for another fuel, electricity, which is almost exclusively produced in the U.S. and has different and an independent set of local and regional factors influencing its reliability and resiliency. As (Bordoff and O’Sullivan 2022) point out, electricity is much more likely to be produced locally and regionally; less than three percent of global electricity was traded across international borders in 2018, compared with two-thirds of global oil supplies in 2014. As a result, the greater use of electricity as transportation fuel will move the U.S. towards the goal of energy independence.

U.S. energy security analysis has traditionally focused on the benefits of reduction of U.S. oil imports. However, even when oil imports get close to zero, energy security concerns remain for oil because of the global, integrated nature of the oil market. Unless the U.S. entirely disengages from international oil trade, oil price shocks starting anywhere in the world will continue to be transmitted to oil prices in the U.S. and those price shocks still will have adverse impacts on U.S. households. An increased movement towards electrification does not eliminate energy security concerns. Supply shocks for electricity also happen, but they are typically of a different nature than oil shocks: they are local or regional instead of global, and they may involve a combination of electricity outages and/or retail electricity price increases.

Recent geopolitical events are an example of how the energy price and energy price stability attributes in U.S. energy security remain an important concern even after the U.S. has become a net exporter of crude oil and petroleum products. (Bordoff and O'Sullivan 2022) suggest that energy security will join climate change as a top concern for policymakers as a result of the Russian-Ukrainian war, which has disrupted energy supplies and increased global energy prices. They argue that these dual priorities–energy security and climate change–are poised to reshape national energy planning, energy trade flows, and the broader global economy. One consequence of the Russian-Ukrainian War, according to Bordoff and O'Sullivan, is that countries across the world will increasingly be looking inward, prioritizing domestic energy production and regional cooperation even as they transition to net-zero carbon emissions. These changes will likely be defined by greater, not less, government intervention in the world's energy sector.

11.3 Electricity Security Impacts

Addressing the issue of U.S. energy security, this section offers comparisons of electricity and gasoline as transportation fuels in terms of cost per mile driven and their relative price stability and volatility. In the U.S. during the past decade, the cost per mile driven for a new PEV charging at home has been consistently lower than that for a new gasoline-powered vehicle using regular gasoline. This result is robust to the spatial variation in relative electricity and gasoline prices in different U.S. states. The impact of fuel costs on consumers is not only about average fuel cost levels but also fuel cost stability. On the metric of fuel cost stability, retail electricity also has fared better than gasoline because retail electricity prices have been more predictable and less volatile for vehicle owners than gasoline prices. The predictability is partly a result of the electricity rate setting process–most consumers pay a set tariff (i.e., electricity price) that only changes at monthly or annual intervals. The section also presents data to support the idea that an increased use of electricity as a transportation fuel in U.S. LMDVs moves the U.S. towards greater energy independence.

11.3.1 Recent Fuel Costs for Gasoline-Powered Vehicles Compared to PEVs in the U.S.

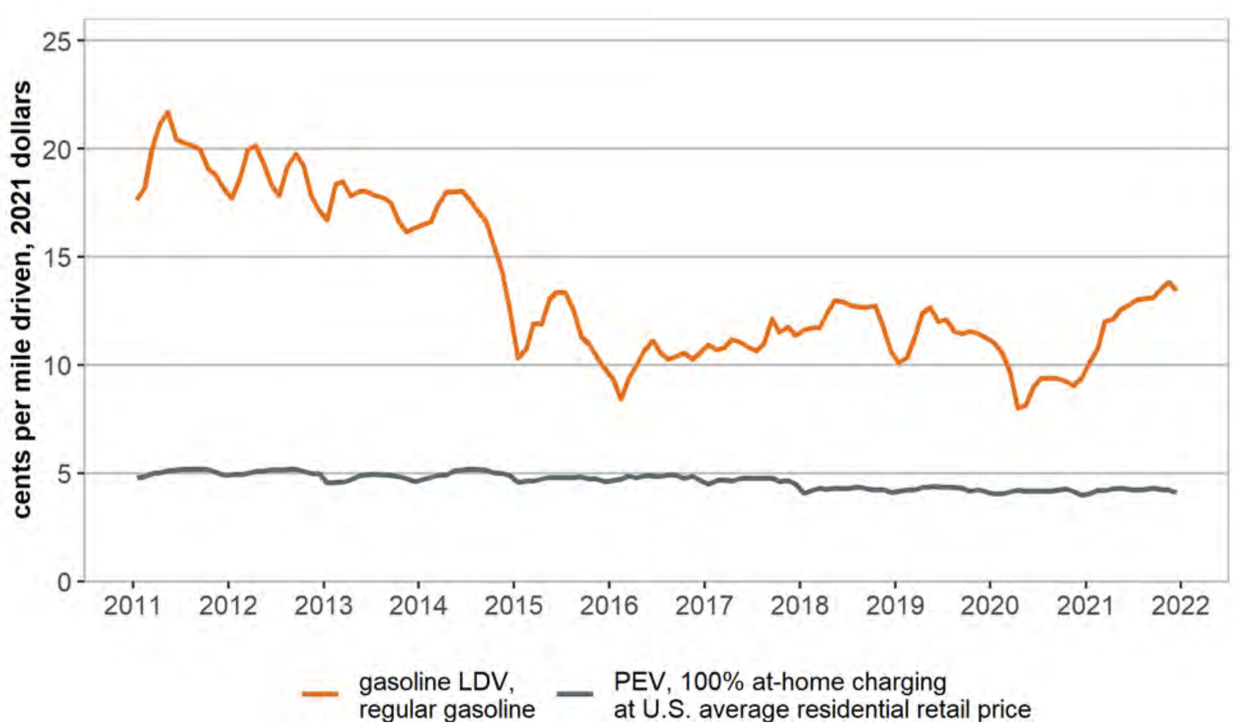
11.3.1.1 National (i.e., U.S.) Analysis

To compare fuel costs of PEVs versus gasoline-powered vehicles, the relevant units are dollars per mile instead of dollars per gallon of gasoline equivalent (or other energy content unit) because of the higher end-use efficiency of the electric motor relative to the internal combustion engine (ICE). This is a central feature of the comparison between PEVs and gasoline-powered vehicles. The relative cost of gasoline and electric fuel in the U.S. will depend on three main factors: the efficiency of the vehicle; the prevailing prices of gasoline and electricity (electricity prices being more stable over time), and the market in which the PEV is recharged (electricity costs tend to vary significantly across states to a greater degree than gasoline prices, and commercial recharging costs are higher than residential charging costs).

Most PEV charging to date in the U.S. uses at-home chargers, and thus EPA's analysis of fuel costs hinges on prices observed by U.S. households: retail, regular gasoline prices (in dollars per gallon) and retail residential electricity rates (in cents per kilowatt-hour). As PEV adoption extends to drivers without at-home charging capabilities in the future, commercial charging rates will play a larger role in a national analysis of PEV fuel costs, but home recharging is expected to continue to play a dominant role.

Comparing fuel costs for PEVs and gasoline LD vehicles requires converting retail prices into a common unit (U.S. cents per mile driven) that accounts for the differences in energy content between gasoline and electricity as well as the higher efficiency of electric drivetrains relative to internal combustion engines, expressed as fuel economies (miles per gallon of gasoline equivalent (gge)).[178] The fuel economy data used to compute fuel costs per mile driven are on-road new vehicle values by model year (i.e., the average fuel economy across all sold new gasoline LD vehicles or PEVs of a same model year). The data for PEVs includes only battery electric vehicles (BEVs), but also applies to plug-in hybrid electric vehicles (PHEVs) for the miles driven in electric vehicle mode, and the data for gasoline vehicles includes conventional hybrids.[179] On-road fuel economy increased from 22.2 miles per gge in 2011 to 24.6 miles per gge in 2021 for new gasoline LD vehicles and from 97 miles per gge to 112.8 miles per gge for new PEVs.

Figure 11-2 shows the average U.S. fuel cost per mile driven for two vehicle-fuel combinations, gasoline-powered LD vehicles using regular gasoline and PEVs charging at-home at the residential retail rate, and Figure 11-3 presents the same information for a subset of individual states in the U.S.



[178] The conversion factor from kilowatt-hours to gasoline gallon equivalents (gge) is 33.705kWh/gge (EPA 2016).
[179] It should be noted that the time unit for the fuel economy data, the "model year", does not coincide exactly with a calendar year.

Figure 11-2. Average U.S. fuel cost per vehicle mile driven of gasoline-powered vehicles and PEVs from 2011 to 2021 Sources: Electricity prices: (EIA 2022); Gasoline prices: (EIA 2022); Fuel economies: (EPA 2022)

Monthly fuel cost per mile driven has been consistently and substantially lower for new PEVs than new gasoline LD vehicles. The average fuel cost per mile driven from January 2011 to December 2021 was 13.7 cents per mile for new gasoline vehicles using regular gasoline and 4.6 cents per mile for a new PEV charged at-home 100 percent of the time at the average residential retail rate. The average annual fuel savings of new PEVs in comparison to a new gasoline vehicle using regular gasoline over the ten-year time frame of 2011 to 2021 was $1,260. We recognize that, to date, the bulk of PEVs sold tend to be in the small or mid-size car segments and, thus, more energy efficient. This is evolving as more PEV models are offered. For Model Year 2022, an analysis of fuel costs for every LD vehicle model shows that most PEV models have lower fuel costs than most gasoline-powered models regardless of vehicle class and size (DOE 2022).

While vehicle size and prevailing oil prices matter, the lower fuel cost per mile driven for PEVs is largely a result of the much higher efficiency of electric drivetrains relative to internal combustion engines. Comparing U.S. electricity and gasoline prices on a dollar per unit-energy basis, residential electricity has actually been somewhat more expensive than retail gasoline over the last decade: the 2011–2021 averages were 2.6 cents per megajoule (MJ) for regular gasoline and 4.0 cents per MJ for residential retail electricity.[180]

11.3.1.2 State-Level Analysis

The fuel cost per mile driven for new PEVs was lower than the fuel cost for new gasoline LD vehicles in all the states shown in Figure 11-3 (see below) and in every month from 2011 to the end of 2021. However, as stated above, the fuel cost savings do vary significantly across states. The average savings in fuel cost per mile driven for a new PEV versus a new gasoline vehicle ranged from 6.7 cents in Massachusetts to 10.2 cents in California and 11.9 cents in Washington. For the other three states depicted in Figure 11-3, Texas, Ohio and Florida, the fuel savings averaged 8–9 cents per mile. Both California and Massachusetts have some of the highest electricity residential retail rates in the U.S. The large savings afforded by PEVs in California result from that state having higher retail gasoline prices than the rest of the states in Figure 11-3. The savings are even larger for Washington because of a combination of high gasoline prices and low electricity rates due to Washington’s relative abundance of hydroelectric power resources (EIA 2022). Assuming that new gasoline-powered cars and new PEVs are both driven ~14,000 miles per year, the annual average fuel cost savings in the first year of vehicle operation during this period would have ranged from $933 in Massachusetts to $1,643 in Washington (Davis and Boundy 2022). While vehicle use typically declines with age, the decline is slow, and 15 years later the average car would still provide 62 percent of these annual savings (Davis and Boundy 2022).

[180] 1 kWh equals 3.6 MJ, and a typical gallon of gasoline contains 120,280 Btu or 126.8 MJ.

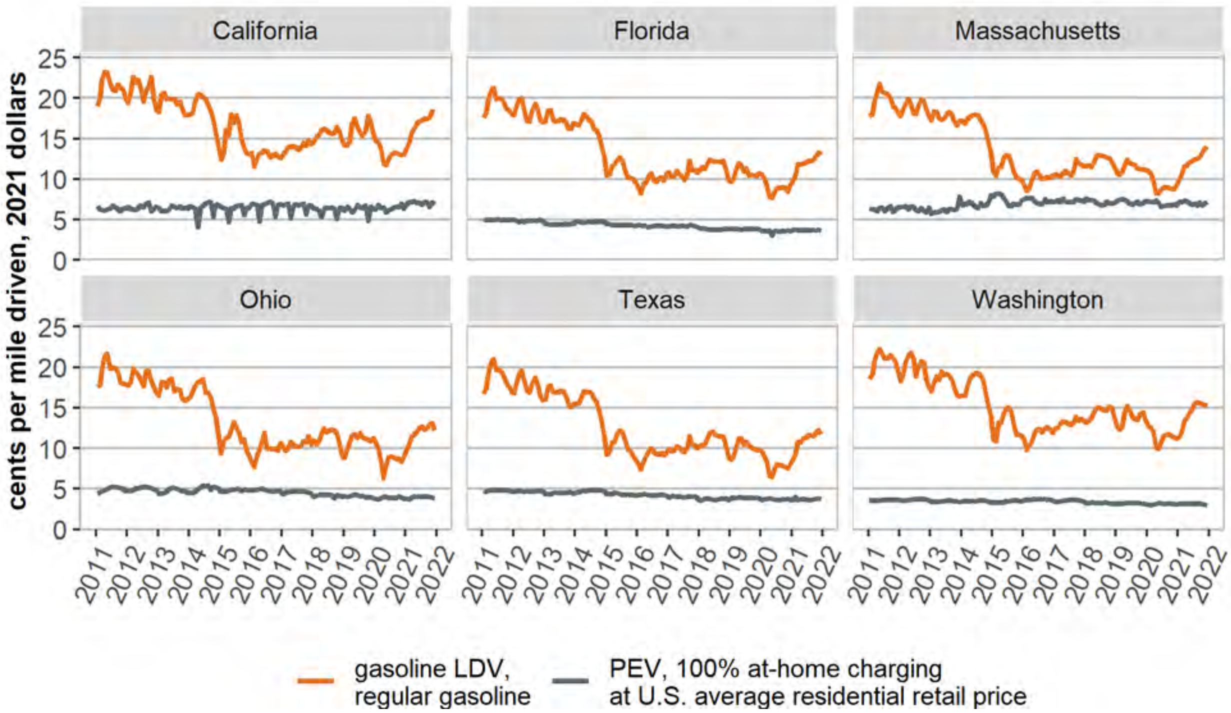


Figure 11-3. Fuel cost per mile driven by gasoline-powered vehicles and PEVs for six states from 2011 to 2021 Sources: Electricity prices: (EIA 2022); Gasoline prices: (EIA 2022); Fuel economies: (EPA 2022)

11.3.2 Fuel Price Stability/Volatility

Absolute differences in fuel costs between PEVs and ICE vehicles, discussed above, are an important aspect of the "affordability" component of IEA's definition of energy security, but fuel price stability is another important consideration from the consumer's perspective.[181] While U.S. retail electricity prices vary widely with location, charging equipment, and charging behavior, they are generally more stable over time than U.S. gasoline prices. Figure 11-4 displays the monthly percentage price changes for U.S. retail gasoline and residential electricity. The monthly change in U.S. average residential electricity prices was less than 5 percent (in absolute value) in every month during the 2011–2021 period. For regular gasoline, prices changed up or down by more than 5 percent in 30 percent of months over that period. The volatility of monthly U.S. retail prices from January 2011 to December 2021 was 21 percent for residential electricity prices and 60 percent for regular gasoline prices.[182]

[181] The International Energy Agency (IEA) defines energy security as the uninterrupted availability of energy sources at affordable prices. (IEA 2019)

[182] Volatility is calculated as the standard deviation of the monthly price returns multiplied by the squared root of the number of periods (months).

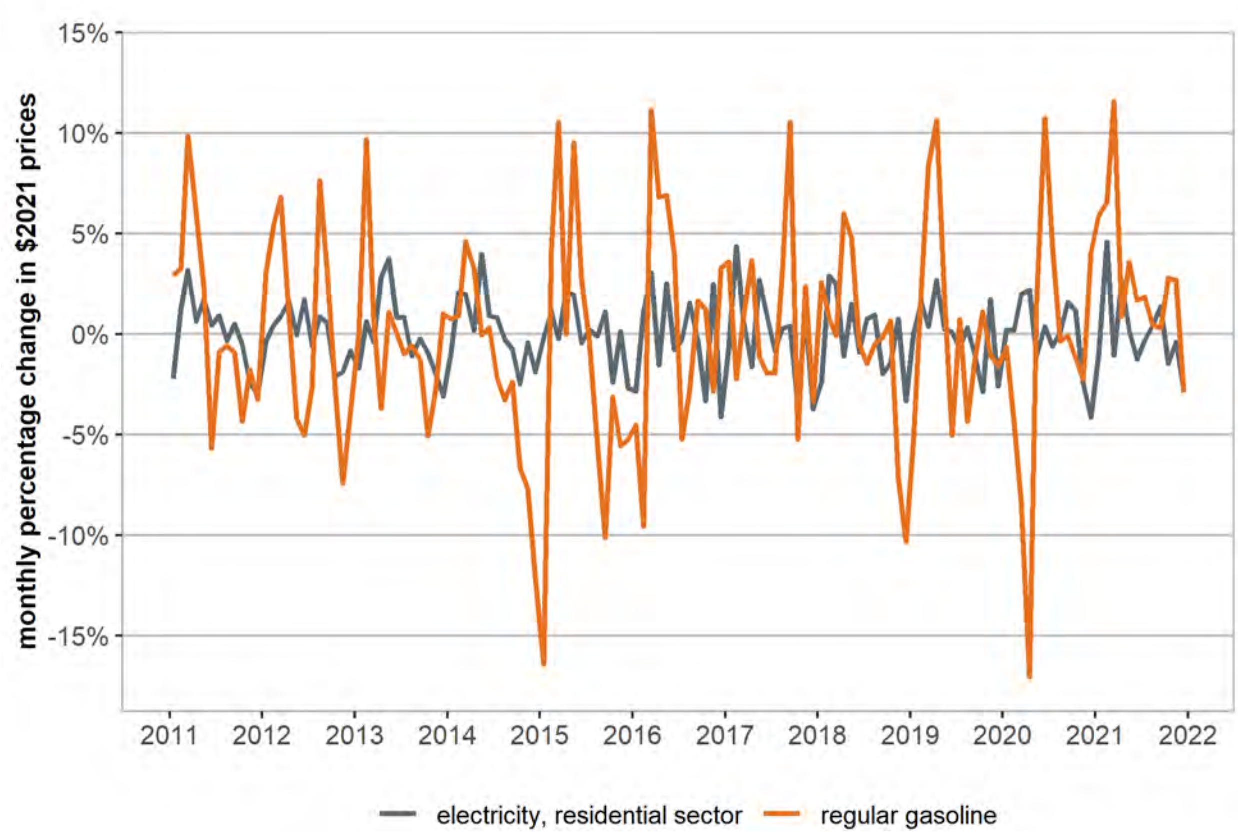


Figure 11-4. Monthly percentage changes in U.S. retail electricity and gasoline prices from 2011 to 2021 Source: (EIA 2022)

Another desirable attribute of PEVs for fuel cost stability is that PEVs diversify and, thereby, help stabilize total road-vehicle fuel costs. Diversification benefits are gained when the prices of the two fuels do not move together. In fact, historically when oil prices increased, electricity prices have tended to decrease, and vice-versa. Looking at fuel price trends over roughly the last decade, from January 2011 to December 2021, monthly U.S. residential electricity prices have been negatively correlated, -0.37, with monthly U.S. average gasoline prices.[183] A negative correlation helps plug-in hybrid electric vehicle (PHEV) owners and multi-vehicle households with access to gasoline LD vehicles and PEVs, and the nation as a whole, by diversifying transportation fuel cost risk. During all of the 2011–2021 period, the cost of at-home PEV charging resulted in lower fuel costs than gasoline refilling. The value of a household being able to switch between PEVs and gasoline-powered vehicles depending upon prevailing fuel prices (or between electricity and gasoline for a PHEV), is sometime labeled the “real option value”. Real option value could increase if the residential electricity costs of PEVs increase, or commercial recharging costs decrease, and the relative ranking of home or commercial PEV

[183] The estimated correlation coefficient is a Pearson correlation coefficient with a p-value of 0.0069.

charging versus gasoline refueling costs changes more frequently in the future as oil prices fluctuate.[184]

11.3.3 Energy Independence

The substitution of electricity for oil for powering U.S. vehicles will reduce U.S reliance on fuel imports. Although the U.S. has become a net exporter of crude oil and petroleum liquids, it still imports significant volumes of crude oil to meet the preferred barrel specifications of domestic refineries. See Table 11-1 below for estimates of U.S. oil import reductions from this proposed LMDV (2027–2032) rule. Figure 11-5 shows that the U.S. has been a very small net importer of electricity over the most recent decade: net U.S. imports accounted for an average of only 1.2 percent of total U.S. electricity use from 2011 to 2020. The EIA projects net U.S. imports of electricity to decrease further from that average percentage in the next decades across all the Annual Energy Outlook (AEO) 2022 scenarios. By 2050, the AEO scenarios project net U.S. electricity imports to range from 0.7 percent in the Low Renewables Cost scenario to 0.9 percent in the High Renewables Cost scenario. However, all the AEO 2022 scenarios model a significantly lower level of PEV penetration–U.S. PEV sales account for 9 percent to 24 percent of U.S. LD vehicle sales in 2050–compared to higher projected PEV penetration rates in EPA's proposed LMDV (2027–2032) rule.

[184] "Real option value" analysis applies the concepts used to value the financial assets called "options" to investments in certain real/physical assets. Unlike traditional discounted cashflow analysis which states that investment in a project/asset should only happen if its expected net present value is greater than zero, real option analysis takes into account the extra value that can be realized when cashflows are uncertain and the asset holder can choose between the different options. In the LMDV case considered here with PEVs and gasoline-powered vehicles, real option value results when households can switch between the PEVs and gasoline-powered vehicles when fuel costs fluctuate. Vehicle switching in this case, allows households to purchase the least costly fuel.

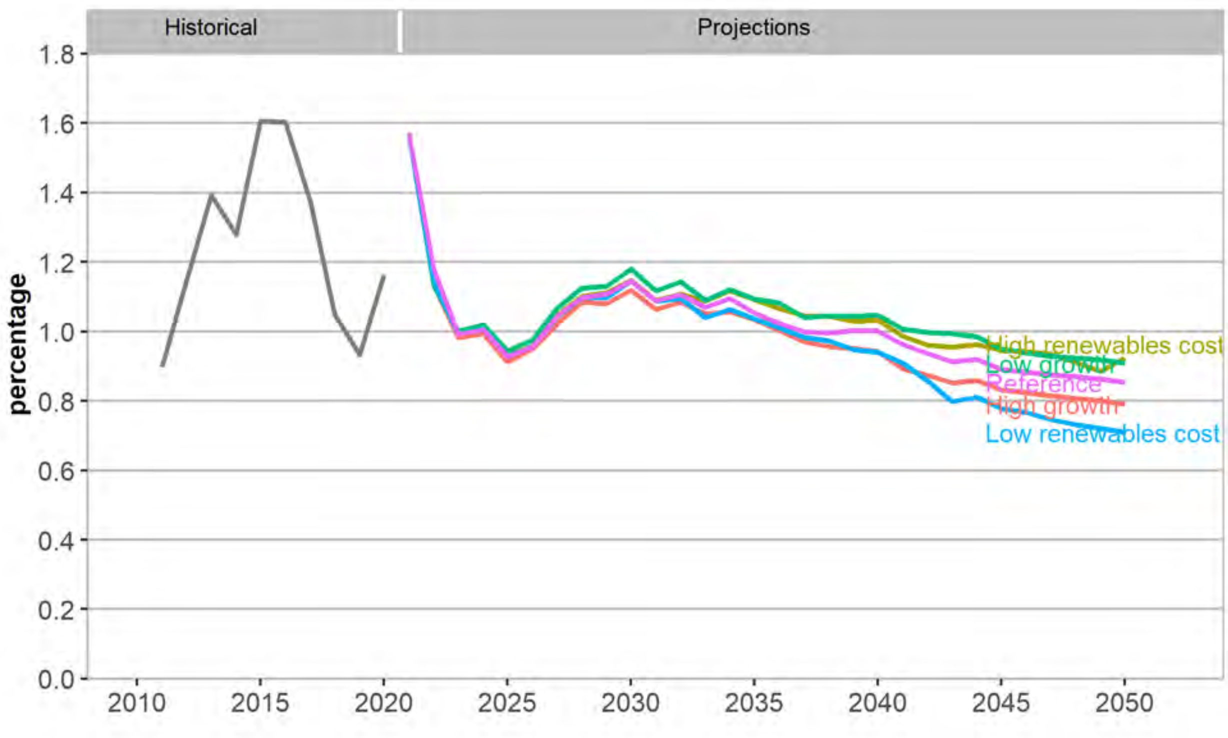


Figure 11-5. U.S. electricity net imports as percentage of total electricity use from 2011 to 2020 and projected U.S. electricity net imports from 2021 to 2050. **Source: (EIA 2022), (EIA 2022), (EIA 2022), (EIA 2022)**

In the past decade, the U.S. has traded electricity with only two countries: Canada and Mexico, both in North America. The U.S. imports more electricity than it exports from both countries. On average, from 2011 to 2020, the volume of electricity imported from Canada was equal to 1.4 percent of U.S. electricity use and the volume exported to Canada was 0.23 percent of U.S. electricity use. Average traded electricity volumes with Mexico were lower; imports from Mexico were equivalent to 0.13 percent of U.S. electricity use and export volumes to Mexico were 0.07 percent of U.S. electricity use. Although net U.S. imports represent a very small fraction of total electricity use at the national level, they can play a larger role in some regional electricity grids in the U.S. For example, ISO-NE–the electricity transmission grid operator in New England–reported that 16 percent of the net energy for load in their system in 2021 originated in Canadian electricity imports (ISO New England 2022).

In addition, EPA uses ICF's Integrated Planning Model (IPM) to estimate the impacts of this proposed rule on U.S. electricity markets and also international electricity dispatches. Only Canadian electricity dispatches are estimated as electricity dispatched from Mexico is de minimis. The IPM results show that net U.S. electricity international dispatch is very small as an overall percentage of total U.S. electricity demand. U.S. net electricity imports are less than 1 percent for all years and trending towards zero by 2050 for both the "no action" and "proposal" case of this proposed rule. See Tables 5–12 and 5–13 of Chapter 5 of the DRIA for more detail on the impacts of this proposed rule on net U.S. electricity international dispatch impacts.

11.4 Oil Security Impacts

11.4.1 U.S. Oil Import Reductions

Over the time frame of analysis of this proposed rule, 2027–2055, the U.S. Department of Energy's (DOE) Energy Information Administration's (EIA) Annual Energy Outlook (AEO) 2021 (Reference Case) projects that the U.S. will be both an exporter and an importer of crude oil[185] (EIA 2021). 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 be relatively stable, between 3.0 and 3.4 MMBD, from 2027 through 2050. See Table 11-1 below. U.S. crude oil imports, meanwhile, are projected to range between 6.7 and 7.6 MMBD between 2027 and 2050. The AEO 2021 also projects that U.S. net oil refined product exports will remain relatively stable from 2027 (5.6 MMBD) through 2035 (5.5 MMBD) before dropping off to 4.4 MMBD by 2050.

U.S. oil consumption is estimated to have decreased from 19.8 MMBD in 2019 to 17.5 MMBD in 2020 and 19.1 MMBD in 2021 as a result of social distancing and quarantines that limited personal mobility as a result of the COVID-19 pandemic (EIA 2022)[186]. AEO 2021 projects that U.S. oil consumptions will continue to increase from 19.1 MMBD in 2027 to 20.3 MMBD in 2050 (EIA 2021). It is not just U.S. crude oil imports alone, but both imports and consumption of petroleum from all sources and their role in economic activity, that exposes the U.S. to risk from price shocks in the world oil price. During the 2027–2055 time frame, the U.S. is projected to continue to consume significant quantities of oil and to rely on significant quantities of crude oil imports. As a result, U.S. oil markets are expected to remain tightly linked to trends in the world crude oil market.

In Chapter 9, EPA estimates changes in U.S. petroleum consumption as a result of this proposed rule. For this energy security analysis, we undertake a detailed analysis of differences in U.S. fuel consumption, crude oil imports/exports, and exports of petroleum products for the time frame 2027–2050 using the AEO 2021 (Reference Case) in comparison with an alternative AEO 2021 sensitivity case, Low Economic Growth. The Low Economic Growth Case is used since oil demand decreases in comparison to the Reference Case. EPA estimates that approximately 90.7 percent of the change in fuel consumption resulting from these proposed standards is likely to be reflected in reduced U.S. imports of crude oil over the time frame of analysis of this proposed rule.[187] The 90.7 percent oil import reduction factor is calculated by taking the ratio of the changes in U.S. net crude oil and refined petroleum product imports

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[185] We are using AEO 2021, as opposed to the more recent AEO 2022, for the quantitative analysis of this proposed rule to maintain consistency with other parts of the analysis (i.e., air quality modeling) of this proposed rule. The AEO 2021 projects oil market trends through 2050. The time frame for EPA's analysis of this proposed rule is from 2027 to 2055. Thus, we report oil market trends to 2050 based upon AEO 2021 in Table 11-1. We also report U.S. oil import reductions through 2055 in Table 11-1 as well.

[186] Calculated using series "Petroleum Consumption (Excluding Biofuels) Annual" (Table 1.3) and "Petroleum Consumption Total Heat Content Annual" (Table A3).

[187] We looked at changes in U.S. crude oil imports/exports and net petroleum products in the AEO 2021 Reference Case, Table 11. Petroleum and Other Liquids Supply and Disposition, in comparison to an alternative case, the Low Economic Growth Case. See the spreadsheet in the Docket, "AEO2021 Change in product demand on imports".

divided by the change in U.S. oil consumption in the two different AEO cases considered. Thus, on balance, each gallon of petroleum reduced as a result of this proposed LMDV rule is anticipated to reduce total U.S. imports of petroleum by 0.907 gallons.

Based upon the changes in oil consumption estimated by EPA and the 90.7 percent oil import reduction factor, the reductions in U.S. oil imports as a result of this proposed rule are estimated in Table 11-1 below for the 2027–2055 time frame.[188] Included in Table 11-1 are estimates of U.S. crude oil exports and imports, net oil refined product exports, net crude oil and refined petroleum product exports and U.S. oil consumption for the years 2027–2050 based on the AEO 2021 (EIA 2021).

Table 11-1 Projected trends in U.S. crude oil exports/imports, net refined oil product exports, net crude oil and refined petroleum product imports, oil consumption and U.S. oil import reductions resulting from the proposed LMDV rule from 2027 to 2050 (MMBD)[a]

	2027	2030	2032	2035	2040	2045	2050	2055
U.S. Crude Oil Exports	3.3	3.1	3.1	3.3	3.2	3.1	3.1	-
U.S. Crude Oil Imports	7.2	6.9	6.9	7.0	7.5	7.3	7.6	-
U.S. Net Refined Petroleum Product Exports[b]	5.6	5.7	5.7	5.5	5.3	5.0	4.4	-
U.S. Net Crude Oil and Petroleum Product Exports	1.8	2.0	2.0	1.9	1.2	0.9	0.1	-
U.S. Oil Consumption[c]	19.1	19.1	19.1	19.3	19.5	19.9	20.3	-
Reduction in U.S. Oil Imports from the Proposed Standards[d]	0.0	0.3	0.5	1.0	1.6	2.0	2.3	2.3

Table Notes:

[a] The AEO 2021 Reference Case, Table A11. Values have been rounded off from the AEO 2021, so the totals may not add up to the AEO estimates.

[b] Calculated from AEO Table A11 as Net Product Exports minus Ethanol, Biodiesel, and Other Biomass-derived Liquid Net Exports.

[c] Calculated from AEO Table A11 as “Total Primary Supply” minus “Biofuels”.

d Oil import reductions differ estimates in Table 9-42, Impacts on Oil Consumption and Oil Imports under the proposed standards, due to rounding.

11.4.2 Oil Security Premiums Used for this Proposed 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 peer-review methodology developed at ORNL (Leiby 2008). 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 (Leiby, Jones, et al. 1997). This same approach was first used to estimate energy security benefits for the 2010 RFS2 final rule (75 FR 14670) and the 2010 final rulemaking to establish light-duty vehicle greenhouse gas emission standards and corporate average fuel economy standards for MY 2012–2016 vehicles (75 FR 25324). ORNL has updated this methodology periodically for EPA to

[188] The AEO 2021 projects oil market trends through 2050. The time frame for EPA's analysis of this proposed rule is from 2027 to 2055. Thus, we report oil market trends to 2050 based upon AEO 2021 in Table 11-1. We also report U.S. oil import reductions through 2055 in Table 11-1 as well.

account for updated projections of future energy market and economic trends reported in the U.S. EIA's AEO. For this proposed rule, EPA updated the ORNL methodology using the AEO 2021.

The ORNL methodology is used to compute the oil import premium (concept defined in Chapter 11.1) 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 proposed 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 2021 into its model.[189] EPA only 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 (EPA 2016).

In the time frame covered by this proposed LMDV 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 crude oil and refined petroleum products

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[189] The oil market projection data used for the calculation of the oil import premiums came from AEO 2021, supplemented by the latest EIA international projections from the Annual Energy Outlook (AEO)/International Energy Outlook (IEO) 2019. 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 2021. Global and OECD Europe supply/demand projections as well as OPEC oil production share are from IEO 2019. The need to combine AEO 2021 and IEO 2019 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.

in the time frame covered by the proposed LMDV standards, 2027-2032. As a result, reductions in U.S. oil consumption and, in turn, U.S. oil imports, still lower the world oil price modestly. But the net effect of the lower world oil price is now 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 proposed rule on the costs associated with existing energy security policies (e.g., maintaining the Strategic Petroleum Reserve or strategic military deployments), which are discussed below.

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 proposed rule. The recent economics literature (discussed in Chapter 11.2.1) 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 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 proposal. We are not accounting for how U.S. tight oil is influencing the macroeconomic oil security premiums in this proposed rule, other than how tight oil significantly reduces the need for U.S. oil imports.

First, we assess the price elasticity of demand for oil. In previous EPA light-duty vehicle rulemakings (i.e., Model Year 2012–2016, Model Year 2017–2025) EPA used a short-run elasticity of demand for oil of -0.045 (EPA 2010) (EPA 2016). In the most recent EPA rule setting GHG emissions standards for passenger cars and light trucks in model years 2023 through 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 (EPA 2021). 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. Most of the world's oil demand is concentrated in the transportation sector and there are limited alternatives to oil use in this sector. According to the IEA, the share of global oil consumption attributed to the transportation sector grew from 60 percent in 2000 to 66 percent in 2019 (IEA 2022). The next largest sector by oil consumption, and an area of recent growth, is petrochemicals. There are limited alternatives to oil use in this sector, particularly in the time frame of this proposed rule. Thus, 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.[190] 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 (i.e., Model Year 2012–2016, Model Year 2017–2025), EPA used an elasticity of GDP to an oil shock of –0.032 (EPA 2010) (EPA 2016). In the most recent EPA rule setting GHG emissions standards for passenger cars and light trucks through model years 2023 through 2026, we used an elasticity of GDP of –0.021, an update of previously used elasticities based on the below considerations (EPA 2021). 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 proposed 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 2021–2022 time frame.[191] Increased tight oil production still results in energy security benefits though, through its impact of reducing U.S. oil imports in the ORNL model.

Table 11-2 below provides estimates of EPA's macroeconomic oil security premium estimates for 2027–2055. The macroeconomic oil security premiums are relatively steady over the time period of this proposed rule at $3.41/barrel (8 cents/gallon) in 2027 and $3.55/barrel in 2030 (8 cents/gallon), $3.91/barrel in 2035 (9 cents per gallon), $4.39/barrel 10 cents per gallon) in 2040 and $5.15/barrel (12 cents/gallon) in 2050 and 2055 (in 2020 U.S. dollars).

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[190] EPA and ORNL have worked together to develop an updated estimate of the short-run elasticity of demand for oil for use in the ORNL model.

[191] 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.

Table 11-2 Macroeconomic oil security premiums for 2027–2055 (2020$/barrel)[a,b]

Year	Avoided Macroeconomic Disruption/Adjustment Costs (Range)
2027	$3.41 ($0.74 - $6.36)
2030	$3.55 ($0.65 - $6.68)
2032	$3.70 ($0.68-$6.94)
2035	$3.91 ($0.73-$7.34)
2040	$4.39 ($1.08-$8.09)
2045	$4.73 ($1.23-$8.64)
2050	$5.15 ($1.52-$9.28
2055	$5.15 ($1.52-$9.28)

Table Notes:

a The top values in each cell are mean values. Values in parentheses are 90 percent confidence intervals.

b The AEO 2021 only provides oil market trend estimates to 2050. We use the same macroeconomic oil security premium for 2055 as the value for 2050.

11.4.3 Cost of Existing U.S. Oil 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 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 (Energy Policy and Conservation Act 1975). Emergency SPR drawdowns have taken place in 1991 (Operation Desert Storm), 2005 (Hurricane Katrina), 2011 (Libyan Civil War), and 2022 (War in Ukraine) (DOE 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, the U.S. President directed the U.S. DOE to conduct two emergency SPR drawdowns in response to ongoing oil supply disruptions. The first drawdown resulted in a sale of 30 million barrels in March 2022 (DOE 2022). The second drawdown, announced in April, authorized a total release of approximately one MMBD from May to October 2022 (DOE 2022). For 2023, the DOE has announced plans to sell 26 million barrels of oil between April and June (DOE 2023). While the costs for building and maintaining the SPR are more clearly related to U.S. oil use and imports, historically these costs have not varied 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 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 proposed rule.

Since "military forces are, to a great extent, multipurpose and fungible" across theaters and missions and because the military budget is presented along regional accounts rather than by mission, according to (Crane, et al. 2009), the allocation to particular missions is not always clear. 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).

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, Behrens and Blodgett 1997). (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. 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 more stable oil supply and price to the U.S. economy. 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–\$74 billion annually. Delucchi and Murphy assume that military costs from U.S. oil import reductions can be scaled proportionally, attempting to address the incremental issue.

(Crane, et al. 2009) 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 (SAFE 2018). 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.

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 proposed rule. Partial reduction of U.S. oil use likely diminishes the magnitude of the 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. 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 proposed rule.

11.4.4 Oil Security Benefits of Proposed Rule

Estimates of the total annual oil security benefits of the proposed standards are based on the ORNL oil import premium methodology with updated oil import premium estimates reflecting the recent energy security literature and using the AEO 2021. 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 proposed rule. The energy security benefits of this proposal are presented in Table 10-9 of Chapter 10, Non-Emissions Benefits of the Proposal, Light-Duty and Medium-Duty.

Chapter 11 References

Balke, Nathan S., and Stephen Brown. 2018. "Oil supply shocks and the U.S. economy: An estimated DSGE model." Energy Policy 116: 357-372. doi:https://doi.org/10.1016/j.enpol.2018.02.027.

Baumeister, Christiane, and Gert Peersman. 2013. "Time-Varying Effects of Oil Supply Shocks on the US Economy." American Economic Journal: Macroeconomics 5 (4): 1-28.

Baumeister, Christiane, and James D. Hamilton. 2019. "Structural Interpretation of Vector Autoregressions with Incomplete Identification: Revisiting the Role of Oil Supply and Demand Shocks." American Economic Review 109 (5): 1873-1910. doi:10.1257/aer.20151569.

Baumeister, Christiane, Gert Peersman, and Ine Van Robays. 2010. "The Economic Consequences of Oil Shocks: Differences across Countries and Time." RBA Annual Conference Papers, Reserve Bank of Australia. Sydney. https://www.rba.gov.au/publications/confs/2009/baumeister-peersman-vanrobays.html.

Bistline, John. 2021. "Variability in Deeply Decarbonized Electricity Systems." Environmental Science & Technology 55 (9): 5629-5635. doi:10.1021/acs.est.0c06708.

Bjørnland, Hilde C., Frode Martin Nordvik, and Maximilian Rohrer. 2020. "Supply flexibility in the shale patch: Evidence from North Dakota." Journal of Applied Econometrics 36 (3): 273-292. doi:10.1002/jae.2808.

Blanchard, Olivier J, and Jordi Galí. 2010. "The Macroeconomic Effects of Oil Price Shocks: Why are the 2000s so different from the 1970s?" In International Dimensions of Monetary Policy, 373-421. University of Chicago Press.

Bohi, Douglas R., and David Montgomery. 1982. "Social Cost of Imported Oil and U.S. Import Policy." Annual Review of Energy 7: 37-60. doi:10.1146/annurev.eg.07.110182.000345.

Bordoff, Jason, and Meghan L O'Sullivan. 2022. "Green Upheaval: The New Geopolitics of Energy." Foreign Affairs, January. https://www.foreignaffairs.com/articles/world/2021-11-30/geopolitics-energy-green-upheaval.

—. 2022. "The New Energy Order: How Governments Will Transform Energy Markets." Foreign Affairs, July. https://www.foreignaffairs.com/articles/energy/2022-06-07/markets-new-energy-order.

Borlaug, Brennan, Shawn Salisbury, Mindy Gerdes, and Matteo Muratori. 2020. "Levelized Cost of Charging Electric Vehicles in the United States." Joule 4 (7): 1470-1485. doi:10.1016/j.joule.2020.05.013.

Breetz, Hanna L, and Deborah Salon. 2018. "Do electric vehicles need subsidies? Ownership costs for conventional, hybrid, and electric vehicles in 14 U.S. cities." Energy Policy 120: 238-249. doi:10.1016/j.enpol.2018.05.038.

Broadman, Harry G. 1986. The social cost of imported oil, Energy Policy 14 (3): 242-252.

Broadman, Harry G, and William H Hogan. 1988. The Numbers Say Yes, The Energy Journal 9 (3): 7-29.

Brown, Stephen P.A. 2018. "New estimates of the security costs of U.S. oil consumption." Energy Policy 113: 171-192. doi:https://doi.org/10.1016/j.enpol.2017.11.003.

Cashin, Paul, Kamiar Mohaddes, Maziar Raissi, and Mehdi Raissi. 2014. "The differential effects of oil demand and supply shocks on the." Energy Economics 44: 113-134. doi:https://doi.org/10.1016/j.eneco.2014.03.014.

Crane, Keith, Andreas Goldthau, Michael Toman, Thomas Light, Stuart E. Johnson, Alireza Nader, Angela Rabasa, and Harun Dogo. 2009. Imported Oil and U.S. National Security. Rand Corporation, 1-100. http://www.rand.org.

Crowley, Kevin, and David Wethe. 2021. "Shale Bets on Dividends to Match Supermajors, Revive Sector." Bloomberg, August 2. https://www.bloomberg.com/news/articles/2021-08-02/shale-heavyweights-shower-investors-with-dividends-on-oil-rally .

Davis, Stacy C, and Robert G Boundy. 2022. Transportation Energy Data Book Edition 40. ORNL/TM-2022/2376, Oak Ridge National Laboratory, Table 3.14 Annual Mileage for Cars and Light Trucks by Vehicle Age.

Delucchi, Mark A., and James J. Murphy. 2008. "US military expenditures to protect the use of Persian Gulf oil for motor vehicles." Energy Policy (36): 2253-2264. doi:0.1016/j.enpol.2008.03.006.

DOE. 2022. Demand Response and Time-Variable Pricing Programs. Accessed September 5, 2022. https://www.energy.gov/eere/femp/demand-response-and-time-variable-pricing-programs.

—. 2022. DOE Announces Emergency Notice of Sale of Crude Oil from the Strategic Petroleum Reserve to Address Oil Supply Disruptions. March 2. https://www.energy.gov/fecm/articles/doe-announces-emergency-notice-sale-crude-oil-strategic-petroleum-reserve-address-oil.

—. 2022. DOE Announces Second EmergencyNotice of Sale of Crude Oil From TheStrategic Petroleum Reserve toAddress Putin’s Energy Price Hike. April 1. https://www.energy.gov/articles/doe-announces-second-emergency-notice-sale-crude-oil-strategic-petroleum-reserve-address.

—. 2023. DOE Issues Notice of Congressionally Mandated Sale to Purchase Crude Oil from the Strategic Petroleum Reserve. February 13. https://www.energy.gov/ceser/articles/doe-issues-notice-congressionally-mandated-sale-purchase-crude-oil-strategic.

—. 2022. FOTW #1251, August 15, 2022: Electric Vehicles Have the Lowest Annual Fuel Cost of All Light-Duty Vehicles. August 15. https://www.energy.gov/eere/vehicles/articles/fotw-1251-august-15-2022-electric-vehicles-have-lowest-annual-fuel-cost-all.

DOE. 2017. "Valuation of Energy Security for the United States. Report to Congress." Washington, DC.

EIA. 2019. Saudi Arabia crude oil production outage affects global crude oil and gasoline prices. September 23. Accessed 12 2022. https://www.eia.gov/todayinenergy/detail.php?id=41413.

—. 2021. "Annual Energy Outlook 2021. Table A11: Petroleum and Other Liquids Supply and Disposition (Reference Case)."

—. 2022. "Annual Energy Outlook 2022. Table 8: Electricity Supply, Disposition, Prices, and Emissions."

—. 2022. "Annual Energy Outlook 2022. Table A11: Petroleum and Other Liquids Supply and Disposition (Reference Case)."

—. 2022. "Annual Energy Outlook 2022: Table 10: Electricity Trade."

—. 2022. "Annual Energy Review 2022. Table 1.3: Electricity Net Import Projections."

—. 2022. "Annual Energy Review 2022. Table 2.14: Electricity Supply and Disposition."

EIA. 2022. Monthly Energy Review. https://www.eia.gov/totalenergy/data/monthly/.

—. 2022. "Monthly Energy Review, December 2022. Table 3.1. Petroleum Overview."

—. 2022. Oil and petroleum products explained. November 02. Accessed 12 06, 2022. https://www.eia.gov/energyexplained/oil-and-petroleum-products/imports-and-exports.php.

EIA. 2022. Petroleum and Other Liquids: Crude Oil Production. https://www.eia.gov/dnav/pet/pet_crd_crpdn_adc_mbbl_m.htm.

EIA. 2022. Petroleum and Other Liquids: Spot Prices. https://www.eia.gov/dnav/pet/pet_pri_spt_s1_d.htm.

EIA. 2022. Petroleum and Other Liquids: Weekly Retail Gasoline and Diesel Prices. https://www.eia.gov/dnav/pet/PET_PRI_GND_DCUS_NUS_W.htm.

EIA. 2022. Residential electricity sales and average prices. Electricity sales to ultimate customers. https://www.eia.gov/opendata/browser/electricity/retail-sales.

EIA. 2023. "Today in Energy. Crude oil prices increased in first-half of 2022 and declined in second half of 2022."

—. 2021. U.S. electricity customers experienced eight hours of power interruptions in 2020. November 10. Accessed December 2022. https://www.eia.gov/todayinenergy/detail.php?id=50316.

—. 2022. U.S. STATES: State Profiles and Energy Estimates. https://www.eia.gov/state/.

EIA. 2022. U.S. Tight Oil Production by Play. Accessed 12 14, 2022. https://www.eia.gov/energyexplained/oil-and-petroleum-products/data/US-tight-oil-production.xlsx.

EMF. 1982. World Oil: EMF 6 Summary Report. Stanford, CA: Stanford Energy Modeling Forum.

1975. "Energy Policy and Conservation Act." Public Law No. 94-163. December 22.

Engemann, Kristie M, Kevin L Kliesen, and Michael T Owyang. 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. doi:10.20955/wp.2010.007.

EPA. 2010. "Final Rulemaking to Establish Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards for Model Year 2012–2016 Vehicles, Joint Technical Support Document." EPA-420-R-10-901.

EPA. 2016. "Final Rulemaking to Establish Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards for Model Year 2017–2025 Vehicles, Joint Technical Support Document." EPA-420-D-16-900.

EPA. 2016. "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-D-16-900." https://nepis.epa.gov/Exe/ZyPDF.cgi/P100OXEO.PDF?Dockey=P100OXEO.PDF.

EPA. 2021. "Revised 2023 and Later Model Year Light Duty Vehicle GHG Emissions Standards, Regulatory Impact Analysis." EPA-420-R-21-028.

EPA. 2022. "The 2022 EPA Automotive Trends Report: Greenhouse Gas Emissions, Fuel Economy, and Technology since 1975." Office of Transportation and Air Quality. EPA-420-R-22-029.

Federal Reserve Bank of Dallas. 2022. Dallas Fed Energy Survey: Special Questions. March 9. https://www.dallasfed.org/research/surveys/des/2022/2201.aspx#tab-questions.

Feng, Kairui, Ning Lin, Siyuan Xian, and Mikhail V Chester. 2020. "Can we evacuate from hurricanes with electric vehicles?" Transportation Research Part D 86: 102458. doi:10.1016/j.trd.2020.102458.

GAO. 2020. Effects of the Repeal of the Crude Oil Export Ban. Report to Congress, United States Government Accountability Office. https://www.gao.gov/assets/gao-21-118.pdf.

Ge, Yanbo, Christina Simeone, Andrew Duvall, and Eric Wood. 2021. There's No Place Like Home: Residential Parking, Electrical Access, and Implications for the Future of Electric Vehicle Charging Infrastructure. Technical Report NREL/TP-5400-81065, National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy22osti/81065.pdf.

Greene, David L. 2010. "Measuring energy security: Can the United States achieve oil independence?" Energy Policy 38 (4): 1614-1621. doi:10.1016/j.enpol.2009.01.041.

Greene, David L. 2010. "Measuring energy security: Can the United States achieve oil independence?" Energy Policy 38 (4): 1614-1621. doi:10.1016/j.enpol.2009.01.041.

Grove, Andy. 2008. "Our Electric Future." American Enterprise Institute, July 10. https://www.aei.org/articles/our-electric-future/.

Hamilton, James D. 2012. "Oil Prices, Exhaustible Resources, and Economic Growth." In Handbook of Energy and Climate Change. https://econweb.ucsd.edu/~jhamilto/handbook_climate.pdf.

Hardman, Scott, Kelly L Fleming, Eesha Khare, and Mahmoud M Ramadan. 2021. "A perspective on equity in the transition to electric vehicles." MIT Science Policy Review 2: 46-54. doi:10.38105/spr.e10rdoaoup.

Hogan, William W. 1981. "Import Management and Oil Emergencies." In Energy and Security, 261-301. Cambridge: Ballinger Publishing Co.

IEA. 2019. Energy security. December 2. Accessed 12 2022. https://www.iea.org/areas-of-work/ensuring-energy-security.

—. 2022. Energy Statistics Data Browser. https://www.iea.org/data-and-statistics/data-tools/energy-statistics-data-browser?country=WORLD&fuel=Oil&indicator=OilProductsConsBySector.

2022. "Inflation Reduction Act." Public Law No. 117-169. August 16.

ISO New England. 2022. Resource Mix. https://www.iso-ne.com/about/key-stats/resource-mix.

Jenn, Alan, and Jake Highleyman. 2022. "Distribution grid impacts of electric vehicles: A California case study." iScience 25 (1). doi:10.1016/j.isci.2021.103686.

Kemp, John. 2021. "U.S. Shale Restraint Pushes Oil Prices to Multi-year High." Reuters, June 4. https://www.reuters.com/business/energy/us-shale-restraint-pushes-oil-prices-multi-year-high-kemp-2021-06-04.

Kilian, Lutz. 2009. "Not All Oil Price Shocks Are Alike: Disentangling Demand and Supply Shocks in the Crude Oil Market." American Economic Review 99 (3): 1053-1069. https://www.aeaweb.org/articles?id=10.1257/aer.99.3.1053.

Kilian, Lutz, and Daniel P. Murphy. 2014. "The Role of Inventories and Speculative Trading in the Global Market for Crude Oil." Journal of Applied Econometrics 29: 454-478. doi:https://doi.org/10.1002/jae.2322.

Kilian, Lutz, and Robert J. Vigfusson. 2014. "The Role of Oil Price Shocks in Causing U.S. Recessions." Center for Financial Studies. Working Paper Series 460.

Kim, Dong Heon. 2012. "What is an oil shock? Panel data evidence." Empirical Economics 43: 121-143. doi:10.1007/s00181-011-0459-y.

Koplow, Douglas, and Aaron Martin. 1998. Fueling Global Warming: Federal Subsidies to Oil in the United States. Washington D.C.: Greenpeace.

Krupnick, Alan, Richard Morgenstern, Nathan Balke, Stephen P.A. Brown, Ana María Herrera, and Shashank Mohan. 2017. Oil Supply Shocks, US Gross Domestic Product, and the Oil Security Premium. Resources for the Future. https://www.rff.org/publications/reports/oil-supply-shocks-us-gross-domestic-product-and-the-oil-security-premium/.

Leiby, Paul N. 2008. Estimating the Energy Security Benefits of Reduced U.S. Oil Imports. ORNL/TM-2007/028, Oak Ridge National Laboratory.

Leiby, Paul N, Donald W Jones, T Randall Curlee, and Russell Lee. 1997. Oil Imports: An Assessment of Benefits and Costs. Oak Ridge, Tennessee: Oak Ridge National Laboratory.

Lemoine, Derek. 2010. "Valuing Plug-In Hybrid Electric Vehicles' Battery Capacity Using a Real Options Framework." Energy Journal. doi:10.2139/ssrn.1322164.

Liu, Zhe, Juhyun Song, Joseph Kubal, Naresh Susarla, Kevin W Knehr, Ehsan Islam, Paul Nelson, and Shabbir Ahmed. 2021. "Comparing total cost of ownership of battery electric vehicles and internal combustion engine vehicles." Energy Policy 158: 112564–112577. doi:10.1016/j.enpol.2021.112564.

Lutsey, Nic, and Michael Nicholas. 2019. Update on electric vehicle costs in the United States through 2030. Working Paper 2019-06, ICCT. https://theicct.org/publication/update-on-electric-vehicle-costs-in-the-united-states-through-2030/.

McLean, Bethany. 2018. "The Next Financial Crisis Lurks Underground." The New York Times, September 1. https://www.nytimes.com/2018/09/01/opinion/the-next-fi nancial-crisis-lurks-underground.html.

Melodia, Lauren, and Kristina Karlsson. 2022. Energy Price Stability: The Peril of Fossil Fuels and the Promise of Renewables. Issue Brief, Roosevelt Institute. https://rooseveltinstitute.org/publications/energy-price-stability/.

Michalek, Jeremy J, Mikhail Chester, Paulina Jaramillo, Constantine Samaras, Ching-Shin Norman Shiau, and Lester B Lave. 2011. "Valuation of plug-in vehicle life-cycle air emissions and oil displacement benefits." Proceedings of the National Academy of Sciences 108 (40): 16554-16558. doi:10.1073/pnas.1104473108.

Moore, John L, Carl E Behrens, and John E Blodgett. 1997. Oil Imports: An Overview and Update of Economic and Security Effects. CRS Report 98-1, Congressional Research Service: Environment and Natural Resources Policy Division.

Muratori, Matteo. 2018. "Impact of uncoordinated plug-in electric vehicle charging on residential power demand." Nature Energy 3: 193-201. doi:10.1038/s41560-017-0074-z.

National Research Council. 2010. Hidden Costs of Energy: Unpriced Consequences of Energy Production and Use. Washington DC: National Academies Press.

Newell, Richard G., and Brian C. Prest. 2019. "The Unconventional Oil Supply Boom: Aggregate Price Response from Microdata." The Energy Journal 40 (3). doi:10.5547/01956574.40.3.rnew.

Nordhaus, William D. 2007. "Who's Afraid of a Big Bad Oil Shock?" Brookings Papers on Economic Activity 2007 (2): 219-238. doi:10.1353/eca.2008.0013.

Oladosu, Gbadebo A., Paul. N. Leiby, David C. Bowman, Rocio Uría-Martínez, and Megan Johnson. 2018. "Impacts of oil price shocks on the United States economy: A meta-analysis of the oil price elasticity of GDP for net oil-importing economies." Energy Policy 115 (Virtual Special Issue entitled 'Oil Supply Disruptions, U.S. Economic Activity and Oil Security'): 523-544. 10.1016/j.enpol.2018.01.032.

Parry, Ian W. H., and Joel Darmstadter. 2003. The Cost of U.S. Oil Dependency. Washington, D.C.: Resources for the Future.

Plummer, James L, Hung-Po Chao, Dermot Gately, and Richard J Gilbert. 1982. "Basic Concepts, Assumptions, and Numerical Results." In Energy Vulnerability, 13-36. Cambridge: Ballinger Publishing Co.

Powell, Siobhan, Gustavo Cezar, Liang Min, Ines Azevedo, and Ram Rajagopal. 2022. "Charging infrastructure access and operation to reduce the grid impacts of deep electric vehicle adoption." Natural Energy 1-14. doi:0.1038/s41560-022-01105-7.

Ramey, Valerie A, and Daniel J Vine. 2010. "Oil, Automobiles, and the U.S. Economy: How Much Have Thinks Really Changed?" NBER Macroeconomics Annual 25 (1): 333-368. doi:10.1086/657541.

Rasmussen, Tobias, and Agustin Roitman. 2011. "Oil Shocks in a Global Perspective: Are They Really that Bad?" IMF Working Papers (11/194). https://papers.ssrn.com/sol3/papers.cfm?abstract_id=1910497.

SAFE. 2018. The Military Cost of Defending the Global Oil Supply. Issue Brief, Securing America's Energy Future. http://secureenergy.org/wp-content/uploads/2020/03/Military-Cost-of-Defending-the-Global-Oil-Supply.-Sep.-18.-2018.pdf.

Sieren-Smith, Bridget, Ankit Jain, Alireza Eshraghi, Simon Hurd, Julia Ende, Josh Huneycutt, Andrew Ngo, Mark LeBel, Carl Linvill, and David Roland-Holst. 2021. Utility Costs and Affordability of the Grid of the Future. An Evaluation of Electric Costs, Rates and Equity Issues. California Public Utilities Commission.

Slowik, Peter, Aaron Isenstadt, Logan Pierce, and Stephanie Searle. 2022. Assessment of Light-duty Electric Vehicle Costs and Consumer Benefits in the United States in the 2022-2035 Time Frame. White Paper, ICCT. https://theicct.org/publication/ev-cost-benefits-2035-oct22/.

Stein, Fred. 2013. "Ending America’s Energy Insecurity: Why Electric Vehicles Should Drive the United States to Energy Independence." Homeland Security Affairs 4. https://www.hsaj.org/articles/236.

Stern, Roger J. 2010. "United States cost of military force projection in the Persian Gulf, 1976–2007." Energy Policy 38: 2816-2825. doi:10.1016/j.enpol.2010.01.013.

Trinko, David, Emily Porter, Jamie Dunckley, Thomas Bradley, and Timothy Coburn. 2021. "Combining Ad Hoc Text Mining and Descriptive Analytics to Investigate Public EV Charging Prices in the United States." Energies 14 (17). doi:10.3390/en14175240.

Union of Concerned Scientists. 2017. "Going From Pump to Plug." https://www.ucsusa.org/resources/going-pump-plug.

Uría-Martínez, Rocío, Paul N. Leiby, Gbadebo Oladosu, David C. Bowman, and Megan M. Johnson. 2018. Using Meta-Analysis to Estimate World Crude Oil Demand Elasticity. Oak Ridge National Laboratory. https://info.ornl.gov/sites/publications/Files/Pub120229.pdf.

Walls, W.D., and Xiaoli Zheng. 2022. "Fracking and Structural Shifts in Oil Supply." The Energy Journal 43 (3). doi:10.5547/01956574.43.3.wwal.

Yilmaz, Murat, and Philip Krein. 2013. "Review of the Impact of Vehicle-to-Grid Technologies on Distribution Systems and Utility Interfaces." IEEE Transactions on Power Electronics 28 (12): 5673-5689. doi:10.1109/TPEL.2012.2227500.

Zamuda, Craig D, Daniel E Bilello, Guenter Conzelmann, Ellen Mecray, Ann Satsangi, Vincent Tidwell, and Brian J Walker. 2018. Energy Supply, Delivery, and Demand. Vol. II, in Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, 174-201. doi:10.7930/NCA4.2018.CH4.

Chapter 12: Small Business Flexibilities

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 of any rule subject to notice-and-comment rulemaking requirements under the Administrative Procedure Act or any other statute. As a part of this analysis, an agency is directed to convene a Small Business Advocacy Review Panel (SBAR Panel or 'the Panel'), unless the agency certifies that the rule will not have a significant economic impact on a substantial number of small entities. During such a Panel process, the agency would gather information and recommendations from Small Entity Representatives (SERs) on how to reduce the impact of the rule on small entities. As discussed below, EPA is certifying that this rule will not have a significant economic impact on a substantial number of small entities, and thus we have not conducted an SBAR Panel for this rulemaking. The following discussion provides an overview of small entities in the vehicle market. Small entities include small businesses, small organizations, and small governmental jurisdictions. For the purposes of assessing the impacts of the rule on small entities, a small entity is defined as: (1) a small business that meets the definition for business based on the Small Business Administration's (SBA) size standards (Title 13 CFR 121.201 2023), (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; and (3) a small organization that is any not-for-profit enterprise which is independently owned and operated and is not dominant in its field.

There are three types of small entities that could potentially be impacted by the proposed GHG standards: 1) small entity vehicle manufacturers; 2) alternative fuel converters, which are companies that take a vehicle for which an OEM has already accounted for GHG compliance and convert it to operate on a cleaner fuel such as natural gas or propone; and 3) -independent commercial importers (ICIs), which are firms that import vehicles from other countries for individual vehicle purchasers.

EPA initiated the Small Business Advocacy Review Panel process and had a pre panel meeting with small businesses representing the small entity manufacturers, the alternative fuel converters, and the ICIs. EPA presented the areas it expected to make changes in this NPRM at a high level and heard from the small businesses their initial concerns if any on the potential changes based on this rulemaking. EPA also learned in more detail how these entities conduct their business to help assess the impact the standards proposed in this NPRM may have and enable EPA to mitigate any impacts.

EPA is certifying that this rule will have no significant economic impact on a substantial number of small entities (No SISNOSE). EPA has focused its assessment of potential small business impacts on three key aspects of the proposed standards, including GHG emissions standards, criteria pollutants (NMOG+NOx fleet-average standards) and PM emissions standards), and EV battery warranty and durability.

Under the current light-duty GHG program, small entities are exempt from the GHG standards. EPA is proposing to continue the current exemption for all three types of small entities, including small entity manufacturers, Alternate Fuel Convertors, and Independent Commercial Importers (ICIs). However, EPA is proposing to add some environmental protections for imported vehicles, as described below. EPA is also proposing to continue the current provision allowing small entity manufacturers to opt into the GHG program to earn credits to sell in the credit market. The only small entity vehicle manufacturers in the market at this time produce only electric vehicles. EPA is requesting comment on the potential need for small entity manufacturers to have an annual vehicle production cap (e.g., 200-500 vehicles per year) on vehicles eligible for the exemption. On average, historical production data indicates that small entities' annual sales have been well below this range as shown in Table 1. EPA believes that capping the number of vehicles exempted could be an appropriate protection for GHG emissions, while still allowing small entities to produce vehicles consistent with typical past annual sales.

Table 3 Small Entity Production from 2017 to 2021

	Karma	RUF	Koenigsegg	Pagani	Rimac
2017	0	0	0	46	1
2018	295	2	10	10	0
2019	83	1	12	0	1
2020	153	6	4	0	0
2021	78	7	11	0	0

While ICI's imported vehicles have not been accounted for in a manufacturer's GHG average there are typically only a small number of vehicles imported each year. Since 2014, none of the current ICIs have imported more than 15 vehicles each year. Under existing EPA regulations, each ICI' is currently limited to importing 50 vehicles per year. EPA is proposing to reduce the limit to 25 non-ZEV vehicles per year, as a means of limiting the potential environmental impact of importing vehicles with potentially high GHG emissions. Importing of ZEVs will not count against the 25 vehicles limit and EPA will put in language to clarify this fact. Table 2 below shows the number of vehicles imported by each of the current ICIs. EPA believes this lower vehicle limit is important for capping the potential for high-emitting imported vehicles, because, unlike with criteria pollutant emissions as discussed below, there are very limited add-on emissions control options for reducing the GHG emissions of an imported vehicle. This action will have no financial impact on the ICI businesses, as it still far above the average number of vehicles imported by ICIs in recent years.

Table 4 ICI Import Records

		2014	2015	2016	2017	2018	2019	2020	2021	2022
Current ICIs	G & K	7	7	6	6	8	12	6	10	8
	JK Technologies	13	15	8	10	10	9	3	4	5
	Wallace Labs	0	0	15	1	7	5	4	4	10

EPA also has evaluated the potential impacts on small businesses for the proposed criteria pollutant emissions standards, including both the NMOG+ NOx standard and the PM standard.

EPA's proposed NMOG+NOx standards should have no impact on the existing small entity manufacturers which produce only electric vehicles. The proposed standards are expected to have minimal impact on both the alternate fuel convertors and ICIs. Alternate fuel convertors are getting vehicles that would already meet the standard on gasoline or diesel fuel and have the ability to make changes, such as calibration, so the vehicles continue to meet the standard on an alternate fuel such as propane or natural gas. ICIs take vehicles that were certified in a foreign country and make the vehicle meet the EPA standard for the year the vehicle was built. This may require catalyst and calibration changes depending on the vehicle's original requirements. Based on the pre panel meeting, EPA believes changes to the NMOG+ NOx standard will require a similar amount of effort for both alternative fuel convertors and ICIs to meet the new standard when compared to the previous (Tier 3) emissions standard.

The proposed PM standard could potentially have a unique impact on each type of small entity. The current small entity manufacturers all produce only EVs which have no tailpipe emissions and therefore would automatically comply with the PM standard. Alternative fuel convertors buy OEM vehicles that already would need to be compliant for PM but must test the vehicle on the converted fuel and show that it still meets the standard. There would be an increased testing burden to measure PM on the cold temperature test (as discussed further in Preamble Section III.C.2), but alternative fuel vehicles are already exempted from doing any cold testing under existing EPA regulations. EPA is proposing to continue this exemption for cold temperature testing, and thus there would be no impact on alternative fuel converters. ICI's must do a complete set of emissions tests for an imported vehicle that do not already have an existing certificate (referred to as non-conforming vehicles). ICI's currently only have to test non-methane hydrocarbons (NMHC) on the cold test; to minimize the testing burden on ICIs EPA is proposing to exempt ICI from measuring PM during cold testing. ICIs will only need to comply with the new PM levels on the FTP75 and US06. The stringency of the proposed PM standard may lead to OEMs choosing to comply by the use of gasoline particulate filters (GPFs). Most of the ICE vehicles since 2014 have been imported from Europe where GPFs are mandatory, so EPA estimates that there will be no financial impact to ICIs based on additional testing or ensuring imported vehicles are compliant with emissions standards.

The final aspect of the NPRM that could have potential impacts on small entities is battery durability and warranty (Preamble Section III.F.2 and Preamble Section III.F.3). The current small entity manufacturers all have warranties that meet or exceed our proposed requirements. EPA is proposing to exempt small entities form meeting the proposed battery durability and warranty requirements since the reporting requirements would be an added financial burden that is not necessary given their current warranties.

Chapter 12 References

Title 13 CFR 121.201. 2023.

Chapter 13: Compliance Effects

This chapter summarizes the outputs from OMEGA2 related to the proposed GHG standards and the three alternatives which were presented in III.E of the preamble.

In the following sections we provide detailed modeling results of GHG targets, projected achieved compliance GHG rates, as well as vehicle costs and technology penetrations. These projections are grouped by car and truck regulatory classes, and in select tables, using EPA's classification of body style in its OMEGA model.

13.1 Light-Duty Vehicles

13.1.1 GHG Targets and Compliance Levels

13.1.1.1 CO_2 g/mi

Shown below are the projected average GHG targets for each manufacturer, as well as their corresponding average achieved compliance, in g/mi, for cars and trucks. A combined fleet g/mi comparison is not shown, because a fleet g/mi value, even with a sales-weighted average of car and truck values, would not accurately represent the differences in lifetime VMT for the car and truck fleets used in the compliance calculations for each OEM.

13.1.1.1.1 Proposed standards

OEM-specific GHG emissions targets for the proposed standards are shown in Table 13-1 and Table 13-2 for cars and trucks, respectively[192]. Similarly, projected achieved GHG emissions levels are given for cars and trucks in Table 13-3 and Table 13-4.

[192] Only manufacturers with annual sales exceeding 25,000 units are provided in the tables in this chapter. However, the industry sales-weighted averages include all vehicles and manufacturers (even those not shown).

Table 13-1: Projected GHG Targets, Proposed Standards - Cars

Manufacturer	2027	2028	2029	2030	2031	2032
BMW	135	117	99	91	83	74
Ford	135	117	99	91	82	73
General Motors	134	116	98	90	82	72
Honda	133	116	98	91	82	73
Hyundai	134	116	98	91	82	73
JLR	136	118	100	92	83	74
Kia	134	116	98	90	82	73
Mazda	133	116	98	90	82	73
Mercedes Benz	135	117	99	91	83	74
Mitsubishi	131	114	97	90	81	72
Nissan	133	116	98	90	82	73
Stellantis	135	118	100	92	83	73
Subaru	134	116	98	90	82	72
Tesla	137	119	101	92	84	74
Toyota	133	116	98	91	82	73
Volvo	137	119	101	92	84	74
VW	133	116	98	90	82	73
TOTAL	**134**	**116**	**99**	**91**	**82**	**73**

Table 13-2: Projected GHG Targets, Proposed Standards - Trucks

Manufacturer	2027	2028	2029	2030	2031	2032
BMW	158	139	117	107	98	87
Ford	179	154	130	119	108	96
General Motors	175	150	128	117	106	94
Honda	152	133	113	104	95	84
Hyundai	149	130	111	102	93	82
JLR	161	140	118	109	99	86
Kia	155	131	111	103	93	83
Mazda	146	128	109	101	91	81
Mercedes Benz	156	136	115	107	97	86
Mitsubishi	137	121	104	96	87	77
Nissan	157	136	115	107	98	87
Stellantis	166	144	122	113	102	91
Subaru	145	126	107	99	89	79
Tesla	173	150	126	116	105	93
Toyota	157	136	116	107	97	86
Volvo	155	135	115	106	96	85
VW	155	135	113	106	96	85
TOTAL	**163**	**142**	**120**	**110**	**100**	**89**

Table 13-3: Achieved GHG Levels, Proposed Standards - Cars

Manufacturer	2027	2028	2029	2030	2031	2032
BMW	137	129	96	61	45	43
Ford	106	102	85	92	81	96
General Motors	106	77	72	74	70	63
Honda	119	115	100	70	78	59
Hyundai	130	111	95	74	69	65
JLR	141	101	127	88	84	73
Kia	121	110	96	74	60	51
Mazda	128	112	97	75	79	72
Mercedes Benz	124	108	75	61	67	62
Mitsubishi	106	94	77	55	56	53
Nissan	117	103	86	69	78	66
Stellantis	114	89	74	81	80	76
Subaru	75	56	94	81	77	76
Tesla	0	0	0	0	0	0
Toyota	122	110	91	81	55	45
Volvo	105	81	54	47	65	67
VW	112	73	39	48	54	29
TOTAL	**115**	**100**	**84**	**72**	**68**	**60**

Table 13-4: Achieved GHG Levels, Proposed Standards - Trucks

Manufacturer	2027	2028	2029	2030	2031	2032
BMW	170	128	136	133	135	117
Ford	158	155	127	125	111	81
General Motors	216	175	138	134	123	105
Honda	147	122	104	99	76	82
Hyundai	159	135	115	104	123	112
JLR	156	136	105	88	104	114
Kia	152	125	109	84	80	80
Mazda	136	118	104	85	90	90
Mercedes Benz	185	155	154	119	101	102
Mitsubishi	136	114	93	82	92	92
Nissan	144	140	126	107	73	74
Stellantis	218	158	126	119	113	98
Subaru	137	113	83	74	90	90
Tesla	0	0	0	0	0	0
Toyota	151	145	121	108	115	107
Volvo	169	143	114	97	109	109
VW	158	151	147	113	102	108
TOTAL	**176**	**149**	**123**	**113**	**106**	**95**

13.1.1.1.2 Alternative 1

Table 13-5 and Table 13-6 show the OEM-specific targets for Alternative 1. Achieved levels are presented, by manufacturer, in Table 13-7 and Table 13-8.

Table 13-5: Projected GHG Targets, Alternative 1 - Cars

Manufacturer	2027	2028	2029	2030	2031	2032
BMW	125	107	89	81	73	63
Ford	125	107	89	81	73	63
General Motors	124	106	89	80	72	63
Honda	124	106	88	81	72	63
Hyundai	124	106	89	81	72	63
JLR	126	108	90	82	74	64
Kia	124	106	88	81	72	63
Mazda	123	106	88	80	72	63
Mercedes Benz	125	107	89	81	73	63
Mitsubishi	122	105	87	80	71	62
Nissan	123	106	88	81	72	63
Stellantis	125	108	90	82	73	63
Subaru	124	106	88	80	72	62
Tesla	127	109	91	82	74	64
Toyota	124	106	89	81	73	63
Volvo	127	109	91	82	74	64
VW	124	106	88	80	72	62
TOTAL	**124**	**106**	**89**	**81**	**72**	**63**

Table 13-6: Projected GHG Targets, Alternative 1 - Trucks

Manufacturer	2027	2028	2029	2030	2031	2032
BMW	147	128	108	98	87	75
Ford	167	143	119	108	97	84
General Motors	163	139	117	106	95	83
Honda	142	123	105	96	86	74
Hyundai	139	120	101	93	83	72
JLR	150	129	108	99	88	76
Kia	145	120	101	93	83	72
Mazda	136	118	99	91	82	71
Mercedes Benz	149	128	107	98	88	76
Mitsubishi	128	112	94	87	78	68
Nissan	146	126	106	97	87	76
Stellantis	155	133	112	102	92	80
Subaru	135	117	98	90	80	69
Tesla	161	138	115	105	94	82
Toyota	147	126	105	96	86	75
Volvo	145	125	105	96	86	75
VW	143	125	106	97	86	75
TOTAL	**153**	**131**	**110**	**100**	**90**	**78**

Table 13-7: Achieved GHG Levels, Alternative 1 - Cars

Manufacturer	2027	2028	2029	2030	2031	2032
BMW	137	131	109	77	50	53
Ford	106	98	88	63	52	66
General Motors	108	81	67	44	39	28
Honda	119	116	85	74	72	69
Hyundai	129	104	82	62	64	63
JLR	139	68	38	22	23	25
Kia	124	108	82	66	68	63
Mazda	128	104	77	57	54	46
Mercedes Benz	128	109	83	85	78	84
Mitsubishi	105	86	69	52	55	51
Nissan	117	92	74	59	49	40
Stellantis	113	77	71	74	46	49
Subaru	70	55	93	75	52	62
Tesla	0	0	0	0	0	0
Toyota	122	100	80	51	34	28
Volvo	105	79	64	47	57	54
VW	74	102	104	91	71	78
TOTAL	**113**	**97**	**80**	**62**	**53**	**51**

Table 13-8: Achieved GHG Levels, Alternative 1 - Trucks

Manufacturer	2027	2028	2029	2030	2031	2032
BMW	169	131	95	96	141	138
Ford	158	139	124	103	100	68
General Motors	211	149	128	111	111	92
Honda	147	122	90	71	77	75
Hyundai	159	136	109	91	107	103
JLR	156	132	103	84	90	90
Kia	143	125	96	78	69	74
Mazda	136	114	89	78	81	81
Mercedes Benz	167	141	113	68	69	78
Mitsubishi	134	101	82	68	69	65
Nissan	140	130	105	87	91	95
Stellantis	217	145	122	94	92	73
Subaru	137	113	84	75	86	77
Tesla	0	0	0	0	0	0
Toyota	151	139	118	104	115	106
Volvo	169	132	107	86	94	86
VW	179	135	91	76	93	87
TOTAL	**175**	**137**	**113**	**94**	**97**	**84**

13.1.1.1.3 Alternative 2

Table 13-9 and Table 13-10 show the OEM-specific targets for Alternative 2. Achieved levels are presented, by manufacturer, in Table 13-11 and Table 13-12.

Table 13-9: Projected GHG Targets, Alternative 2 - Cars

Manufacturer	2027	2028	2029	2030	2031	2032
BMW	145	127	109	101	93	83
Ford	145	127	109	101	92	83
General Motors	143	126	108	100	92	82
Honda	143	126	108	100	92	83
Hyundai	144	126	108	100	92	83
JLR	146	128	109	101	93	84
Kia	144	126	108	100	92	83
Mazda	142	125	108	100	92	82
Mercedes Benz	145	127	109	101	93	83
Mitsubishi	141	124	107	99	91	82
Nissan	143	126	108	100	92	82
Stellantis	145	127	109	102	93	83
Subaru	143	126	107	100	91	82
Tesla	147	129	111	103	94	84
Toyota	143	126	108	100	92	83
Volvo	148	129	111	102	93	84
VW	143	126	108	100	92	82
TOTAL	**144**	**126**	**108**	**100**	**92**	**83**

Table 13-10: Projected GHG Targets, Alternative 2 - Trucks

Manufacturer	2027	2028	2029	2030	2031	2032
BMW	168	147	127	118	108	96
Ford	190	166	142	130	119	107
General Motors	186	161	139	128	117	105
Honda	162	142	122	113	104	94
Hyundai	158	139	120	111	102	92
JLR	171	150	128	119	109	95
Kia	165	140	121	112	103	92
Mazda	154	136	117	109	100	90
Mercedes Benz	165	146	126	117	107	96
Mitsubishi	145	129	112	105	96	86
Nissan	166	145	126	116	107	97
Stellantis	176	154	133	123	113	101
Subaru	154	135	116	108	98	88
Tesla	184	161	138	127	116	104
Toyota	167	146	126	117	107	96
Volvo	164	144	124	115	105	95
VW	163	144	124	115	106	95
TOTAL	**173**	**152**	**130**	**121**	**111**	**99**

Table 13-11: Achieved GHG Levels, Alternative 2 - Cars

Manufacturer	2027	2028	2029	2030	2031	2032
BMW	135	128	93	108	71	50
Ford	106	91	74	73	95	102
General Motors	128	95	70	82	83	59
Honda	121	118	96	85	76	70
Hyundai	134	128	101	98	83	75
JLR	144	172	182	169	161	137
Kia	122	124	95	91	72	60
Mazda	137	118	105	103	82	77
Mercedes Benz	136	155	123	114	95	87
Mitsubishi	115	109	92	93	88	78
Nissan	120	108	84	80	70	77
Stellantis	132	110	89	86	86	84
Subaru	82	95	99	108	105	94
Tesla	0	0	0	0	0	0
Toyota	125	113	91	87	65	43
Volvo	112	92	84	98	111	102
VW	74	94	77	85	74	64
TOTAL	**119**	**110**	**87**	**87**	**77**	**68**

Table 13-12: Achieved GHG Levels, Alternative 2 - Trucks

Manufacturer	2027	2028	2029	2030	2031	2032
BMW	170	161	138	115	124	129
Ford	158	167	136	116	109	92
General Motors	223	169	144	133	125	118
Honda	148	143	119	125	108	95
Hyundai	162	147	118	128	122	99
JLR	188	168	143	145	144	130
Kia	141	148	114	110	91	88
Mazda	159	152	136	129	130	109
Mercedes Benz	200	152	120	121	106	102
Mitsubishi	154	143	121	118	110	97
Nissan	151	150	134	129	112	80
Stellantis	229	160	130	122	119	109
Subaru	145	130	112	119	115	101
Tesla	0	0	0	0	0	0
Toyota	159	162	132	126	124	122
Volvo	192	172	148	142	134	118
VW	184	161	134	129	113	103
TOTAL	**183**	**158**	**132**	**124**	**117**	**106**

13.1.1.1.4 Alternative 3

Table 13-13 and Table 13-14 show the OEM-specific targets for Alternative 3. Achieved levels are presented, by manufacturer, in Table 13-15 and Table 13-16.

Table 13-13: Projected GHG Targets, Alternative 3 - Cars

Manufacturer	2027	2028	2029	2030	2031	2032
BMW	140	127	113	100	87	73
Ford	140	126	113	100	87	73
General Motors	138	126	112	99	86	72
Honda	138	126	112	99	86	73
Hyundai	139	126	112	99	86	73
JLR	141	128	114	100	87	74
Kia	139	126	112	99	86	73
Mazda	138	125	112	99	86	73
Mercedes Benz	140	127	114	100	87	74
Mitsubishi	136	124	111	98	85	72
Nissan	138	126	112	99	86	73
Stellantis	140	127	113	100	87	73
Subaru	138	126	112	99	86	72
Tesla	142	129	115	101	88	74
Toyota	138	126	112	99	86	73
Volvo	143	129	115	101	88	74
VW	138	126	112	99	86	73
TOTAL	**139**	**126**	**112**	**99**	**86**	**73**

Table 13-14: Projected GHG Targets, Alternative 3 - Trucks

Manufacturer	2027	2028	2029	2030	2031	2032
BMW	178	159	140	122	104	87
Ford	195	174	154	135	114	95
General Motors	197	174	154	134	113	94
Honda	171	154	136	120	101	84
Hyundai	168	152	134	117	99	83
JLR	181	162	143	125	105	86
Kia	176	152	135	118	100	83
Mazda	164	147	130	115	97	81
Mercedes Benz	175	157	139	122	104	86
Mitsubishi	154	140	125	110	93	77
Nissan	176	158	140	123	104	86
Stellantis	187	166	147	129	110	91
Subaru	163	146	130	114	95	79
Tesla	195	174	153	134	113	93
Toyota	176	158	140	123	104	86
Volvo	174	156	138	120	102	85
VW	173	156	138	121	103	86
TOTAL	**183**	**163**	**144**	**126**	**107**	**89**

Table 13-15: Achieved GHG Levels, Alternative 3 - Cars

Manufacturer	2027	2028	2029	2030	2031	2032
BMW	136	97	85	62	60	56
Ford	117	135	115	88	63	85
General Motors	129	120	99	85	71	65
Honda	120	108	108	96	80	60
Hyundai	133	112	106	93	80	67
JLR	144	173	185	170	153	117
Kia	121	110	106	89	66	57
Mazda	135	107	100	98	89	74
Mercedes Benz	138	101	88	88	81	64
Mitsubishi	114	106	97	90	73	55
Nissan	123	105	106	89	73	54
Stellantis	131	125	119	94	74	68
Subaru	82	90	102	107	97	78
Tesla	0	0	0	0	0	0
Toyota	133	115	104	96	78	58
Volvo	111	88	70	64	67	55
VW	80	68	86	82	70	55
TOTAL	**122**	**110**	**103**	**89**	**73**	**62**

Table 13-16: Achieved GHG Levels, Alternative 3 - Trucks

Manufacturer	2027	2028	2029	2030	2031	2032
BMW	168	157	164	163	129	104
Ford	175	181	155	130	110	84
General Motors	225	191	167	145	124	101
Honda	152	132	120	109	94	87
Hyundai	161	134	126	125	125	98
JLR	188	166	145	146	133	107
Kia	140	120	101	91	80	76
Mazda	159	150	149	130	114	92
Mercedes Benz	196	183	181	147	117	101
Mitsubishi	152	139	127	121	112	96
Nissan	160	137	129	114	95	88
Stellantis	228	185	159	138	118	99
Subaru	144	125	114	118	110	90
Tesla	0	0	0	0	0	0
Toyota	169	164	146	126	111	99
Volvo	191	172	158	151	135	110
VW	183	153	137	135	113	97
TOTAL	**188**	**167**	**147**	**131**	**112**	**94**

13.1.1.2 CO_2 Mg

Shown below are the projected average GHG targets for each manufacturer, as well as their corresponding average achieved compliance, in Mg, for cars, trucks, and the combined fleet. Total emissions are calculated by multiplying the relevant CO_2 emission rate, the production volume of applicable vehicles, and the expected lifetime vehicle miles traveled (VMT) of those vehicles. The equation to calculate total Mg (for either total emissions, or credits based on the difference between target g/mi and achieved g/mi) is:

$$CO_2\ (Mg) = (CO_2\ (g/mi) \times VMT \times Production) / 1{,}000{,}000$$

In the above equation, "VMT" is in miles, and specified in the regulations as 195,264 miles for cars and 225,865 for trucks. When using these equations to calculate values for cars and trucks in aggregate, we use a production weighted average of the car and truck VMT values.

13.1.1.2.1 Proposed standards

OEM-specific GHG emissions targets for the proposed standards (in Mg) are shown in Table 13-17, Table 13-18, and Table 13-19 for cars, trucks, and the combined fleet, respectively. Similarly, projected achieved GHG emissions (in Mg) are given for cars, trucks, and the combined fleet in Table 13-20, Table 13-21, and Table 13-22. Finally, overall credits or debits earned are provided for the combined fleet on a manufacturer-specific basis, in Table 13-23.

Table 13-17: Projected GHG Targets (Mg), Proposed Standards - Cars

Manufacturer	2027	2028	2029	2030	2031	2032
BMW	5,091,076	4,482,814	3,834,746	3,576,737	3,278,332	2,906,949
Ford	12,921,363	11,456,020	9,809,548	9,111,663	8,333,236	7,406,773
General Motors	19,880,592	17,643,576	15,131,637	14,044,454	12,774,852	11,348,172
Honda	20,487,741	18,056,558	15,544,825	14,431,748	13,228,332	11,715,789
Hyundai	15,131,453	13,377,798	11,481,251	10,657,511	9,731,226	8,623,810
JLR	142,373	124,988	107,245	99,111	91,716	81,023
Kia	7,777,133	6,829,572	5,884,835	5,460,408	5,048,145	4,448,328
Mazda	3,138,485	2,788,394	2,401,375	2,248,925	2,046,205	1,818,581
Mercedes Benz	4,467,668	3,945,841	3,387,156	3,159,587	2,874,472	2,557,223
Mitsubishi	1,415,160	1,249,288	1,078,460	1,006,639	912,826	812,341
Nissan	17,778,679	15,730,647	13,535,632	12,590,751	11,537,354	10,227,611
Stellantis	9,353,558	8,264,397	7,106,572	6,588,895	6,011,507	5,312,072
Subaru	2,837,220	2,520,831	2,175,765	2,031,656	1,871,219	1,664,402
Tesla	2,216,521	1,937,768	1,679,457	1,537,450	1,425,760	1,253,596
Toyota	21,992,964	19,429,686	16,718,150	15,492,249	14,242,094	12,605,690
Volvo	583,538	514,381	440,917	406,432	370,516	328,807
VW	7,888,276	6,997,575	6,014,856	5,603,817	5,103,534	4,540,678
TOTAL	**153,473,059**	**135,675,676**	**116,611,884**	**108,309,703**	**99,122,439**	**87,866,548**

Table 13-18: Projected GHG Targets (Mg), Proposed Standards - Trucks

Manufacturer	2027	2028	2029	2030	2031	2032
BMW	4,585,917	4,069,028	3,433,605	3,175,730	2,870,067	2,546,508
Ford	51,565,944	45,145,105	38,266,619	34,833,245	31,508,729	27,924,230
General Motors	62,254,967	53,949,631	46,138,573	41,986,088	38,150,861	33,655,269
Honda	24,788,279	21,874,742	18,689,609	17,185,259	15,683,277	13,780,819
Hyundai	390,487	343,903	293,675	267,065	243,128	213,533
JLR	3,640,854	3,186,197	2,716,766	2,486,827	2,255,786	1,948,220
Kia	6,710,436	5,694,380	4,860,482	4,483,838	4,086,903	3,582,678
Mazda	4,338,956	3,858,754	3,309,762	3,089,838	2,787,793	2,465,273
Mercedes Benz	4,525,924	4,015,467	3,400,141	3,184,025	2,870,676	2,543,195
Mitsubishi	2,034,619	1,824,916	1,578,988	1,475,375	1,324,649	1,179,383
Nissan	16,912,134	14,849,698	12,666,297	11,690,662	10,685,309	9,412,617
Stellantis	63,656,884	55,278,306	47,390,264	43,224,338	39,366,294	34,617,037
Subaru	20,375,971	18,096,047	15,628,506	14,526,483	13,015,614	11,551,607
Tesla	433,602	377,300	322,947	293,310	267,304	234,225
Toyota	42,141,432	36,924,639	31,560,895	28,960,844	26,240,750	23,125,665
Volvo	2,968,623	2,616,517	2,245,552	2,080,273	1,876,706	1,659,992
VW	14,427,239	12,726,343	10,785,567	10,099,673	9,075,062	8,027,615
TOTAL	**326,089,198**	**285,127,535**	**243,539,630**	**223,274,057**	**202,520,153**	**178,654,821**

Table 13-19: Projected GHG Targets (Mg), Proposed Standards - Combined

Manufacturer	2027	2028	2029	2030	2031	2032
BMW	9,676,993	8,551,841	7,268,350	6,752,467	6,148,399	5,453,457
Ford	64,487,307	56,601,125	48,076,167	43,944,908	39,841,965	35,331,003
General Motors	82,135,559	71,593,208	61,270,210	56,030,542	50,925,713	45,003,442
Honda	45,276,019	39,931,300	34,234,435	31,617,007	28,911,609	25,496,608
Hyundai	15,521,940	13,721,702	11,774,926	10,924,576	9,974,354	8,837,343
JLR	3,783,227	3,311,184	2,824,010	2,585,938	2,347,501	2,029,243
Kia	14,487,569	12,523,953	10,745,317	9,944,246	9,135,048	8,031,006
Mazda	7,477,441	6,647,148	5,711,137	5,338,763	4,833,998	4,283,854
Mercedes Benz	8,993,592	7,961,308	6,787,297	6,343,611	5,745,148	5,100,418
Mitsubishi	3,449,779	3,074,204	2,657,449	2,482,014	2,237,475	1,991,724
Nissan	34,690,813	30,580,345	26,201,929	24,281,413	22,222,662	19,640,228
Stellantis	73,010,441	63,542,703	54,496,836	49,813,233	45,377,801	39,929,109
Subaru	23,213,192	20,616,878	17,804,271	16,558,139	14,886,833	13,216,008
Tesla	2,650,122	2,315,069	2,002,404	1,830,760	1,693,065	1,487,821
Toyota	64,134,396	56,354,325	48,279,045	44,453,093	40,482,844	35,731,354
Volvo	3,552,160	3,130,897	2,686,470	2,486,705	2,247,222	1,988,799
VW	22,315,514	19,723,918	16,800,422	15,703,490	14,178,596	12,568,293
TOTAL	**479,562,257**	**420,803,211**	**360,151,514**	**331,583,760**	**301,642,592**	**266,521,369**

Table 13-20: Achieved GHG Levels (Mg), Proposed Standards - Cars

Manufacturer	2027	2028	2029	2030	2031	2032
BMW	5,184,002	4,940,134	3,707,063	2,405,553	1,762,767	1,718,999
Ford	10,201,303	9,938,462	8,459,397	9,183,562	8,208,390	9,696,628
General Motors	15,710,377	11,683,229	11,009,187	11,533,201	10,866,052	9,824,717
Honda	18,224,481	17,981,721	15,777,062	11,143,242	12,602,021	9,462,690
Hyundai	14,688,431	12,772,168	11,052,595	8,703,179	8,178,183	7,702,989
JLR	147,940	106,799	136,883	95,333	91,885	80,326
Kia	7,031,023	6,490,078	5,750,388	4,471,761	3,695,053	3,112,022
Mazda	3,020,258	2,695,925	2,376,712	1,856,574	1,969,680	1,799,619
Mercedes Benz	4,088,748	3,644,510	2,551,652	2,098,035	2,334,299	2,151,849
Mitsubishi	1,138,709	1,031,710	851,708	621,242	628,541	598,267
Nissan	15,546,157	14,008,977	11,832,099	9,627,341	10,989,653	9,233,292
Stellantis	7,875,138	6,236,802	5,240,860	5,824,713	5,778,423	5,536,104
Subaru	1,590,438	1,205,798	2,083,948	1,838,377	1,766,658	1,759,293
Tesla	0	0	0	0	0	0
Toyota	20,031,917	18,383,178	15,496,475	13,781,883	9,471,044	7,789,008
Volvo	445,468	346,723	234,737	207,161	290,394	296,466
VW	6,616,698	4,393,966	2,382,044	3,004,519	3,346,113	1,800,241
TOTAL	**131,933,221**	**116,214,446**	**99,233,987**	**86,595,798**	**82,118,708**	**72,715,073**

Table 13-21: Achieved GHG Levels (Mg), Proposed Standards - Trucks

Manufacturer	2027	2028	2029	2030	2031	2032
BMW	4,933,415	3,758,808	3,995,566	3,923,128	3,967,083	3,451,368
Ford	45,621,962	45,443,335	37,374,958	36,653,276	32,512,389	23,644,934
General Motors	76,759,011	62,804,517	49,903,778	48,132,447	44,461,267	37,700,767
Honda	23,961,309	19,992,389	17,285,982	16,342,784	12,589,264	13,454,573
Hyundai	417,488	355,211	304,444	272,159	323,080	289,316
JLR	3,535,202	3,095,691	2,404,230	2,001,884	2,378,567	2,587,222
Kia	6,583,708	5,434,657	4,803,662	3,670,916	3,525,620	3,485,653
Mazda	4,040,644	3,550,230	3,168,207	2,605,941	2,756,712	2,756,208
Mercedes Benz	5,390,165	4,568,891	4,570,989	3,536,227	2,982,035	3,022,149
Mitsubishi	2,018,519	1,719,915	1,415,167	1,266,103	1,404,174	1,415,397
Nissan	15,595,848	15,318,234	13,805,975	11,747,252	8,009,637	8,071,035
Stellantis	83,272,673	60,765,551	48,776,713	45,837,855	43,286,368	37,305,858
Subaru	19,221,507	16,130,549	12,085,194	10,791,109	13,148,828	13,098,622
Tesla	0	0	0	0	0	0
Toyota	40,607,266	39,383,249	32,982,740	29,204,468	31,307,422	28,737,015
Volvo	3,237,235	2,766,920	2,234,733	1,903,298	2,134,105	2,125,143
VW	14,691,218	14,263,541	13,955,782	10,773,613	9,573,331	10,188,530
TOTAL	**350,286,970**	**299,684,909**	**249,405,966**	**228,964,961**	**214,646,091**	**191,586,773**

Table 13-22: Achieved GHG Levels (Mg), Proposed Standards - Combined

Manufacturer	2027	2028	2029	2030	2031	2032
BMW	10,117,416	8,698,942	7,702,628	6,328,681	5,729,850	5,170,368
Ford	55,823,265	55,381,798	45,834,355	45,836,838	40,720,779	33,341,562
General Motors	92,469,387	74,487,746	60,912,964	59,665,648	55,327,318	47,525,484
Honda	42,185,790	37,974,110	33,063,044	27,486,026	25,191,285	22,917,263
Hyundai	15,105,919	13,127,380	11,357,039	8,975,339	8,501,263	7,992,305
JLR	3,683,142	3,202,489	2,541,113	2,097,217	2,470,452	2,667,548
Kia	13,614,731	11,924,735	10,554,050	8,142,677	7,220,674	6,597,675
Mazda	7,060,902	6,246,154	5,544,919	4,462,514	4,726,391	4,555,827
Mercedes Benz	9,478,913	8,213,402	7,122,640	5,634,262	5,316,334	5,173,998
Mitsubishi	3,157,227	2,751,625	2,266,875	1,887,345	2,032,714	2,013,663
Nissan	31,142,004	29,327,211	25,638,074	21,374,593	18,999,290	17,304,327
Stellantis	91,147,811	67,002,353	54,017,572	51,662,568	49,064,791	42,841,962
Subaru	20,811,946	17,336,347	14,169,142	12,629,485	14,915,486	14,857,915
Tesla	0	0	0	0	0	0
Toyota	60,639,184	57,766,427	48,479,216	42,986,352	40,778,466	36,526,023
Volvo	3,682,703	3,113,643	2,469,470	2,110,458	2,424,499	2,421,609
VW	21,307,916	18,657,507	16,337,825	13,778,132	12,919,444	11,988,770
TOTAL	**482,220,191**	**415,899,355**	**348,639,953**	**315,560,759**	**296,764,799**	**264,301,846**

Table 13-23: GHG Credits/Debits Earned (Mg), Proposed Standards - Combined

Manufacturer	2027	2028	2029	2030	2031	2032
BMW	(440,423)	(147,101)	(434,278)	423,786	418,549	283,089
Ford	8,664,042	1,219,327	2,241,812	(1,891,930)	(878,815)	1,989,441
General Motors	(10,333,828)	(2,894,538)	357,245	(3,635,106)	(4,401,605)	(2,522,042)
Honda	3,090,229	1,957,190	1,171,391	4,130,981	3,720,324	2,579,345
Hyundai	416,021	594,322	417,887	1,949,237	1,473,091	845,037
JLR	100,085	108,695	282,897	488,721	(122,951)	(638,305)
Kia	872,839	599,217	191,267	1,801,569	1,914,374	1,433,331
Mazda	416,539	400,994	166,218	876,248	107,606	(271,973)
Mercedes Benz	(485,322)	(252,093)	(335,343)	709,349	428,814	(73,580)
Mitsubishi	292,552	322,579	390,574	594,669	204,760	(21,939)
Nissan	3,548,808	1,253,133	563,855	2,906,821	3,223,372	2,335,901
Stellantis	(18,137,370)	(3,459,650)	479,264	(1,849,335)	(3,686,990)	(2,912,853)
Subaru	2,401,246	3,280,531	3,635,128	3,928,654	(28,653)	(1,641,906)
Tesla	2,650,122	2,315,069	2,002,404	1,830,760	1,693,065	1,487,821
Toyota	3,495,212	(1,412,102)	(200,171)	1,466,741	(295,622)	(794,669)
Volvo	(130,543)	17,254	217,000	376,246	(177,277)	(432,810)
VW	1,007,598	1,066,411	462,597	1,925,358	1,259,153	579,523
TOTAL	**(2,657,934)**	**4,903,857**	**11,511,560**	**16,023,002**	**4,877,793**	**2,219,523**

13.1.1.2.2 Alternative 1

OEM-specific GHG emissions targets for Alternative 1 (in Mg) are shown in Table 13-24, Table 13-25, and Table 13-26 for cars, trucks, and the combined fleet, respectively. Projected achieved GHG emissions (in Mg) are given for cars, trucks, and the combined fleet in Table 13-27, Table 13-28, and Table 13-29. Overall credits or debits earned are provided for the combined fleet on a manufacturer-specific basis, in Table 13-30.

Table 13-24: Projected GHG Targets (Mg), Alternative 1 - Cars

Manufacturer	2027	2028	2029	2030	2031	2032
BMW	4,715,912	4,095,468	3,433,113	3,175,010	2,883,059	2,500,753
Ford	11,969,168	10,457,110	8,765,952	8,100,730	7,306,502	6,357,537
General Motors	18,412,440	16,095,390	13,535,584	12,473,309	11,217,636	9,763,073
Honda	18,980,636	16,502,990	13,788,858	12,708,885	11,527,714	9,992,768
Hyundai	14,017,005	12,077,115	10,220,210	9,378,705	8,464,206	7,350,186
JLR	131,675	114,328	96,882	88,590	80,982	69,927
Kia	7,201,545	6,232,130	5,278,311	4,854,242	4,430,374	3,822,839
Mazda	2,907,636	2,544,664	2,150,211	1,997,187	1,788,227	1,558,117
Mercedes Benz	4,129,372	3,588,788	3,022,014	2,792,219	2,512,022	2,186,809
Mitsubishi	1,310,555	1,136,117	965,725	893,549	800,451	698,344
Nissan	16,464,577	14,260,660	12,068,886	11,136,075	10,054,007	8,737,265
Stellantis	8,666,061	7,548,045	6,350,572	5,829,098	5,255,007	4,553,709
Subaru	2,629,183	2,303,538	1,957,087	1,810,204	1,648,154	1,434,304
Tesla	2,053,603	1,770,482	1,510,277	1,370,436	1,256,202	1,080,586
Toyota	20,374,547	17,733,633	14,987,767	13,773,540	12,529,396	10,863,132
Volvo	540,625	469,215	395,668	361,053	325,384	282,552
VW	7,329,904	6,379,518	5,354,184	4,958,638	4,473,053	3,891,425
TOTAL	**142,176,558**	**123,605,917**	**104,131,070**	**95,933,187**	**86,763,010**	**75,326,848**

Table 13-25: Projected GHG Targets (Mg), Alternative 1 - Trucks

Manufacturer	2027	2028	2029	2030	2031	2032
BMW	4,283,186	3,753,461	3,158,040	2,884,357	2,545,602	2,214,539
Ford	48,158,011	41,767,919	34,805,720	31,511,863	28,132,374	24,517,570
General Motors	58,156,445	49,916,061	41,961,928	37,920,978	34,018,125	29,590,834
Honda	23,151,909	20,190,094	17,108,580	15,595,575	13,954,226	12,092,369
Hyundai	364,669	313,578	265,345	238,835	215,661	186,009
JLR	3,394,080	2,937,324	2,476,632	2,241,456	2,013,434	1,713,434
Kia	6,269,075	5,234,989	4,420,811	4,028,778	3,639,954	3,132,079
Mazda	4,052,085	3,552,072	3,003,494	2,772,081	2,470,689	2,149,478
Mercedes Benz	4,316,153	3,762,339	3,155,592	2,917,500	2,586,201	2,235,305
Mitsubishi	1,900,510	1,675,776	1,432,531	1,327,023	1,178,954	1,032,051
Nissan	15,814,318	13,680,241	11,522,088	10,528,917	9,369,463	8,125,355
Stellantis	59,455,718	51,086,139	43,097,966	39,035,115	34,994,456	30,316,915
Subaru	19,028,769	16,704,018	14,243,570	13,096,079	11,601,424	10,134,543
Tesla	404,934	348,314	294,368	264,379	238,266	205,273
Toyota	39,359,239	34,035,131	28,652,921	26,008,151	23,293,634	20,213,770
Volvo	2,772,505	2,416,814	2,045,598	1,870,129	1,669,957	1,455,840
VW	13,377,891	11,811,549	9,999,316	9,192,266	8,111,056	7,081,382
TOTAL	**304,574,272**	**263,460,949**	**221,883,111**	**201,649,528**	**180,228,213**	**156,565,782**

Table 13-26: Projected GHG Targets (Mg), Alternative 1 - Combined

Manufacturer	2027	2028	2029	2030	2031	2032
BMW	8,999,098	7,848,929	6,591,153	6,059,368	5,428,661	4,715,291
Ford	60,127,179	52,225,029	43,571,672	39,612,592	35,438,877	30,875,106
General Motors	76,568,885	66,011,451	55,497,512	50,394,287	45,235,761	39,353,907
Honda	42,132,545	36,693,084	30,897,438	28,304,459	25,481,940	22,085,138
Hyundai	14,381,674	12,390,694	10,485,554	9,617,540	8,679,867	7,536,195
JLR	3,525,755	3,051,651	2,573,514	2,330,046	2,094,416	1,783,361
Kia	13,470,620	11,467,119	9,699,122	8,883,020	8,070,327	6,954,919
Mazda	6,959,721	6,096,736	5,153,705	4,769,268	4,258,916	3,707,594
Mercedes Benz	8,445,525	7,351,126	6,177,606	5,709,719	5,098,223	4,422,114
Mitsubishi	3,211,065	2,811,893	2,398,256	2,220,572	1,979,405	1,730,395
Nissan	32,278,895	27,940,901	23,590,974	21,664,991	19,423,470	16,862,620
Stellantis	68,121,778	58,634,184	49,448,538	44,864,213	40,249,464	34,870,624
Subaru	21,657,952	19,007,556	16,200,657	14,906,282	13,249,578	11,568,847
Tesla	2,458,537	2,118,797	1,804,645	1,634,815	1,494,468	1,285,859
Toyota	59,733,786	51,768,764	43,640,688	39,781,691	35,823,030	31,076,902
Volvo	3,313,130	2,886,029	2,441,266	2,231,182	1,995,341	1,738,392
VW	20,707,794	18,191,067	15,353,501	14,150,904	12,584,109	10,972,807
TOTAL	**446,750,829**	**387,066,866**	**326,014,181**	**297,582,715**	**266,991,223**	**231,892,631**

Table 13-27: Achieved GHG Levels (Mg), Alternative 1 - Cars

Manufacturer	2027	2028	2029	2030	2031	2032
BMW	5,168,300	5,021,911	4,213,081	3,008,943	1,959,781	2,076,664
Ford	10,199,352	9,568,639	8,676,175	6,264,726	5,212,193	6,646,973
General Motors	16,000,502	12,313,027	10,299,662	6,895,993	6,133,611	4,371,704
Honda	18,255,203	18,113,465	13,242,767	11,712,532	11,487,093	11,016,306
Hyundai	14,586,338	11,771,265	9,461,300	7,173,378	7,436,478	7,371,139
JLR	145,601	71,876	41,087	23,832	24,740	27,442
Kia	7,170,213	6,353,416	4,900,143	3,946,259	4,190,206	3,865,367
Mazda	3,020,258	2,511,850	1,891,281	1,408,923	1,338,506	1,153,691
Mercedes Benz	4,218,661	3,631,637	2,803,422	2,926,901	2,687,376	2,902,370
Mitsubishi	1,128,811	933,738	765,592	577,902	615,196	576,357
Nissan	15,556,381	12,407,646	10,149,390	8,131,565	6,822,287	5,586,299
Stellantis	7,799,560	5,422,028	5,012,615	5,254,356	3,276,001	3,534,147
Subaru	1,488,842	1,200,961	2,067,695	1,683,921	1,185,604	1,416,150
Tesla	0	0	0	0	0	0
Toyota	20,078,276	16,654,648	13,517,173	8,701,353	5,853,174	4,768,886
Volvo	444,717	341,270	277,674	205,484	252,289	238,511
VW	4,377,868	6,156,898	6,315,660	5,631,838	4,398,316	4,828,647
TOTAL	**130,028,568**	**112,876,738**	**93,996,496**	**73,839,628**	**63,168,254**	**60,733,098**

Table 13-28: Achieved GHG Levels (Mg), Alternative 1 - Trucks

Manufacturer	2027	2028	2029	2030	2031	2032
BMW	4,921,893	3,844,455	2,797,483	2,843,867	4,150,263	4,049,708
Ford	45,622,660	40,666,205	36,336,738	30,197,856	29,205,091	19,903,575
General Motors	75,125,737	53,579,583	46,121,186	39,881,370	39,736,426	32,875,225
Honda	23,913,800	20,137,969	14,755,813	11,634,127	12,546,655	12,104,986
Hyundai	416,319	353,653	287,533	233,852	278,214	263,117
JLR	3,512,983	2,997,842	2,342,875	1,900,124	2,036,885	2,047,225
Kia	6,190,392	5,420,217	4,188,824	3,405,613	3,007,276	3,189,539
Mazda	4,040,644	3,427,540	2,694,651	2,395,456	2,439,562	2,458,476
Mercedes Benz	4,832,578	4,132,026	3,320,636	2,007,296	2,014,283	2,292,319
Mitsubishi	1,992,670	1,513,234	1,237,934	1,037,106	1,046,692	990,505
Nissan	15,077,767	14,067,232	11,450,233	9,407,873	9,822,839	10,173,409
Stellantis	83,002,652	55,802,220	47,072,302	35,826,862	34,897,455	27,403,108
Subaru	19,208,578	16,239,724	12,171,445	10,917,840	12,524,702	11,263,190
Tesla	0	0	0	0	0	0
Toyota	40,475,942	37,559,085	32,182,064	28,014,264	31,066,566	28,542,354
Volvo	3,232,699	2,553,715	2,092,843	1,675,236	1,825,270	1,669,826
VW	16,652,730	12,728,632	8,627,118	7,228,190	8,735,162	8,163,602
TOTAL	**348,616,595**	**275,314,233**	**227,843,395**	**188,749,021**	**195,464,505**	**167,502,242**

Table 13-29: Achieved GHG Levels (Mg), Alternative 1 - Combined

Manufacturer	2027	2028	2029	2030	2031	2032
BMW	10,090,193	8,866,366	7,010,564	5,852,810	6,110,044	6,126,371
Ford	55,822,012	50,234,844	45,012,914	36,462,582	34,417,284	26,550,548
General Motors	91,126,239	65,892,610	56,420,848	46,777,363	45,870,037	37,246,928
Honda	42,169,003	38,251,433	27,998,579	23,346,659	24,033,748	23,121,292
Hyundai	15,002,657	12,124,918	9,748,834	7,407,230	7,714,692	7,634,256
JLR	3,658,584	3,069,719	2,383,963	1,923,956	2,061,625	2,074,667
Kia	13,360,605	11,773,633	9,088,967	7,351,872	7,197,482	7,054,906
Mazda	7,060,902	5,939,390	4,585,933	3,804,379	3,778,068	3,612,168
Mercedes Benz	9,051,239	7,763,663	6,124,058	4,934,197	4,701,659	5,194,689
Mitsubishi	3,121,482	2,446,972	2,003,526	1,615,008	1,661,888	1,566,862
Nissan	30,634,147	26,474,879	21,599,623	17,539,438	16,645,126	15,759,708
Stellantis	90,802,211	61,224,248	52,084,916	41,081,218	38,173,456	30,937,254
Subaru	20,697,420	17,440,685	14,239,140	12,601,762	13,710,305	12,679,340
Tesla	0	0	0	0	0	0
Toyota	60,554,218	54,213,733	45,699,238	36,715,617	36,919,740	33,311,240
Volvo	3,677,416	2,894,986	2,370,517	1,880,720	2,077,559	1,908,337
VW	21,030,598	18,885,531	14,942,778	12,860,028	13,133,478	12,992,248
TOTAL	**478,645,162**	**388,190,970**	**321,839,892**	**262,588,649**	**258,632,759**	**228,235,340**

Table 13-30: GHG Credits/Debits Earned (Mg), Alternative 1 - Combined

Manufacturer	2027	2028	2029	2030	2031	2032
BMW	(1,091,094)	(1,017,437)	(419,411)	206,558	(681,383)	(1,411,080)
Ford	4,305,167	1,990,185	(1,441,242)	3,150,011	1,021,593	4,324,558
General Motors	(14,557,354)	118,841	(923,335)	3,616,924	(634,276)	2,106,979
Honda	(36,458)	(1,558,349)	2,898,858	4,957,801	1,448,192	(1,036,154)
Hyundai	(620,983)	265,776	736,721	2,210,310	965,175	(98,061)
JLR	(132,829)	(18,067)	189,551	406,090	32,791	(291,306)
Kia	110,015	(306,514)	610,155	1,531,149	872,846	(99,987)
Mazda	(101,181)	157,346	567,772	964,889	480,848	95,427
Mercedes Benz	(605,714)	(412,537)	53,548	775,522	396,564	(772,575)
Mitsubishi	89,583	364,921	394,730	605,564	317,518	163,534
Nissan	1,644,747	1,466,022	1,991,351	4,125,554	2,778,345	1,102,912
Stellantis	(22,680,433)	(2,590,064)	(2,636,378)	3,782,995	2,076,007	3,933,370
Subaru	960,532	1,566,871	1,961,517	2,304,521	(460,727)	(1,110,493)
Tesla	2,458,537	2,118,797	1,804,645	1,634,815	1,494,468	1,285,859
Toyota	(820,432)	(2,444,969)	(2,058,550)	3,066,074	(1,096,710)	(2,234,338)
Volvo	(364,286)	(8,957)	70,749	350,462	(82,218)	(169,945)
VW	(322,804)	(694,464)	410,723	1,290,876	(549,369)	(2,019,441)
TOTAL	**(31,894,333)**	**(1,124,105)**	**4,174,289**	**34,994,066**	**8,358,463**	**3,657,291**

13.1.1.2.3 Alternative 2

OEM-specific GHG emissions targets for Alternative 2 (in Mg) are shown in Table 13-31, Table 13-32, and Table 13-33 for cars, trucks, and the combined fleet, respectively. Projected achieved GHG emissions (in Mg) are given for cars, trucks, and the combined fleet in Table 13-34, Table 13-35 and Table 13-36. Overall credits or debits earned are provided for the combined fleet on a manufacturer-specific basis, in Table 13-37.

Table 13-31: Projected GHG Targets (Mg), Alternative 2 - Cars

Manufacturer	2027	2028	2029	2030	2031	2032
BMW	5,469,214	4,861,680	4,226,802	3,956,713	3,669,385	3,294,201
Ford	13,871,182	12,402,818	10,787,026	10,135,481	9,328,046	8,374,326
General Motors	21,333,140	19,075,838	16,632,981	15,562,481	14,305,565	12,869,654
Honda	21,998,539	19,576,358	17,101,232	16,006,107	14,842,440	13,278,261
Hyundai	16,253,251	14,510,923	12,616,228	11,823,749	10,902,857	9,765,831
JLR	152,964	134,837	117,552	109,272	102,293	91,468
Kia	8,342,190	7,423,897	6,483,402	6,068,799	5,665,711	5,047,575
Mazda	3,376,620	3,024,590	2,641,427	2,495,675	2,293,339	2,060,074
Mercedes Benz	4,823,808	4,280,028	3,717,676	3,498,692	3,225,946	2,890,813
Mitsubishi	1,524,614	1,360,804	1,189,443	1,123,928	1,028,481	925,687
Nissan	19,097,856	17,042,314	14,883,071	13,966,983	12,942,559	11,592,418
Stellantis	10,042,227	8,933,164	7,800,186	7,304,187	6,735,133	6,026,082
Subaru	3,048,551	2,726,466	2,392,097	2,255,571	2,099,327	1,887,960
Tesla	2,379,572	2,097,547	1,845,519	1,705,034	1,597,886	1,419,537
Toyota	23,625,937	21,053,675	18,378,670	17,173,140	15,951,385	14,294,321
Volvo	627,487	557,253	484,184	449,931	413,594	371,058
VW	8,497,476	7,575,931	6,596,562	6,208,138	5,717,304	5,138,473
TOTAL	**164,862,483**	**146,991,280**	**128,202,208**	**120,134,023**	**111,091,704**	**99,570,976**

Table 13-32: Projected GHG Targets (Mg), Alternative 2 - Trucks

Manufacturer	2027	2028	2029	2030	2031	2032
BMW	4,874,383	4,323,076	3,739,493	3,491,806	3,171,797	2,833,303
Ford	54,871,678	48,399,568	41,629,787	38,260,278	34,872,121	31,243,376
General Motors	66,200,586	57,866,675	50,116,651	45,983,512	42,132,028	37,584,080
Honda	26,375,695	23,326,611	20,292,367	18,717,165	17,184,933	15,359,871
Hyundai	415,423	368,504	319,480	290,374	268,246	239,035
JLR	3,861,907	3,405,301	2,941,875	2,699,890	2,478,157	2,162,785
Kia	7,141,549	6,102,570	5,303,658	4,889,893	4,512,997	4,004,130
Mazda	4,591,920	4,100,316	3,572,062	3,351,388	3,047,256	2,739,577
Mercedes Benz	4,827,059	4,338,822	3,753,949	3,493,219	3,177,163	2,844,767
Mitsubishi	2,160,085	1,952,476	1,714,869	1,621,689	1,469,880	1,323,791
Nissan	17,970,831	15,893,993	13,793,655	12,756,596	11,691,650	10,517,203
Stellantis	67,632,164	59,309,189	51,548,583	47,284,393	43,414,325	38,602,504
Subaru	21,669,854	19,356,597	16,934,798	15,851,167	14,316,098	12,880,045
Tesla	461,393	404,799	351,674	321,016	295,114	261,607
Toyota	44,778,219	39,531,499	34,318,914	31,597,339	28,927,634	25,764,212
Volvo	3,142,189	2,783,951	2,418,273	2,244,197	2,054,404	1,847,310
VW	15,222,252	13,622,357	11,816,580	11,020,457	10,006,324	8,996,970
TOTAL	**346,554,702**	**305,402,956**	**264,840,896**	**244,126,712**	**223,252,650**	**199,412,853**

Table 13-33: Projected GHG Targets (Mg), Alternative 2 - Combined

Manufacturer	2027	2028	2029	2030	2031	2032
BMW	10,343,596	9,184,756	7,966,295	7,448,519	6,841,182	6,127,504
Ford	68,742,859	60,802,385	52,416,813	48,395,760	44,200,167	39,617,702
General Motors	87,533,726	76,942,513	66,749,631	61,545,993	56,437,593	50,453,735
Honda	48,374,234	42,902,969	37,393,600	34,723,272	32,027,373	28,638,132
Hyundai	16,668,674	14,879,427	12,935,708	12,114,123	11,171,103	10,004,866
JLR	4,014,871	3,540,138	3,059,427	2,809,163	2,580,450	2,254,252
Kia	15,483,739	13,526,467	11,787,060	10,958,692	10,178,709	9,051,705
Mazda	7,968,540	7,124,906	6,213,489	5,847,063	5,340,594	4,799,651
Mercedes Benz	9,650,867	8,618,850	7,471,625	6,991,911	6,403,110	5,735,580
Mitsubishi	3,684,700	3,313,280	2,904,312	2,745,617	2,498,361	2,249,478
Nissan	37,068,687	32,936,307	28,676,726	26,723,579	24,634,209	22,109,621
Stellantis	77,674,391	68,242,352	59,348,769	54,588,579	50,149,458	44,628,587
Subaru	24,718,406	22,083,063	19,326,896	18,106,738	16,415,425	14,768,004
Tesla	2,840,965	2,502,346	2,197,192	2,026,050	1,893,000	1,681,145
Toyota	68,404,155	60,585,174	52,697,584	48,770,479	44,879,019	40,058,533
Volvo	3,769,676	3,341,204	2,902,457	2,694,127	2,467,998	2,218,368
VW	23,719,727	21,198,288	18,413,142	17,228,595	15,723,628	14,135,443
TOTAL	**511,417,185**	**452,394,235**	**393,043,104**	**364,260,735**	**334,344,354**	**298,983,829**

Table 13-34: Achieved GHG Levels (Mg), Alternative 2 - Cars

Manufacturer	2027	2028	2029	2030	2031	2032
BMW	5,105,676	4,889,603	3,613,103	4,216,531	2,795,835	1,971,022
Ford	10,201,303	8,883,099	7,297,873	7,332,114	9,613,798	10,297,965
General Motors	19,024,845	14,318,141	10,790,055	12,801,056	12,975,006	9,205,109
Honda	18,560,569	18,347,050	15,116,493	13,577,307	12,179,055	11,217,735
Hyundai	15,123,166	14,757,149	11,782,992	11,547,657	9,846,254	8,850,667
JLR	150,540	182,172	195,713	182,025	177,289	149,788
Kia	7,066,638	7,315,345	5,684,232	5,527,206	4,423,598	3,660,527
Mazda	3,252,491	2,847,751	2,575,269	2,569,765	2,058,780	1,937,338
Mercedes Benz	4,527,069	5,229,330	4,199,782	3,932,887	3,290,900	3,004,550
Mitsubishi	1,242,324	1,192,627	1,024,298	1,053,640	994,208	888,119
Nissan	16,029,938	14,716,991	11,535,299	11,160,615	9,789,372	10,837,908
Stellantis	9,144,814	7,708,507	6,351,058	6,159,876	6,214,591	6,083,049
Subaru	1,753,093	2,059,809	2,196,640	2,434,815	2,412,697	2,158,722
Tesla	0	0	0	0	0	0
Toyota	20,695,975	18,905,940	15,517,881	14,970,541	11,190,632	7,363,661
Volvo	475,527	397,413	365,880	429,802	492,265	452,220
VW	4,413,531	5,666,221	4,715,916	5,307,779	4,631,177	4,009,794
TOTAL	**137,119,018**	**127,790,627**	**103,203,495**	**103,449,119**	**93,243,983**	**82,241,566**

Table 13-35: Achieved GHG Levels (Mg), Alternative 2 - Trucks

Manufacturer	2027	2028	2029	2030	2031	2032
BMW	4,930,657	4,718,005	4,063,130	3,398,022	3,641,464	3,803,259
Ford	45,621,962	48,792,361	39,809,794	34,058,157	31,871,792	26,978,835
General Motors	79,423,067	60,645,517	52,050,844	47,779,581	44,898,956	42,319,581
Honda	24,219,750	23,585,493	19,725,493	20,683,808	17,876,638	15,601,972
Hyundai	425,591	389,138	314,286	335,737	318,939	257,545
JLR	4,246,111	3,817,254	3,275,656	3,303,225	3,274,016	2,958,815
Kia	6,087,125	6,479,380	5,012,786	4,815,374	3,984,315	3,842,545
Mazda	4,721,984	4,593,587	4,161,409	3,959,667	3,974,306	3,325,501
Mercedes Benz	5,835,654	4,497,741	3,553,066	3,608,339	3,119,039	3,018,782
Mitsubishi	2,289,157	2,163,514	1,848,162	1,819,988	1,683,466	1,487,890
Nissan	16,337,378	16,385,552	14,744,799	14,102,141	12,194,390	8,720,402
Stellantis	87,942,987	61,310,675	50,404,593	46,931,345	45,756,650	41,454,125
Subaru	20,379,483	18,633,599	16,240,229	17,421,692	16,777,726	14,802,405
Tesla	0	0	0	0	0	0
Toyota	42,794,233	43,856,734	35,897,234	34,107,009	33,712,264	32,784,704
Volvo	3,687,748	3,326,090	2,885,865	2,780,807	2,625,992	2,301,162
VW	17,122,920	15,291,343	12,730,842	12,321,264	10,609,378	9,692,149
TOTAL	**366,511,198**	**318,879,007**	**267,101,854**	**251,794,899**	**236,676,089**	**213,659,213**

Table 13-36: Achieved GHG Levels (Mg), Alternative 2 - Combined

Manufacturer	2027	2028	2029	2030	2031	2032
BMW	10,036,333	9,607,608	7,676,233	7,614,553	6,437,299	5,774,282
Ford	55,823,265	57,675,460	47,107,667	41,390,271	41,485,590	37,276,799
General Motors	98,447,913	74,963,658	62,840,899	60,580,637	57,873,962	51,524,690
Honda	42,780,319	41,932,543	34,841,986	34,261,115	30,055,693	26,819,707
Hyundai	15,548,756	15,146,287	12,097,278	11,883,394	10,165,193	9,108,211
JLR	4,396,651	3,999,426	3,471,369	3,485,249	3,451,305	3,108,603
Kia	13,153,763	13,794,726	10,697,018	10,342,580	8,407,914	7,503,072
Mazda	7,974,475	7,441,338	6,736,678	6,529,432	6,033,086	5,262,840
Mercedes Benz	10,362,723	9,727,071	7,752,847	7,541,225	6,409,940	6,023,332
Mitsubishi	3,531,480	3,356,142	2,872,460	2,873,627	2,677,674	2,376,010
Nissan	32,367,316	31,102,544	26,280,098	25,262,757	21,983,762	19,558,310
Stellantis	97,087,801	69,019,182	56,755,651	53,091,221	51,971,241	47,537,175
Subaru	22,132,576	20,693,408	18,436,869	19,856,507	19,190,423	16,961,127
Tesla	0	0	0	0	0	0
Toyota	63,490,208	62,762,675	51,415,114	49,077,550	44,902,896	40,148,365
Volvo	4,163,275	3,723,503	3,251,744	3,210,609	3,118,257	2,753,383
VW	21,536,451	20,957,564	17,446,758	17,629,043	15,240,555	13,701,943
TOTAL	**503,630,216**	**446,669,634**	**370,305,349**	**355,244,019**	**329,920,072**	**295,900,779**

Table 13-37: GHG Credits/Debits Earned (Mg), Alternative 2 - Combined

Manufacturer	2027	2028	2029	2030	2031	2032
BMW	307,263	(422,852)	290,062	(166,034)	403,883	353,223
Ford	12,919,594	3,126,926	5,309,146	7,005,489	2,714,577	2,340,903
General Motors	(10,914,187)	1,978,855	3,908,733	965,356	(1,436,369)	(1,070,955)
Honda	5,593,915	970,426	2,551,614	462,157	1,971,680	1,818,425
Hyundai	1,119,918	(266,860)	838,431	230,729	1,005,910	896,655
JLR	(381,780)	(459,287)	(411,942)	(676,087)	(870,855)	(854,350)
Kia	2,329,976	(268,259)	1,090,042	616,112	1,770,795	1,548,634
Mazda	(5,935)	(316,432)	(523,189)	(682,369)	(692,491)	(463,189)
Mercedes Benz	(711,856)	(1,108,221)	(281,222)	(549,314)	(6,830)	(287,752)
Mitsubishi	153,220	(42,862)	31,853	(128,011)	(179,313)	(126,532)
Nissan	4,701,371	1,833,763	2,396,628	1,460,822	2,650,446	2,551,311
Stellantis	(19,413,410)	(776,830)	2,593,118	1,497,358	(1,821,783)	(2,908,588)
Subaru	2,585,830	1,389,655	890,027	(1,749,769)	(2,774,999)	(2,193,123)
Tesla	2,840,965	2,502,346	2,197,192	2,026,050	1,893,000	1,681,145
Toyota	4,913,947	(2,177,501)	1,282,470	(307,071)	(23,877)	(89,832)
Volvo	(393,599)	(382,299)	(349,288)	(516,482)	(650,259)	(535,015)
VW	2,183,277	240,724	966,384	(400,448)	483,073	433,500
TOTAL	**7,786,969**	**5,724,601**	**22,737,755**	**9,016,716**	**4,424,282**	**3,083,050**

13.1.1.2.4 Alternative 3

OEM-specific GHG emissions targets for Alternative 3 (in Mg) are shown in Table 13-38, Table 13-39 and Table 13-40 for cars, trucks, and the combined fleet, respectively. Projected achieved GHG emissions (in Mg) are given for cars, trucks, and the combined fleet in Table 13-41, Table 13-42 and Table 13-43. Overall credits or debits earned are provided for the combined fleet on a manufacturer-specific basis, in Table 13-44.

Table 13-38: Projected GHG Targets (Mg), Alternative 3 - Cars

Manufacturer	2027	2028	2029	2030	2031	2032
BMW	5,285,122	4,873,075	4,394,626	3,924,647	3,439,604	2,902,799
Ford	13,570,387	12,523,449	11,270,690	10,064,519	8,802,573	7,423,180
General Motors	20,610,721	19,043,434	17,221,033	15,373,039	13,398,569	11,325,060
Honda	21,256,643	19,559,218	17,732,590	15,788,422	13,883,775	11,701,172
Hyundai	15,697,796	14,481,561	13,107,855	11,678,319	10,207,497	8,607,379
JLR	147,763	134,746	122,022	107,920	95,872	80,571
Kia	8,057,872	7,394,385	6,714,875	5,981,034	5,295,728	4,441,962
Mazda	3,262,202	3,022,696	2,743,717	2,466,231	2,148,623	1,816,485
Mercedes Benz	4,658,444	4,301,034	3,879,546	3,466,062	3,026,495	2,556,302
Mitsubishi	1,473,228	1,359,847	1,234,767	1,110,263	960,873	811,180
Nissan	18,465,597	17,021,980	15,437,350	13,786,526	12,108,685	10,210,221
Stellantis	9,702,444	8,936,272	8,082,953	7,219,455	6,323,642	5,314,438
Subaru	2,944,461	2,724,126	2,482,328	2,228,405	1,965,933	1,662,317
Tesla	2,298,366	2,095,565	1,916,197	1,682,907	1,495,627	1,252,096
Toyota	22,838,022	21,040,319	19,070,186	16,963,826	14,925,402	12,579,420
Volvo	605,925	557,011	503,168	444,670	388,627	328,521
VW	8,206,320	7,576,471	6,843,940	6,135,908	5,354,149	4,528,598
TOTAL	**159,465,556**	**146,998,697**	**133,077,194**	**118,708,400**	**104,074,783**	**87,756,322**

Table 13-39: Projected GHG Targets (Mg), Alternative 3 - Trucks

Manufacturer	2027	2028	2029	2030	2031	2032
BMW	5,174,534	4,688,733	4,133,007	3,617,479	3,072,390	2,555,018
Ford	57,112,878	51,351,024	45,633,939	39,786,295	33,542,401	27,797,449
General Motors	70,220,235	62,589,986	55,703,757	48,152,229	40,762,472	33,602,105
Honda	27,954,739	25,317,246	22,608,833	19,755,164	16,706,467	13,755,324
Hyundai	440,748	399,761	355,233	305,250	260,705	214,548
JLR	4,097,075	3,687,553	3,275,655	2,836,819	2,403,802	1,940,308
Kia	7,575,890	6,627,070	5,915,498	5,149,420	4,371,237	3,584,246
Mazda	4,870,021	4,439,460	3,962,927	3,517,865	2,965,832	2,460,570
Mercedes Benz	5,120,628	4,665,184	4,118,753	3,649,433	3,071,236	2,546,343
Mitsubishi	2,292,191	2,118,885	1,912,824	1,700,873	1,419,273	1,177,642
Nissan	19,024,809	17,265,184	15,400,716	13,456,643	11,369,667	9,355,901
Stellantis	71,760,813	63,925,152	57,028,741	49,518,358	42,079,205	34,570,064
Subaru	22,991,091	20,968,641	18,856,756	16,645,752	13,880,967	11,530,262
Tesla	489,496	438,136	391,588	337,153	285,740	233,945
Toyota	47,429,987	42,759,734	38,071,393	33,194,434	28,133,968	23,176,680
Volvo	3,334,762	3,018,117	2,688,958	2,354,484	1,990,161	1,655,698
VW	16,156,068	14,772,853	13,149,076	11,592,204	9,705,859	8,066,856
TOTAL	**366,425,327**	**329,377,366**	**293,514,438**	**255,837,178**	**216,247,848**	**178,410,301**

Table 13-40: Projected GHG Targets (Mg), Alternative 3 - Combined

Manufacturer	2027	2028	2029	2030	2031	2032
BMW	10,459,656	9,561,808	8,527,633	7,542,126	6,511,994	5,457,818
Ford	70,683,265	63,874,473	56,904,628	49,850,814	42,344,974	35,220,629
General Motors	90,830,956	81,633,419	72,924,790	63,525,268	54,161,041	44,927,165
Honda	49,211,382	44,876,464	40,341,423	35,543,586	30,590,242	25,456,496
Hyundai	16,138,544	14,881,322	13,463,088	11,983,569	10,468,202	8,821,926
JLR	4,244,837	3,822,299	3,397,677	2,944,739	2,499,675	2,020,879
Kia	15,633,762	14,021,455	12,630,373	11,130,454	9,666,964	8,026,208
Mazda	8,132,223	7,462,155	6,706,644	5,984,096	5,114,455	4,277,055
Mercedes Benz	9,779,072	8,966,218	7,998,299	7,115,495	6,097,731	5,102,645
Mitsubishi	3,765,418	3,478,732	3,147,590	2,811,136	2,380,146	1,988,821
Nissan	37,490,406	34,287,164	30,838,066	27,243,170	23,478,352	19,566,122
Stellantis	81,463,256	72,861,424	65,111,693	56,737,813	48,402,847	39,884,502
Subaru	25,935,552	23,692,768	21,339,084	18,874,157	15,846,900	13,192,580
Tesla	2,787,862	2,533,701	2,307,784	2,020,059	1,781,366	1,486,041
Toyota	70,268,009	63,800,053	57,141,579	50,158,261	43,059,369	35,756,100
Volvo	3,940,688	3,575,127	3,192,125	2,799,154	2,378,788	1,984,219
VW	24,362,388	22,349,324	19,993,016	17,728,112	15,060,008	12,595,455
TOTAL	**525,890,883**	**476,376,063**	**426,591,633**	**374,545,578**	**320,322,631**	**266,166,623**

Table 13-41: Achieved GHG Levels (Mg), Alternative 3 - Cars

Manufacturer	2027	2028	2029	2030	2031	2032
BMW	5,122,608	3,723,696	3,316,706	2,427,785	2,388,634	2,193,402
Ford	11,428,596	13,374,378	11,505,693	8,870,808	6,405,551	8,646,457
General Motors	19,261,866	18,139,978	15,231,906	13,195,226	11,057,378	10,154,968
Honda	18,508,923	16,833,777	17,151,781	15,281,144	12,807,677	9,592,063
Hyundai	15,023,488	12,913,431	12,389,462	10,932,578	9,458,589	7,907,517
JLR	150,541	182,477	199,136	183,465	168,051	127,522
Kia	7,027,555	6,476,946	6,364,800	5,377,368	4,052,836	3,502,198
Mazda	3,191,379	2,588,172	2,446,509	2,449,434	2,214,032	1,857,681
Mercedes Benz	4,582,955	3,399,151	2,993,679	3,063,475	2,798,163	2,228,552
Mitsubishi	1,238,034	1,166,389	1,087,688	1,012,968	824,452	623,961
Nissan	16,406,441	14,274,531	14,582,847	12,367,993	10,254,480	7,630,987
Stellantis	9,046,443	8,755,000	8,489,537	6,787,025	5,401,155	4,898,269
Subaru	1,752,861	1,961,205	2,278,345	2,427,423	2,218,472	1,803,250
Tesla	0	0	0	0	0	0
Toyota	22,054,465	19,265,683	17,676,074	16,404,593	13,417,064	10,052,010
Volvo	469,995	378,865	303,790	282,409	295,842	241,801
VW	4,736,115	4,114,700	5,234,029	5,092,103	4,332,437	3,450,659
TOTAL	**140,351,610**	**127,846,774**	**121,566,816**	**106,420,718**	**88,267,387**	**75,064,295**

Table 13-42: Achieved GHG Levels (Mg), Alternative 3 - Trucks

Manufacturer	2027	2028	2029	2030	2031	2032
BMW	4,889,445	4,631,937	4,844,028	4,839,472	3,781,585	3,042,950
Ford	51,044,089	53,623,367	45,817,073	38,420,852	32,209,490	24,496,734
General Motors	80,024,637	68,449,896	60,204,636	52,318,739	44,681,980	36,230,079
Honda	24,811,719	21,785,837	19,902,785	17,948,203	15,516,836	14,273,001
Hyundai	423,733	353,406	334,239	327,890	327,557	252,844
JLR	4,249,270	3,773,918	3,323,123	3,313,087	3,034,390	2,423,729
Kia	6,052,204	5,232,723	4,454,594	3,979,499	3,507,331	3,276,886
Mazda	4,732,642	4,516,972	4,556,364	3,993,427	3,469,286	2,802,417
Mercedes Benz	5,732,844	5,439,695	5,368,625	4,407,064	3,461,554	2,985,645
Mitsubishi	2,267,508	2,098,074	1,940,013	1,873,009	1,706,556	1,462,008
Nissan	17,359,113	14,987,762	14,164,169	12,453,475	10,368,235	9,563,360
Stellantis	87,581,743	71,424,347	61,552,271	52,758,827	45,300,693	37,540,415
Subaru	20,261,349	17,948,795	16,583,953	17,303,578	16,071,044	13,100,879
Tesla	0	0	0	0	0	0
Toyota	45,504,316	44,368,723	39,779,548	34,208,098	30,024,708	26,516,260
Volvo	3,659,143	3,334,636	3,081,382	2,956,352	2,642,680	2,151,899
VW	17,049,204	14,423,842	12,992,355	12,918,564	10,613,742	9,185,490
TOTAL	**376,086,754**	**336,747,041**	**299,243,957**	**264,320,009**	**227,027,890**	**189,566,862**

Table 13-43: Achieved GHG Levels (Mg), Alternative 3 - Combined

Manufacturer	2027	2028	2029	2030	2031	2032
BMW	10,012,053	8,355,633	8,160,734	7,267,256	6,170,219	5,236,352
Ford	62,472,685	66,997,745	57,322,766	47,291,660	38,615,041	33,143,191
General Motors	99,286,504	86,589,874	75,436,543	65,513,965	55,739,359	46,385,047
Honda	43,320,642	38,619,613	37,054,565	33,229,347	28,324,513	23,865,063
Hyundai	15,447,221	13,266,837	12,723,701	11,260,468	9,786,146	8,160,361
JLR	4,399,811	3,956,395	3,522,259	3,496,552	3,202,441	2,551,251
Kia	13,079,760	11,709,669	10,819,395	9,356,867	7,560,167	6,779,084
Mazda	7,924,021	7,105,145	7,002,872	6,442,861	5,683,317	4,660,098
Mercedes Benz	10,315,799	8,838,845	8,362,304	7,470,539	6,259,717	5,214,198
Mitsubishi	3,505,542	3,264,463	3,027,701	2,885,977	2,531,008	2,085,969
Nissan	33,765,554	29,262,292	28,747,015	24,821,468	20,622,716	17,194,347
Stellantis	96,628,186	80,179,348	70,041,808	59,545,853	50,701,847	42,438,684
Subaru	22,014,209	19,909,999	18,862,298	19,731,001	18,289,517	14,904,129
Tesla	0	0	0	0	0	0
Toyota	67,558,781	63,634,406	57,455,622	50,612,691	43,441,772	36,568,269
Volvo	4,129,138	3,713,501	3,385,171	3,238,760	2,938,522	2,393,700
VW	21,785,319	18,538,542	18,226,384	18,010,668	14,946,179	12,636,149
TOTAL	**516,438,364**	**464,593,815**	**420,810,773**	**370,740,727**	**315,295,277**	**264,631,157**

Table 13-44: GHG Credits/Debits Earned (Mg), Alternative 3 - Combined

Manufacturer	2027	2028	2029	2030	2031	2032
BMW	447,603	1,206,175	366,899	274,870	341,775	221,466
Ford	8,210,580	(3,123,272)	(418,137)	2,559,154	3,729,933	2,077,438
General Motors	(8,455,548)	(4,956,455)	(2,511,753)	(1,988,697)	(1,578,318)	(1,457,882)
Honda	5,890,740	6,256,851	3,286,858	2,314,239	2,265,730	1,591,433
Hyundai	691,324	1,614,485	739,387	723,102	682,056	661,566
JLR	(154,973)	(134,096)	(124,582)	(551,813)	(702,767)	(530,371)
Kia	2,554,002	2,311,786	1,810,979	1,773,587	2,106,797	1,247,123
Mazda	208,202	357,011	(296,229)	(458,764)	(568,862)	(383,043)
Mercedes Benz	(536,726)	127,373	(364,005)	(355,044)	(161,987)	(111,553)
Mitsubishi	259,877	214,269	119,889	(74,841)	(150,862)	(97,148)
Nissan	3,724,852	5,024,872	2,091,050	2,421,702	2,855,636	2,371,776
Stellantis	(15,164,930)	(7,317,924)	(4,930,115)	(2,808,040)	(2,299,000)	(2,554,181)
Subaru	3,921,342	3,782,768	2,476,786	(856,844)	(2,442,617)	(1,711,549)
Tesla	2,787,862	2,533,701	2,307,784	2,020,059	1,781,366	1,486,041
Toyota	2,709,229	165,647	(314,043)	(454,430)	(382,403)	(812,169)
Volvo	(188,450)	(138,374)	(193,046)	(439,606)	(559,735)	(409,481)
VW	2,577,069	3,810,783	1,766,632	(282,556)	113,829	(40,695)
TOTAL	**9,452,518**	**11,782,248**	**5,780,860**	**3,804,851**	**5,027,354**	**1,535,466**

13.1.2 Projected Manufacturing Costs per Vehicle

EPA has performed an assessment of the estimated per-vehicle production costs for manufacturers to meet the proposed MY 2027-2032 standards, relative to the No Action case. The fleet average costs per vehicle have been grouped, as in past rules, by regulatory class. EPA's OMEGA model also tracks vehicles by body style (sedans, crossovers/SUVs and pickups). We have included summary tables in this format. The costs in this section represent compliance costs to the industry and are not necessarily the same as the costs experienced by the consumer when purchasing a new vehicle. For example, the costs presented here do not include any state and Federal purchase incentives that are available to consumers. Also, the manufacturer decisions for the pricing of individual vehicles may not align exactly with the production cost impacts for that particular vehicle. EPA's OMEGA model assumes that manufacturers distribute compliance costs through limited cross-subsidization of prices between vehicles in order to maintain an appropriate mix of debit- and credit-generating vehicles that achieves compliance in a cost-minimizing fashion.

13.1.2.1 Proposed GHG Standards

Incremental costs per vehicle for the proposed standards (compared to the No Action case) are summarized by regulatory class in Table 13-45 and by body style in Table 13-46.

Table 13-45: Projected Manufacturing Costs Per Vehicle, Proposed Standards

	2027	2028	2029	2030	2031	2032
Cars	$249	$102	$32	$100	$527	$844
Trucks	$891	$767	$653	$821	$1,100	$1,385
Total	**$633**	**$497**	**$401**	**$526**	**$866**	**$1,164**

Table 13-46: Projected Manufacturing Costs Per Vehicle, Proposed Standards (by Body Style)

	2027	2028	2029	2030	2031	2032
Sedans	$181	$79	$51	$194	$625	$1,015
Crossovers/SUVs	$657	$448	$332	$487	$804	$962
Pickups	$1,374	$1,478	$1,333	$1,324	$1,574	$2,266
Total	**$633**	**$497**	**$401**	**$526**	**$866**	**$1,164**

Incremental costs per vehicle for the proposed standards, compared to the No Action case, are shown for each OEM in Table 13-47, Table 13-48, and Table 13-49 for cars, trucks, and the combined fleet, respectively.[193,194]

[193] Only manufacturers with annual sales exceeding 25,000 units are provided in these tables. However, the industry sales-weighted average includes all vehicles and manufacturers (even those not shown).

[194] Some manufacturers in these tables show manufacturing costs for the proposed standards are projected to be lower than in the No Action case. This reflects the combined effects of cost learning with the higher accumulated battery production under the proposed standards, and more ICE technology applied by some manufacturers in the No Action case.

Table 13-47: Projected Manufacturing Costs Per Vehicle, Proposed Standards - Cars

Manufacturer	2027	2028	2029	2030	2031	2032
BMW	$596	$367	$202	$449	$609	$847
Ford	$972	$940	$649	$764	$772	$508
General Motors	$1,206	$1,131	$854	$196	$72	$363
Honda	-$1,146	-$1,314	-$1,232	-$694	$465	$962
Hyundai	$962	$461	$335	$462	$762	$983
JLR	$268	-$1,791	-$1,716	-$1,501	-$1,604	-$1,668
Kia	$895	$416	$317	$608	$948	$1,120
Mazda	-$666	-$723	-$646	-$373	$455	$740
Mercedes Benz	$1,984	$1,388	$864	$919	$1,250	$880
Mitsubishi	$988	$524	$437	$892	$977	$1,138
Nissan	$378	$211	$171	$308	$336	$785
Stellantis	-$501	-$536	-$700	-$278	-$392	$617
Subaru	$8	-$168	-$12	$168	$418	$633
Tesla	-$50	-$316	-$444	-$528	-$580	-$630
Toyota	-$612	-$539	-$469	-$455	$924	$1,269
Volvo	$3,185	$2,475	$1,207	-$306	$567	$686
VW	$246	$578	$1,071	$713	$749	$1,325
TOTAL	**$249**	**$102**	**$32**	**$100**	**$527**	**$844**

Table 13-48: Projected Manufacturing Costs Per Vehicle, Proposed Standards - Trucks

Manufacturer	2027	2028	2029	2030	2031	2032
BMW	$650	$798	$457	$468	$656	$895
Ford	$2,840	$2,539	$2,199	$1,953	$2,102	$2,220
General Motors	$265	$115	$196	$643	$948	$1,383
Honda	-$913	-$862	-$523	-$452	$1,191	$1,217
Hyundai	$1,892	$1,448	$1,095	$1,022	$450	$721
JLR	$2,421	$1,919	$1,481	$1,522	$1,573	$1,053
Kia	$1,835	$853	$638	$975	$1,136	$1,276
Mazda	$1,600	$1,169	$861	$1,054	$1,086	$1,200
Mercedes Benz	$754	$914	$365	$697	$1,018	$1,091
Mitsubishi	-$1,092	$588	$541	$782	$656	$767
Nissan	$1,055	$642	$542	$706	$1,394	$1,560
Stellantis	$293	$607	$537	$605	$815	$1,339
Subaru	$1,420	$1,117	$1,019	$1,328	$856	$1,009
Tesla	-$62	-$392	-$550	-$654	-$719	-$780
Toyota	$1,130	$875	$669	$816	$777	$1,203
Volvo	$527	$608	$455	$820	$837	$1,015
VW	$758	$225	-$288	$366	$787	$785
TOTAL	**$891**	**$767**	**$653**	**$821**	**$1,100**	**$1,385**

Table 13-49: Projected Manufacturing Costs Per Vehicle, Proposed Standards - Combined

Manufacturer	2027	2028	2029	2030	2031	2032
BMW	$618	$539	$303	$456	$628	$866
Ford	$2,321	$2,093	$1,764	$1,616	$1,722	$1,730
General Motors	$572	$448	$412	$494	$655	$1,040
Honda	-$1,035	-$1,098	-$895	-$580	$805	$1,081
Hyundai	$981	$480	$350	$472	$756	$978
JLR	$2,312	$1,729	$1,316	$1,365	$1,405	$909
Kia	$1,263	$587	$441	$749	$1,019	$1,180
Mazda	$514	$260	$134	$362	$779	$976
Mercedes Benz	$1,452	$1,183	$650	$824	$1,152	$969
Mitsubishi	-$143	$559	$493	$833	$804	$938
Nissan	$657	$388	$322	$469	$761	$1,095
Stellantis	$156	$408	$320	$447	$598	$1,209
Subaru	$1,210	$925	$864	$1,152	$789	$951
Tesla	-$52	-$325	-$457	-$542	-$596	-$647
Toyota	$407	$286	$192	$280	$839	$1,231
Volvo	$1,069	$990	$609	$587	$781	$947
VW	$541	$375	$292	$515	$771	$1,019
TOTAL	**$633**	**$497**	**$401**	**$526**	**$866**	**$1,164**

13.1.2.2 Alternative 1

Incremental costs per vehicle for Alternative 1 (compared to the No Action case) are summarized by regulatory class in Table 13-50 and by body style in Table 13-51.

Table 13-50: Projected Manufacturing Costs Per Vehicle, Alternative 1

	2027	2028	2029	2030	2031	2032
Cars	$290	$382	$649	$752	$1,290	$1,461
Trucks	$922	$1,085	$1,436	$1,609	$1,751	$1,989
Total	**$668**	**$804**	**$1,120**	**$1,262**	**$1,565**	**$1,775**

Table 13-51: Projected Manufacturing Costs Per Vehicle, Alternative 1 (by Body Style)

	2027	2028	2029	2030	2031	2032
Sedans	$204	$276	$480	$601	$1,143	$1,301
Crossovers/SUVs	$704	$740	$1,228	$1,422	$1,788	$2,056
Pickups	$1,382	$2,033	$1,871	$1,866	$1,469	$1,544
Total	**$668**	**$804**	**$1,120**	**$1,262**	**$1,565**	**$1,775**

Incremental costs per vehicle for Alternative 1, compared to the No Action case, are shown for each OEM in Table 13-52, Table 13-53, and Table 13-54 for cars, trucks, and the combined fleet, respectively.[195]

[195] Only manufacturers with annual sales exceeding 25,000 units are provided in these tables. However, the industry sales-weighted average includes all vehicles and manufacturers (even those not shown).

Table 13-52: Projected Manufacturing Costs Per Vehicle, Alternative 1 - Cars

Manufacturer	2027	2028	2029	2030	2031	2032
BMW	$592	$333	$753	$814	$731	$970
Ford	$960	$1,033	$1,437	$1,825	$1,661	$1,480
General Motors	$1,311	$1,195	$1,330	$743	$831	$1,123
Honda	-$1,152	-$1,331	-$347	-$232	$1,065	$1,217
Hyundai	$982	$1,466	$1,297	$1,587	$1,738	$1,843
JLR	$690	$400	-$177	-$479	-$540	-$650
Kia	$836	$462	$621	$840	$946	$1,034
Mazda	-$666	-$472	-$16	$148	$1,400	$1,561
Mercedes Benz	$1,385	$1,668	$1,743	$1,667	$2,200	$1,608
Mitsubishi	$1,018	$878	$720	$932	$951	$1,134
Nissan	$374	$1,115	$1,008	$1,077	$1,964	$2,186
Stellantis	-$477	-$306	-$639	$186	$760	$1,595
Subaru	$51	-$166	-$15	$312	$867	$919
Tesla	-$50	-$314	-$470	-$544	-$619	-$665
Toyota	-$619	-$233	$229	$478	$1,452	$1,717
Volvo	$3,183	$2,438	$1,582	-$55	$784	$987
VW	$1,146	$141	$832	$680	$893	$904
TOTAL	**$290**	**$382**	**$649**	**$752**	**$1,290**	**$1,461**

Table 13-53: Projected Manufacturing Costs Per Vehicle, Alternative 1 - Trucks

Manufacturer	2027	2028	2029	2030	2031	2032
BMW	$660	$748	$932	$971	$567	$636
Ford	$2,840	$2,803	$2,756	$2,519	$2,657	$2,747
General Motors	$334	$593	$932	$1,387	$1,476	$1,741
Honda	-$906	-$880	$1,784	$1,618	$2,745	$2,872
Hyundai	$1,902	$1,432	$1,132	$1,161	$741	$933
JLR	$2,795	$2,257	$2,413	$2,309	$2,426	$2,061
Kia	$2,031	$1,113	$1,184	$1,331	$1,560	$1,632
Mazda	$1,600	$1,340	$1,461	$1,457	$2,088	$2,176
Mercedes Benz	$2,512	$2,329	$1,923	$2,073	$2,156	$1,618
Mitsubishi	-$1,035	$1,237	$1,061	$1,373	$1,449	$1,687
Nissan	$1,187	$1,380	$1,515	$1,582	$1,631	$1,758
Stellantis	$311	$936	$1,458	$1,749	$1,964	$2,379
Subaru	$1,422	$1,105	$995	$1,302	$912	$1,262
Tesla	-$62	-$389	-$582	-$673	-$767	-$824
Toyota	$1,142	$1,143	$828	$1,018	$901	$1,215
Volvo	$532	$982	$724	$1,474	$1,574	$1,858
VW	$176	$579	$1,111	$1,446	$1,445	$1,707
TOTAL	**$922**	**$1,085**	**$1,436**	**$1,609**	**$1,751**	**$1,989**

Table 13-54: Projected Manufacturing Costs Per Vehicle, Alternative 1 - Combined

Manufacturer	2027	2028	2029	2030	2031	2032
BMW	$619	$498	$824	$876	$667	$840
Ford	$2,317	$2,309	$2,385	$2,322	$2,372	$2,384
General Motors	$652	$791	$1,063	$1,172	$1,260	$1,533
Honda	-$1,034	-$1,116	$665	$642	$1,853	$1,992
Hyundai	$1,000	$1,466	$1,294	$1,579	$1,719	$1,826
JLR	$2,688	$2,163	$2,280	$2,164	$2,270	$1,918
Kia	$1,304	$716	$840	$1,029	$1,180	$1,262
Mazda	$514	$470	$749	$823	$1,753	$1,876
Mercedes Benz	$1,872	$1,953	$1,820	$1,840	$2,182	$1,612
Mitsubishi	-$98	$1,073	$905	$1,171	$1,220	$1,432
Nissan	$709	$1,224	$1,215	$1,281	$1,830	$2,015
Stellantis	$175	$719	$1,089	$1,470	$1,748	$2,237
Subaru	$1,218	$915	$843	$1,152	$905	$1,210
Tesla	-$52	-$323	-$483	-$559	-$636	-$684
Toyota	$411	$570	$577	$790	$1,135	$1,429
Volvo	$1,074	$1,280	$900	$1,158	$1,410	$1,677
VW	$587	$393	$992	$1,117	$1,205	$1,359
TOTAL	**$668**	**$804**	**$1,120**	**$1,262**	**$1,565**	**$1,775**

13.1.2.3 Alternative 2

Incremental costs per vehicle for Alternative 2 (compared to the No Action case) are summarized by regulatory class in Table 13-55 and by body style in Table 13-56.

Table 13-55: Projected Manufacturing Costs Per Vehicle, Alternative 2

	2027	2028	2029	2030	2031	2032
Cars	$129	-$77	-$6	-$95	$417	$745
Trucks	$686	$651	$599	$637	$927	$1,246
Total	**$462**	**$355**	**$353**	**$337**	**$718**	**$1,041**

Table 13-56: Projected Manufacturing Costs Per Vehicle, Alternative 2 (by Body Style)

	2027	2028	2029	2030	2031	2032
Sedans	$106	-$74	$16	$8	$556	$827
Crossovers/SUVs	$391	$233	$263	$250	$599	$1,029
Pickups	$1,406	$1,656	$1,353	$1,328	$1,511	$1,503
Total	**$462**	**$355**	**$353**	**$337**	**$718**	**$1,041**

Incremental costs per vehicle for Alternative 2, compared to the No Action case, are shown for each OEM in Table 13-57, Table 13-58, and Table 13-59 for cars, trucks, and the combined fleet, respectively.

Table 13-57: Projected Manufacturing Costs Per Vehicle, Alternative 2 - Cars

Manufacturer	2027	2028	2029	2030	2031	2032
BMW	$498	$201	-$143	-$87	$340	$758
Ford	$972	$1,093	$794	$949	$569	$343
General Motors	$903	$1,048	$892	$184	-$115	$474
Honda	-$1,230	-$1,367	-$1,148	-$916	$548	$808
Hyundai	$857	$51	$285	$58	$576	$896
JLR	$220	-$3,168	-$2,820	-$2,743	-$2,861	-$2,784
Kia	$883	-$25	$226	$203	$680	$924
Mazda	-$952	-$877	-$787	-$838	$614	$950
Mercedes Benz	$536	-$349	-$140	-$109	$314	$552
Mitsubishi	$678	$245	$214	-$75	$106	$399
Nissan	$279	$123	$253	$149	$576	$584
Stellantis	-$910	-$768	-$766	-$265	-$389	$558
Subaru	-$60	-$183	-$47	-$223	-$30	$352
Tesla	-$50	-$257	-$361	-$451	-$488	-$534
Toyota	-$717	-$573	-$423	-$469	$837	$1,385
Volvo	$3,311	$2,790	$1,863	$75	$111	$317
VW	$1,131	$227	$573	$241	$499	$776
TOTAL	**$129**	**-$77**	**-$6**	**-$95**	**$417**	**$745**

Table 13-58: Projected Manufacturing Costs Per Vehicle, Alternative 2 - Trucks

Manufacturer	2027	2028	2029	2030	2031	2032
BMW	$476	$84	$332	$643	$772	$725
Ford	$2,840	$2,609	$2,268	$1,897	$2,043	$2,273
General Motors	$131	$286	$174	$693	$984	$1,178
Honda	-$956	-$1,290	-$727	-$866	$643	$999
Hyundai	$1,821	$1,272	$1,107	$794	$553	$1,027
JLR	$2,015	$1,761	$1,510	$1,428	$1,459	$1,031
Kia	$2,082	$289	$545	$483	$956	$1,141
Mazda	$918	$403	$281	$221	$280	$815
Mercedes Benz	$383	$991	$876	$703	$1,011	$1,190
Mitsubishi	-$1,679	-$152	-$15	$37	$284	$714
Nissan	$854	$461	$432	$358	$700	$1,534
Stellantis	-$22	$608	$531	$566	$725	$1,148
Subaru	$1,218	$838	$731	$687	$391	$798
Tesla	-$62	-$318	-$447	-$559	-$604	-$662
Toyota	$915	$615	$572	$590	$721	$929
Volvo	-$52	$92	$33	$196	$477	$900
VW	$23	$28	-$38	$136	$660	$1,015
TOTAL	**$686**	**$651**	**$599**	**$637**	**$927**	**$1,246**

Table 13-59: Projected Manufacturing Costs Per Vehicle, Alternative 2 - Combined

Manufacturer	2027	2028	2029	2030	2031	2032
BMW	$489	$155	$46	$202	$509	$745
Ford	$2,321	$2,186	$1,854	$1,628	$1,622	$1,720
General Motors	$383	$536	$411	$523	$617	$942
Honda	-$1,099	-$1,330	-$948	-$892	$593	$898
Hyundai	$876	$75	$300	$72	$575	$898
JLR	$1,924	$1,510	$1,287	$1,211	$1,231	$830
Kia	$1,352	$98	$349	$311	$786	$1,006
Mazda	$22	-$212	-$234	-$292	$442	$881
Mercedes Benz	$470	$230	$296	$238	$609	$822
Mitsubishi	-$603	$29	$90	-$15	$202	$569
Nissan	$516	$262	$326	$233	$626	$965
Stellantis	-$175	$368	$303	$418	$525	$1,041
Subaru	$1,028	$686	$614	$549	$326	$729
Tesla	-$52	-$264	-$371	-$464	-$501	-$549
Toyota	$237	$120	$155	$143	$770	$1,123
Volvo	$635	$644	$409	$171	$401	$779
VW	$493	$113	$223	$181	$590	$911
TOTAL	**$462**	**$355**	**$353**	**$337**	**$718**	**$1,041**

13.1.2.4 Alternative 3

Incremental costs per vehicle for Alternative 3 (compared to the No Action case) are summarized by regulatory class in Table 13-60 and by body style in Table 13-61.

Table 13-60: Projected Manufacturing Costs Per Vehicle, Alternative 3

	2027	2028	2029	2030	2031	2032
Cars	$27	-$42	-$194	-$84	$539	$945
Trucks	$296	$238	$208	$481	$980	$1,471
Total	**$189**	**$125**	**$45**	**$250**	**$800**	**$1,256**

Table 13-61: Projected Manufacturing Costs Per Vehicle, Alternative 3 (by Body Style)

	2027	2028	2029	2030	2031	2032
Sedans	-$21	-$28	-$208	-$65	$562	$1,030
Crossovers/SUVs	$251	$122	$58	$288	$786	$1,142
Pickups	$320	$421	$467	$698	$1,311	$2,148
Total	**$189**	**$125**	**$45**	**$250**	**$800**	**$1,256**

Incremental costs per vehicle for Alternative 3, compared to the No Action case, are shown for each OEM in Table 13-62, Table 13-63, and Table 13-64 for cars, trucks, and the combined fleet, respectively.

Table 13-62: Projected Manufacturing Costs Per Vehicle, Alternative 3 - Cars

Manufacturer	2027	2028	2029	2030	2031	2032
BMW	$385	$233	-$206	$288	$433	$716
Ford	$339	$138	$136	$728	$1,095	$858
General Motors	$866	$813	$768	$297	$233	$481
Honda	-$1,221	-$1,138	-$1,304	-$999	$559	$1,080
Hyundai	$881	$456	$165	$197	$693	$1,091
JLR	$220	-$3,151	-$2,827	-$2,703	-$2,698	-$2,439
Kia	$901	$372	$113	$373	$909	$1,060
Mazda	-$882	-$644	-$701	-$696	$375	$806
Mercedes Benz	$500	$433	$180	$202	$538	$987
Mitsubishi	$692	$287	$106	$97	$603	$1,198
Nissan	$197	$215	-$126	$54	$568	$1,153
Stellantis	-$879	-$1,015	-$1,052	-$338	-$245	$861
Subaru	-$60	-$147	-$58	-$133	$199	$723
Tesla	-$50	-$206	-$285	-$323	-$383	-$470
Toyota	-$933	-$593	-$579	-$599	$647	$1,165
Volvo	$3,296	$2,746	$1,989	-$199	$954	$1,223
VW	$1,002	$730	$493	$347	$629	$972
TOTAL	**$27**	**-$42**	**-$194**	**-$84**	**$539**	**$945**

Table 13-63: Projected Manufacturing Costs Per Vehicle, Alternative 3 - Trucks

Manufacturer	2027	2028	2029	2030	2031	2032
BMW	$527	$186	$25	$1	$788	$1,295
Ford	$483	$237	$386	$576	$1,193	$1,767
General Motors	$98	$86	$132	$721	$1,197	$1,701
Honda	-$1,056	-$1,034	-$700	-$482	$1,002	$1,232
Hyundai	$1,838	$1,515	$1,069	$900	$629	$1,191
JLR	$2,013	$1,800	$1,557	$1,514	$1,590	$1,920
Kia	$2,099	$1,028	$895	$1,001	$1,307	$1,520
Mazda	$906	$479	$62	$268	$703	$1,274
Mercedes Benz	$469	$111	-$282	$112	$685	$1,075
Mitsubishi	-$1,632	-$4	-$122	$67	$343	$829
Nissan	$597	$762	$565	$723	$1,128	$1,536
Stellantis	$3	$93	$103	$380	$793	$1,368
Subaru	$1,239	$943	$739	$767	$530	$1,094
Tesla	-$62	-$255	-$353	-$401	-$474	-$582
Toyota	$647	$594	$396	$671	$1,033	$1,491
Volvo	-$15	$78	-$70	$163	$550	$1,120
VW	$42	$242	-$37	$127	$770	$1,227
TOTAL	**$296**	**$238**	**$208**	**$481**	**$980**	**$1,471**

Table 13-64: Projected Manufacturing Costs Per Vehicle, Alternative 3 - Combined

Manufacturer	2027	2028	2029	2030	2031	2032
BMW	$441	$214	-$115	$175	$572	$942
Ford	$443	$209	$316	$619	$1,165	$1,506
General Motors	$348	$325	$341	$580	$875	$1,291
Honda	-$1,142	-$1,088	-$1,017	-$754	$767	$1,151
Hyundai	$900	$476	$182	$210	$691	$1,093
JLR	$1,922	$1,548	$1,331	$1,295	$1,364	$1,689
Kia	$1,370	$628	$417	$615	$1,061	$1,235
Mazda	$49	-$60	-$306	-$199	$543	$1,046
Mercedes Benz	$487	$294	-$18	$164	$601	$1,024
Mitsubishi	-$571	$129	-$17	$81	$462	$999
Nissan	$362	$440	$156	$325	$793	$1,307
Stellantis	-$150	-$100	-$100	$252	$607	$1,277
Subaru	$1,045	$781	$620	$631	$479	$1,037
Tesla	-$52	-$211	-$293	-$332	-$393	-$482
Toyota	-$9	$99	-$12	$135	$869	$1,352
Volvo	$661	$624	$353	$88	$634	$1,141
VW	$449	$449	$189	$221	$709	$1,116
TOTAL	**$189**	**$125**	**$45**	**$250**	**$800**	**$1,256**

13.1.3 <u>Technology Penetration Rates</u>

Presented below are the projected technology penetration rates, by manufacturer, for cars and trucks, for the No Action case, and the proposed standards and alternatives.

Tables are provided by manufacturer and regulatory class for BEV penetrations. Summary tables for strong HEV penetrations and a few key ICE technology groupings (TURB12 and Atkinson engines) are also provided.

13.1.3.1 No Action Case

Table 13-65 through Table 13-67 give BEV penetrations for the No Action case, by manufacturer.

Table 13-65: Projected BEV Penetrations, No Action - Cars

Manufacturer	2027	2028	2029	2030	2031	2032
BMW	32%	37%	48%	48%	45%	44%
Ford	38%	31%	36%	37%	38%	37%
General Motors	30%	34%	39%	45%	43%	41%
Honda	37%	39%	44%	44%	43%	42%
Hyundai	29%	37%	42%	44%	43%	42%
JLR	39%	58%	78%	86%	86%	85%
Kia	33%	38%	43%	45%	44%	43%
Mazda	37%	40%	44%	45%	43%	41%
Mercedes Benz	36%	40%	44%	45%	43%	42%
Mitsubishi	30%	34%	39%	42%	40%	39%
Nissan	31%	37%	42%	43%	42%	41%
Stellantis	30%	36%	39%	40%	39%	38%
Subaru	51%	45%	48%	47%	44%	42%
Tesla	100%	100%	100%	100%	100%	100%
Toyota	36%	38%	42%	43%	41%	40%
Volvo	37%	48%	49%	48%	45%	45%
VW	39%	42%	37%	42%	41%	41%
TOTAL	**35%**	**38%**	**42%**	**44%**	**43%**	**42%**

Table 13-66: Projected BEV Penetrations, No Action - Trucks

Manufacturer	2027	2028	2029	2030	2031	2032
BMW	26%	33%	32%	36%	38%	38%
Ford	26%	25%	31%	34%	35%	35%
General Motors	18%	26%	30%	34%	35%	36%
Honda	22%	29%	36%	39%	39%	39%
Hyundai	16%	27%	34%	38%	39%	39%
JLR	26%	31%	35%	36%	36%	35%
Kia	27%	33%	40%	42%	41%	41%
Mazda	20%	28%	35%	39%	39%	39%
Mercedes Benz	20%	29%	36%	39%	39%	39%
Mitsubishi	23%	32%	38%	41%	40%	39%
Nissan	26%	31%	37%	39%	40%	39%
Stellantis	17%	26%	33%	36%	36%	36%
Subaru	21%	31%	37%	40%	40%	39%
Tesla	100%	100%	100%	100%	100%	100%
Toyota	25%	28%	35%	38%	38%	38%
Volvo	23%	29%	36%	39%	39%	37%
VW	25%	32%	44%	43%	43%	42%
TOTAL	**22%**	**28%**	**34%**	**37%**	**37%**	**37%**

Table 13-67: Projected BEV Penetrations, No Action - Combined

Manufacturer	2027	2028	2029	2030	2031	2032
BMW	30%	35%	42%	43%	42%	42%
Ford	29%	26%	32%	35%	36%	36%
General Motors	22%	29%	33%	38%	38%	37%
Honda	30%	35%	40%	42%	41%	40%
Hyundai	29%	36%	42%	43%	43%	42%
JLR	26%	32%	37%	38%	38%	38%
Kia	30%	36%	42%	43%	43%	42%
Mazda	28%	34%	40%	42%	41%	40%
Mercedes Benz	29%	35%	41%	42%	42%	41%
Mitsubishi	26%	33%	39%	41%	40%	39%
Nissan	29%	34%	40%	42%	41%	41%
Stellantis	20%	28%	34%	37%	37%	37%
Subaru	25%	33%	39%	41%	40%	39%
Tesla	100%	100%	100%	100%	100%	100%
Toyota	29%	32%	38%	40%	39%	39%
Volvo	26%	33%	39%	41%	40%	39%
VW	31%	36%	41%	43%	42%	42%
TOTAL	**27%**	**32%**	**37%**	**40%**	**40%**	**39%**

The tables below provide summary technology penetrations for the proposed standards for strong hybrids, TURB12 and ATK. While strong hybrids may include turbocharged engines or Atkinson engines, The TURB12 and ATK penetrations shown are only for non-hybrid versions of those vehicles.

Table 13-68: Projected Strong HEV Penetrations, No Action

	2027	2028	2029	2030	2031	2032
Cars	6%	6%	5%	4%	0%	0%
Trucks	2%	1%	1%	0%	0%	0%
Total	**4%**	**3%**	**3%**	**2%**	**0%**	**0%**

Table 13-69: Projected TURB12 Penetrations, No Action

	2027	2028	2029	2030	2031	2032
Cars	21%	22%	23%	25%	33%	34%
Trucks	2%	1%	2%	6%	8%	8%
Total	**10%**	**9%**	**11%**	**14%**	**18%**	**19%**

Table 13-70: Projected ATK Penetrations, No Action

	2027	2028	2029	2030	2031	2032
Cars	37%	34%	28%	24%	24%	24%
Trucks	63%	70%	63%	57%	55%	55%
Total	**53%**	**55%**	**49%**	**44%**	**42%**	**42%**

13.1.3.2 Proposal

Table 13-71 through Table 13-73 give BEV penetrations for the proposed standards, by manufacturer.

Table 13-71: Projected BEV Penetrations, Proposed Standards - Cars

Manufacturer	2027	2028	2029	2030	2031	2032
BMW	39%	41%	56%	73%	81%	82%
Ford	49%	51%	61%	57%	64%	58%
General Motors	46%	61%	63%	64%	68%	71%
Honda	40%	41%	50%	66%	63%	73%
Hyundai	38%	47%	55%	65%	69%	71%
JLR	46%	52%	40%	58%	61%	65%
Kia	39%	44%	52%	63%	70%	74%
Mazda	37%	45%	55%	66%	65%	68%
Mercedes Benz	44%	51%	66%	73%	69%	74%
Mitsubishi	37%	47%	57%	69%	71%	74%
Nissan	39%	46%	56%	65%	62%	68%
Stellantis	46%	58%	65%	62%	65%	70%
Subaru	57%	68%	56%	65%	66%	67%
Tesla	100%	100%	100%	100%	100%	100%
Toyota	40%	46%	55%	62%	75%	80%
Volvo	43%	56%	72%	80%	75%	75%
VW	43%	63%	81%	77%	75%	86%
TOTAL	**43%**	**51%**	**59%**	**65%**	**69%**	**73%**

Table 13-72: Projected BEV Penetrations, Proposed Standards - Trucks

Manufacturer	2027	2028	2029	2030	2031	2032
BMW	34%	50%	47%	49%	51%	58%
Ford	35%	36%	48%	49%	56%	68%
General Motors	24%	36%	51%	53%	57%	62%
Honda	37%	48%	55%	58%	69%	67%
Hyundai	27%	39%	48%	53%	53%	58%
JLR	39%	47%	59%	68%	62%	61%
Kia	32%	47%	54%	64%	66%	66%
Mazda	36%	47%	57%	65%	63%	63%
Mercedes Benz	29%	39%	39%	54%	60%	61%
Mitsubishi	34%	47%	57%	62%	58%	57%
Nissan	38%	41%	50%	57%	71%	71%
Stellantis	25%	40%	52%	55%	58%	65%
Subaru	30%	43%	58%	67%	62%	63%
Tesla	100%	100%	100%	100%	100%	100%
Toyota	41%	43%	52%	58%	56%	59%
Volvo	38%	43%	55%	63%	59%	59%
VW	34%	37%	39%	56%	61%	58%
TOTAL	**32%**	**41%**	**51%**	**56%**	**60%**	**64%**

Table 13-73: Projected BEV Penetrations, Proposed Standards - Combined

Manufacturer	2027	2028	2029	2030	2031	2032
BMW	37%	44%	52%	63%	70%	72%
Ford	39%	40%	52%	51%	58%	65%
General Motors	31%	44%	55%	57%	60%	65%
Honda	38%	44%	53%	62%	66%	70%
Hyundai	38%	47%	55%	65%	69%	70%
JLR	39%	47%	58%	67%	62%	61%
Kia	37%	45%	52%	63%	68%	71%
Mazda	36%	46%	56%	65%	64%	66%
Mercedes Benz	37%	46%	55%	64%	65%	68%
Mitsubishi	36%	47%	57%	65%	64%	65%
Nissan	39%	44%	54%	62%	66%	69%
Stellantis	29%	43%	55%	56%	60%	66%
Subaru	34%	47%	58%	66%	63%	63%
Tesla	100%	100%	100%	100%	100%	100%
Toyota	40%	44%	54%	60%	64%	68%
Volvo	39%	46%	58%	66%	62%	62%
VW	38%	48%	57%	65%	67%	70%
TOTAL	**36%**	**45%**	**55%**	**60%**	**63%**	**67%**

The tables below provide summary technology penetrations for the proposed standards for strong hybrids, TURB12 and ATK. While strong hybrids may include turbocharged engines or Atkinson engines, The TURB12 and ATK penetrations shown are only for non-hybrid versions of those vehicles.

Table 13-74: Projected Strong HEV Penetrations, Proposed Standards

	2027	2028	2029	2030	2031	2032
Cars	3%	2%	2%	2%	1%	0%
Trucks	4%	2%	2%	1%	1%	1%
Total	**3%**	**2%**	**2%**	**1%**	**1%**	**0%**

Table 13-75: Projected TURB12 Penetrations, Proposed Standards

	2027	2028	2029	2030	2031	2032
Cars	18%	16%	17%	16%	19%	16%
Trucks	2%	1%	1%	2%	4%	4%
Total	**8%**	**7%**	**7%**	**8%**	**10%**	**9%**

Table 13-76: Projected ATK Penetrations, Proposed Standards

	2027	2028	2029	2030	2031	2032
Cars	36%	30%	22%	17%	12%	11%
Trucks	51%	56%	45%	41%	36%	32%
Total	**45%**	**46%**	**36%**	**31%**	**26%**	**23%**

13.1.3.3 Alternative 1

Table 13-77 through Table 13-79 give BEV penetrations for Alternative 1, by manufacturer.

Table 13-77: Projected BEV Penetrations, Alternative 1 - Cars

Manufacturer	2027	2028	2029	2030	2031	2032
BMW	39%	40%	49%	64%	77%	76%
Ford	49%	53%	56%	67%	73%	68%
General Motors	44%	58%	62%	76%	79%	86%
Honda	40%	41%	54%	60%	63%	65%
Hyundai	38%	47%	58%	66%	65%	66%
JLR	46%	65%	80%	89%	89%	88%
Kia	38%	45%	57%	65%	62%	64%
Mazda	37%	47%	58%	70%	70%	75%
Mercedes Benz	42%	49%	59%	58%	59%	60%
Mitsubishi	38%	47%	57%	69%	66%	69%
Nissan	39%	47%	57%	65%	69%	75%
Stellantis	46%	63%	66%	64%	75%	78%
Subaru	60%	68%	56%	65%	75%	71%
Tesla	100%	100%	100%	100%	100%	100%
Toyota	40%	50%	57%	72%	83%	86%
Volvo	43%	57%	66%	78%	77%	78%
VW	62%	48%	46%	54%	65%	61%
TOTAL	**44%**	**50%**	**58%**	**67%**	**72%**	**74%**

Table 13-78: Projected BEV Penetrations, Alternative 1 - Trucks

Manufacturer	2027	2028	2029	2030	2031	2032
BMW	34%	49%	63%	62%	47%	48%
Ford	35%	42%	48%	58%	59%	72%
General Motors	26%	41%	49%	57%	58%	66%
Honda	37%	47%	56%	67%	65%	66%
Hyundai	27%	38%	50%	59%	63%	64%
JLR	39%	48%	58%	66%	64%	65%
Kia	36%	44%	55%	64%	68%	66%
Mazda	36%	46%	57%	62%	60%	60%
Mercedes Benz	32%	42%	53%	71%	71%	69%
Mitsubishi	35%	47%	58%	65%	64%	66%
Nissan	40%	44%	54%	62%	61%	59%
Stellantis	26%	44%	50%	61%	62%	71%
Subaru	30%	42%	58%	66%	62%	66%
Tesla	100%	100%	100%	100%	100%	100%
Toyota	41%	43%	52%	57%	54%	58%
Volvo	38%	46%	56%	63%	61%	64%
VW	25%	44%	61%	70%	64%	66%
TOTAL	**32%**	**44%**	**52%**	**61%**	**60%**	**66%**

Table 13-79: Projected BEV Penetrations, Alternative 1 - Combined

Manufacturer	2027	2028	2029	2030	2031	2032
BMW	37%	43%	54%	64%	65%	65%
Ford	39%	45%	50%	60%	63%	71%
General Motors	32%	47%	53%	63%	65%	73%
Honda	38%	44%	55%	63%	64%	65%
Hyundai	38%	47%	58%	66%	65%	66%
JLR	39%	49%	59%	68%	65%	66%
Kia	37%	45%	56%	65%	64%	65%
Mazda	36%	47%	58%	66%	65%	67%
Mercedes Benz	38%	46%	56%	64%	64%	64%
Mitsubishi	36%	47%	57%	67%	65%	67%
Nissan	40%	46%	56%	64%	66%	68%
Stellantis	29%	47%	53%	62%	64%	72%
Subaru	35%	46%	57%	66%	64%	67%
Tesla	100%	100%	100%	100%	100%	100%
Toyota	40%	46%	54%	63%	66%	70%
Volvo	39%	48%	58%	66%	64%	67%
VW	41%	46%	55%	63%	64%	64%
TOTAL	**37%**	**46%**	**54%**	**63%**	**65%**	**69%**

The tables below provide summary technology penetrations for Alternative 1 for strong hybrids, TURB12 and ATK. While strong hybrids may include turbocharged engines or Atkinson engines, The TURB12 and ATK penetrations shown are only for non-hybrid versions of those vehicles.

Table 13-80: Projected Strong HEV Penetrations, Alternative 1

	2027	2028	2029	2030	2031	2032
Cars	3%	6%	11%	9%	9%	7%
Trucks	4%	3%	7%	6%	6%	5%
Total	**3%**	**4%**	**9%**	**7%**	**7%**	**6%**

Table 13-81: Projected TURB12 Penetrations, Alternative 1

	2027	2028	2029	2030	2031	2032
Cars	17%	13%	9%	7%	8%	7%
Trucks	2%	1%	1%	1%	2%	2%
Total	**8%**	**6%**	**4%**	**4%**	**4%**	**4%**

Table 13-82: Projected ATK Penetrations, Alternative 1

	2027	2028	2029	2030	2031	2032
Cars	36%	29%	23%	16%	11%	11%
Trucks	51%	53%	39%	32%	31%	27%
Total	**45%**	**43%**	**33%**	**26%**	**23%**	**20%**

13.1.3.4 Alternative 2

Table 13-83 through Table 13-85 give BEV penetrations for Alternative 2, by manufacturer.

Table 13-83: Projected BEV Penetrations, Alternative 2 - Cars

Manufacturer	2027	2028	2029	2030	2031	2032
BMW	40%	42%	60%	54%	71%	80%
Ford	49%	56%	67%	67%	58%	57%
General Motors	35%	52%	64%	61%	63%	74%
Honda	39%	41%	53%	59%	65%	68%
Hyundai	36%	40%	53%	55%	62%	65%
JLR	46%	35%	32%	36%	39%	49%
Kia	39%	41%	55%	57%	66%	72%
Mazda	33%	43%	52%	53%	63%	64%
Mercedes Benz	43%	36%	49%	53%	61%	64%
Mitsubishi	33%	41%	50%	51%	53%	59%
Nissan	38%	44%	58%	60%	67%	62%
Stellantis	37%	48%	58%	60%	62%	66%
Subaru	53%	46%	53%	53%	54%	59%
Tesla	100%	100%	100%	100%	100%	100%
Toyota	38%	45%	55%	58%	70%	81%
Volvo	39%	50%	56%	54%	54%	58%
VW	62%	52%	63%	59%	65%	69%
TOTAL	**41%**	**46%**	**58%**	**59%**	**65%**	**69%**

Table 13-84: Projected BEV Penetrations, Alternative 2 - Trucks

Manufacturer	2027	2028	2029	2030	2031	2032
BMW	34%	38%	47%	56%	54%	52%
Ford	35%	32%	45%	54%	58%	65%
General Motors	21%	35%	47%	53%	56%	58%
Honda	36%	38%	51%	49%	56%	62%
Hyundai	26%	33%	46%	42%	52%	60%
JLR	27%	35%	45%	47%	47%	54%
Kia	38%	40%	54%	56%	63%	64%
Mazda	25%	32%	43%	46%	46%	55%
Mercedes Benz	25%	42%	54%	54%	60%	62%
Mitsubishi	26%	33%	44%	47%	50%	56%
Nissan	35%	37%	50%	52%	58%	70%
Stellantis	21%	40%	51%	54%	56%	61%
Subaru	26%	34%	44%	46%	49%	55%
Tesla	100%	100%	100%	100%	100%	100%
Toyota	37%	39%	50%	52%	53%	55%
Volvo	30%	32%	41%	44%	47%	53%
VW	23%	33%	46%	51%	58%	62%
TOTAL	**29%**	**36%**	**48%**	**52%**	**55%**	**60%**

Table 13-85: Projected BEV Penetrations, Alternative 2 - Combined

Manufacturer	2027	2028	2029	2030	2031	2032
BMW	38%	40%	55%	55%	64%	69%
Ford	39%	38%	51%	58%	58%	63%
General Motors	25%	41%	53%	56%	58%	63%
Honda	38%	39%	52%	54%	61%	65%
Hyundai	36%	40%	52%	54%	62%	65%
JLR	28%	35%	44%	46%	47%	53%
Kia	38%	41%	55%	56%	65%	69%
Mazda	29%	37%	48%	50%	54%	59%
Mercedes Benz	35%	39%	51%	53%	60%	63%
Mitsubishi	29%	37%	46%	49%	52%	57%
Nissan	37%	41%	55%	57%	63%	66%
Stellantis	24%	41%	52%	55%	57%	62%
Subaru	30%	36%	45%	47%	50%	56%
Tesla	100%	100%	100%	100%	100%	100%
Toyota	38%	41%	52%	55%	60%	66%
Volvo	32%	36%	45%	46%	48%	54%
VW	40%	41%	53%	54%	61%	65%
TOTAL	**33%**	**40%**	**52%**	**55%**	**59%**	**64%**

The tables below provide summary technology penetrations for Alternative 2 for strong hybrids, TURB12 and ATK. While strong hybrids may include turbocharged engines or Atkinson engines, The TURB12 and ATK penetrations shown are only for non-hybrid versions of those vehicles.

Table 13-86: Projected Strong HEV Penetrations, Alternative 2

	2027	2028	2029	2030	2031	2032
Cars	3%	2%	1%	1%	1%	0%
Trucks	4%	3%	2%	1%	1%	1%
Total	**3%**	**2%**	**2%**	**1%**	**1%**	**0%**

Table 13-87: Projected TURB12 Penetrations, Alternative 2

	2027	2028	2029	2030	2031	2032
Cars	18%	18%	18%	19%	21%	20%
Trucks	2%	1%	1%	4%	5%	4%
Total	**8%**	**8%**	**8%**	**10%**	**12%**	**11%**

Table 13-88: Projected ATK Penetrations, Alternative 2

	2027	2028	2029	2030	2031	2032
Cars	38%	33%	22%	19%	13%	10%
Trucks	55%	60%	48%	43%	38%	35%
Total	**48%**	**49%**	**38%**	**33%**	**28%**	**25%**

13.1.3.5 Alternative 3

Table 13-89 through Table 13-91 give BEV penetrations for Alternative 3, by manufacturer.

Table 13-89: Projected BEV Penetrations, Alternative 3 - Cars

Manufacturer	2027	2028	2029	2030	2031	2032
BMW	40%	58%	63%	74%	75%	77%
Ford	46%	38%	48%	61%	72%	63%
General Motors	34%	39%	48%	57%	66%	69%
Honda	39%	45%	46%	53%	63%	72%
Hyundai	36%	48%	50%	57%	64%	69%
JLR	46%	35%	30%	36%	42%	56%
Kia	39%	46%	47%	56%	67%	71%
Mazda	34%	48%	56%	55%	61%	67%
Mercedes Benz	43%	59%	64%	64%	67%	74%
Mitsubishi	33%	41%	46%	54%	63%	73%
Nissan	36%	45%	47%	55%	65%	74%
Stellantis	38%	41%	44%	56%	67%	72%
Subaru	53%	49%	51%	53%	58%	66%
Tesla	100%	100%	100%	100%	100%	100%
Toyota	34%	44%	49%	56%	65%	74%
Volvo	40%	53%	63%	72%	71%	77%
VW	59%	65%	58%	61%	67%	74%
TOTAL	**40%**	**46%**	**50%**	**58%**	**66%**	**72%**

Table 13-90: Projected BEV Penetrations, Alternative 3 - Trucks

Manufacturer	2027	2028	2029	2030	2031	2032
BMW	35%	39%	36%	37%	54%	63%
Ford	33%	30%	42%	52%	61%	70%
General Motors	20%	31%	41%	50%	57%	64%
Honda	34%	43%	51%	57%	63%	66%
Hyundai	26%	39%	43%	43%	57%	66%
JLR	27%	36%	44%	46%	51%	60%
Kia	38%	49%	57%	61%	66%	68%
Mazda	25%	33%	38%	46%	53%	62%
Mercedes Benz	25%	32%	33%	45%	56%	63%
Mitsubishi	26%	38%	44%	46%	50%	57%
Nissan	32%	42%	51%	57%	65%	66%
Stellantis	21%	31%	40%	47%	55%	64%
Subaru	27%	36%	42%	46%	52%	61%
Tesla	100%	100%	100%	100%	100%	100%
Toyota	33%	38%	45%	52%	59%	64%
Volvo	30%	33%	39%	41%	47%	57%
VW	24%	37%	45%	52%	60%	66%
TOTAL	**27%**	**35%**	**43%**	**51%**	**58%**	**65%**

Table 13-91: Projected BEV Penetrations, Alternative 3 - Combined

Manufacturer	2027	2028	2029	2030	2031	2032
BMW	38%	50%	52%	59%	67%	72%
Ford	37%	32%	43%	54%	64%	68%
General Motors	25%	34%	44%	52%	60%	65%
Honda	37%	44%	48%	54%	63%	69%
Hyundai	36%	47%	50%	57%	64%	69%
JLR	28%	35%	43%	46%	51%	60%
Kia	39%	47%	51%	58%	67%	70%
Mazda	29%	40%	46%	51%	57%	65%
Mercedes Benz	35%	47%	51%	56%	62%	69%
Mitsubishi	29%	39%	45%	49%	56%	64%
Nissan	34%	44%	49%	56%	65%	71%
Stellantis	24%	33%	41%	49%	58%	65%
Subaru	31%	38%	44%	47%	53%	62%
Tesla	100%	100%	100%	100%	100%	100%
Toyota	34%	40%	47%	54%	62%	68%
Volvo	32%	37%	44%	48%	52%	61%
VW	39%	49%	51%	56%	63%	69%
TOTAL	**32%**	**39%**	**46%**	**54%**	**62%**	**68%**

The tables below provide summary technology penetrations for Alternative 3 for strong hybrids, TURB12 and ATK. While strong hybrids may include turbocharged engines or Atkinson engines, The TURB12 and ATK penetrations shown are only for non-hybrid versions of those vehicles.

Table 13-92: Projected Strong HEV Penetrations, Alternative 3

	2027	2028	2029	2030	2031	2032
Cars	2%	2%	1%	1%	0%	0%
Trucks	2%	1%	1%	0%	0%	0%
Total	**2%**	**2%**	**1%**	**0%**	**0%**	**0%**

Table 13-93: Projected TURB12 Penetrations, Alternative 3

	2027	2028	2029	2030	2031	2032
Cars	19%	17%	19%	19%	20%	16%
Trucks	2%	1%	2%	4%	4%	4%
Total	**9%**	**8%**	**9%**	**10%**	**11%**	**9%**

Table 13-94: Projected ATK Penetrations, Alternative 3

	2027	2028	2029	2030	2031	2032
Cars	39%	34%	27%	22%	13%	12%
Trucks	57%	63%	54%	45%	37%	31%
Total	**49%**	**51%**	**43%**	**35%**	**28%**	**23%**

13.1.4 Light-Duty Vehicle Sensitivities

Light-duty sensitivities are described in IV.E of the preamble. This section provides the analytical results for the proposed standards and the three alternative sets of standards across the various sensitivities.

13.1.4.1 State-level ZEV Policies (ACC II)

Table 13-95: Projected targets with ACC II, for No Action case, proposed and alternatives (CO_2 grams/mile) - cars and trucks combined

Table 13-96

	2027	2028	2029	2030	2031	2032
No Action	164	164	165	165	164	164
Proposed	151	131	111	102	93	82
Alternative 1	141	121	102	92	83	72
Alternative 2	161	141	121	112	103	92
Alternative 3	166	149	132	115	99	82

Table 13-97: Projected achieved levels with ACC II, for No Action case, proposed and alternatives (CO_2 grams/mile) - cars and trucks combined

	2027	2028	2029	2030	2031	2032
No Action	146	123	104	100	103	99
Proposed	149	129	107	96	90	81
Alternative 1	145	122	99	83	73	66
Alternative 2	153	132	119	110	100	90
Alternative 3	154	133	122	113	96	81

Table 13-98: BEV penetrations with ACC II, for No Action case, proposed and alternatives - cars and trucks combined

	2027	2028	2029	2030	2031	2032
No Action	32%	42%	49%	52%	52%	54%
Proposed	37%	45%	55%	61%	64%	68%
Alternative 1	38%	47%	55%	63%	68%	72%
Alternative 2	37%	46%	51%	57%	61%	65%
Alternative 3	36%	45%	50%	55%	62%	68%

Table 13-99: Average incremental vehicle cost vs. No Action case with ACC II, proposed and alternatives - cars and trucks combined

	2027	2028	2029	2030	2031	2032	6-yr avg
Proposed	$172	$56	$11	$57	$268	$423	$164
Alternative 1	$454	$639	$1,130	$1,050	$1,212	$1,186	$945
Alternative 2	$106	-$29	-$184	-$188	$73	$235	$2
Alternative 3	$85	-$43	-$221	-$182	$214	$483	$56

13.1.4.2 Battery Costs

13.1.4.2.1 Low Battery Costs

Table 13-100. Projected targets with Low Battery Costs for No Action case, proposed and alternatives (CO_2 grams/mile) - cars and trucks combined

	2027	2028	2029	2030	2031	2032
No Action	162	162	164	164	164	163
Proposed	152	132	111	102	93	82
Alternative 1	141	122	102	93	83	72
Alternative 2	161	141	121	113	103	92
Alternative 3	165	148	131	115	99	82

Table 13-101. Projected achieved levels with Low Battery Costs, for No Action case, proposed and alternatives (CO_2 grams/mile) - cars and trucks combined

	2027	2028	2029	2030	2031	2032
No Action	152	138	108	106	99	111
Proposed	154	130	110	100	83	80
Alternative 1	154	125	102	83	70	65
Alternative 2	157	136	119	96	98	90
Alternative 3	161	141	124	109	95	80

Table 13-102. BEV penetrations with Low Battery Costs, for No Action case, proposed and alternatives - cars and trucks combined

	2027	2028	2029	2030	2031	2032
No Action	34%	39%	51%	52%	55%	51%
Proposed	38%	46%	54%	59%	66%	68%
Alternative 1	38%	46%	54%	63%	68%	71%
Alternative 2	37%	46%	53%	63%	62%	66%
Alternative 3	36%	44%	51%	58%	63%	69%

Table 13-103. Average incremental vehicle cost vs. No Action case for Low Battery Costs, proposed and alternatives - cars and trucks combined

	2027	2028	2029	2030	2031	2032	6-yr avg
Proposed	$623	$553	$303	$313	$365	$490	$441
Alternative 1	$623	$1,441	$1,690	$1,568	$1,392	$1,443	$1,360
Alternative 2	$319	$213	-$13	$112	$7	$286	$154
Alternative 3	$161	$128	-$81	-$22	$64	$446	$116

13.1.4.2.2 High Battery Costs

Table 13-104. Projected targets with High Battery Costs for No Action case, proposed and alternatives (CO_2 grams/mile) - cars and trucks combined

	2027	2028	2029	2030	2031	2032
No Action	166	165	164	163	161	161
Proposed	153	132	112	102	93	82
Alternative 1	143	122	102	92	83	72
Alternative 2	163	142	122	112	103	92
Alternative 3	167	150	133	116	99	82

Table 13-105. Projected achieved levels with High Battery Costs, for No Action case, proposed and alternatives (CO_2 grams/mile) - cars and trucks combined

	2027	2028	2029	2030	2031	2032
No Action	162	153	152	155	160	159
Proposed	151	130	110	100	92	81
Alternative 1	144	121	100	90	82	71
Alternative 2	159	139	119	110	101	92
Alternative 3	164	147	131	115	98	83

Table 13-106. BEV penetrations with High Battery Costs, for No Action case, proposed and alternatives - cars and trucks combined

	2027	2028	2029	2030	2031	2032
No Action	21%	26%	28%	29%	29%	29%
Proposed	33%	41%	51%	55%	60%	65%
Alternative 1	36%	44%	54%	60%	63%	69%
Alternative 2	29%	36%	47%	52%	56%	60%
Alternative 3	27%	33%	42%	50%	58%	64%

Table 13-107. Average incremental vehicle cost vs. No Action case for High Battery Costs, proposed and alternatives - cars and trucks combined

	2027	2028	2029	2030	2031	2032	6-yr avg
Proposed	$1,246	$1,057	$1,329	$1,553	$2,103	$2,505	$1,632
Alternative 1	$1,884	$1,676	$1,768	$1,885	$2,430	$2,750	$2,066
Alternative 2	$888	$874	$1,227	$1,347	$1,938	$2,340	$1,436
Alternative 3	$820	$785	$1,138	$1,484	$2,242	$2,803	$1,545

13.1.4.3 Consumer Acceptance

13.1.4.3.1 Faster BEV Acceptance

Table 13-108. Projected targets with Faster BEV Acceptance for No Action case, proposed and alternatives (CO_2 grams/mile) - cars and trucks combined

	2027	2028	2029	2030	2031	2032
No Action	163	163	164	165	165	166
Proposed	151	132	112	103	93	83
Alternative 1	141	122	102	93	83	72
Alternative 2	161	141	121	113	103	93
Alternative 3	165	148	132	116	99	82

Table 13-109. Projected achieved levels with Faster BEV Acceptance, for No Action case, proposed and alternatives (CO_2 grams/mile) - cars and trucks combined

	2027	2028	2029	2030	2031	2032
No Action	147	131	100	76	79	71
Proposed	157	129	107	86	73	59
Alternative 1	156	128	104	80	66	53
Alternative 2	157	136	116	100	80	71
Alternative 3	159	140	118	96	90	76

Table 13-110. BEV penetrations with Faster BEV Acceptance, for No Action case, proposed and alternatives - cars and trucks combined

	2027	2028	2029	2030	2031	2032
No Action	36%	42%	54%	63%	63%	66%
Proposed	38%	46%	55%	63%	69%	75%
Alternative 1	38%	46%	55%	63%	69%	76%
Alternative 2	38%	46%	54%	61%	69%	73%
Alternative 3	38%	46%	54%	63%	66%	71%

Table 13-111. Average incremental vehicle cost vs. No Action case for Faster BEV Acceptance, proposed and alternatives - cars and trucks combined

	2027	2028	2029	2030	2031	2032	6-yr avg
Proposed	$287	$982	$809	$602	$746	$712	$211
Alternative 1	$317	$1,001	$1,209	$1,533	$1,675	$1,445	$783
Alternative 2	$212	$214	-$34	-$194	$179	$163	-$10
Alternative 3	$54	$33	-$176	-$235	-$66	$53	-$20

13.1.4.3.2 Slower BEV Acceptance

Table 13-112. Projected targets with Slower BEV Acceptance for No Action case, proposed and alternatives (CO_2 grams/mile) - cars and trucks combined

	2027	2028	2029	2030	2031	2032
No Action	164	162	162	161	161	160
Proposed	153	133	112	103	93	82
Alternative 1	143	122	102	92	83	72
Alternative 2	163	142	122	112	103	92
Alternative 3	167	149	132	115	99	82

Table 13-113. Projected achieved levels with Slower BEV Acceptance, for No Action case, proposed and alternatives (CO_2 grams/mile) - cars and trucks combined

	2027	2028	2029	2030	2031	2032
No Action	161	160	154	159	152	158
Proposed	150	131	110	101	92	82
Alternative 1	144	118	99	90	81	74
Alternative 2	160	140	119	111	101	90
Alternative 3	164	148	128	113	97	80

Table 13-114. BEV penetrations with Slower BEV Acceptance, for No Action case, proposed and alternatives - cars and trucks combined

	2027	2028	2029	2030	2031	2032
No Action	22%	23%	28%	27%	33%	31%
Proposed	34%	42%	53%	59%	63%	68%
Alternative 1	36%	47%	55%	61%	66%	69%
Alternative 2	29%	39%	50%	55%	59%	64%
Alternative 3	28%	35%	45%	53%	61%	68%

Table 13-115. Average incremental vehicle cost vs. No Action case for Slower BEV Acceptance, proposed and alternatives - cars and trucks combined

	2027	2028	2029	2030	2031	2032	6-yr avg
Proposed	$877	$1,135	$755	$898	$995	$1,498	$1,026
Alternative 1	$1,336	$1,470	$1,143	$1,244	$1,393	$1,731	$1,386
Alternative 2	$695	$853	$560	$689	$888	$1,344	$838
Alternative 3	$508	$734	$473	$702	$1,005	$1,621	$841

13.2 Medium-Duty Vehicles

13.2.1 GHG Targets and Compliance Levels

13.2.1.1 CO_2 g/mi

Shown below are the projected average GHG targets for each manufacturer, as well as their corresponding average achieved compliance, in g/mi, for vans and pickups. A combined fleet g/mi comparison is not shown, because a fleet g/mi value, even with a sales-weighted average of van and pickup values, would not accurately represent the differences in lifetime VMT for the van and pickup fleets used in the compliance calculations for each OEM.

13.2.1.1.1 Proposed GHG standards

OEM-specific GHG emissions targets for the proposed standards are shown in Table 13-116 and Table 13-117 for vans and pickups, respectively. Similarly, projected achieved GHG emissions levels are given for vans and pickups in Table 13-118 and Table 13-119.

Table 13-116: Projected GHG Targets, Proposed Standards - Medium Duty Vans

Manufacturer	2027	2028	2029	2030	2031	2032
Ford	383	371	337	303	270	238
General Motors	391	377	342	306	273	241
Mercedes Benz	426	412	375	337	302	266
Nissan	391	378	344	309	276	243
Stellantis	399	384	347	310	276	243
TOTAL	**393**	**379**	**345**	**309**	**276**	**243**

Table 13-117: Projected GHG Targets, Proposed Standards - Medium Duty Pickups

Manufacturer	2027	2028	2029	2030	2031	2032
Ford	458	448	410	370	328	288
General Motors	464	454	415	378	335	294
Mercedes Benz	-	-	-	-	-	-
Nissan	424	416	373	336	301	265
Stellantis	464	454	415	376	329	295
TOTAL	**462**	**452**	**413**	**374**	**331**	**292**

Table 13-118: Achieved GHG Levels, Proposed Standards - Medium Duty Vans

Manufacturer	2027	2028	2029	2030	2031	2032
Ford	280	192	114	26	6	5
General Motors	316	218	129	30	0	0
Mercedes Benz	288	198	104	45	45	45
Nissan	282	194	116	42	38	37
Stellantis	295	208	131	72	20	5
TOTAL	**292**	**202**	**119**	**36**	**12**	**10**

Table 13-119: Achieved GHG Levels, Proposed Standards - Medium Duty Pickups

Manufacturer	2027	2028	2029	2030	2031	2032
Ford	523	555	542	526	478	427
General Motors	518	549	538	512	464	404
Mercedes Benz	-	-	-	-	-	-
Nissan	416	443	363	453	460	458
Stellantis	496	526	516	490	450	391
TOTAL	**515**	**546**	**534**	**512**	**466**	**410**

13.2.1.2 CO_2 Mg

Shown below are the projected average GHG targets for each manufacturer, as well as their corresponding average achieved compliance, in Mg, for cars, trucks, and the combined fleet. Total emissions are calculated by multiplying the relevant CO_2 emission rate, the production volume of applicable vehicles, and the expected lifetime vehicle miles traveled (VMT) of those vehicles. The equation to calculate total Mg (for either total emissions, or credits based on the difference between target g/mi and achieved g/mi) is:

CO_2 (Mg) = (CO_2 (g/mi) x VMT x Production) / 1,000,000

In the above equation, "VMT" is in miles, and specified in the regulations as 150,000 miles. When using these equations to calculate values for cars and trucks in aggregate, we use a production weighted average of the car and truck VMT values.

13.2.1.2.1 Proposed standards

OEM-specific GHG emissions targets for the proposed standards (in Mg) are shown in Table 13-120, Table 13-121, and Table 13-122 for vans, pickups, and the combined fleet, respectively. Similarly, projected achieved GHG emissions (in Mg) are given for vans, pickups, and the combined fleet in Table 13-123, Table 13-124, and Table 13-125. Finally, overall credits or debits earned are provided for the combined fleet on a manufacturer-specific basis, in Table 13-126.

Table 13-120: Projected GHG Targets (Mg), Proposed Standards - Medium Duty Vans

Manufacturer	2027	2028	2029	2030	2031	2032
Ford	6,522,743	6,311,012	5,754,284	5,186,343	4,668,259	4,150,724
General Motors	3,910,642	3,775,242	3,435,120	3,088,929	2,777,305	2,469,539
Mercedes Benz	1,862,021	1,801,793	1,642,836	1,482,940	1,337,297	1,189,101
Nissan	685,541	662,963	604,198	544,945	491,168	436,688
Stellantis	1,912,932	1,840,237	1,669,031	1,495,278	1,341,697	1,191,470
TOTAL	**14,893,879**	**14,391,247**	**13,105,469**	**11,798,434**	**10,615,726**	**9,437,522**

Table 13-121: Projected GHG Targets (Mg), Proposed Standards - Medium Duty Pickups

Manufacturer	2027	2028	2029	2030	2031	2032
Ford	12,438,978	12,235,086	11,231,346	10,215,915	9,194,759	8,164,130
General Motors	12,566,840	12,354,816	11,346,578	10,417,371	9,365,128	8,318,738
Mercedes Benz						
Nissan	51,194	50,431	45,506	41,311	37,496	33,442
Stellantis	7,738,363	7,611,465	6,988,697	6,382,832	5,660,795	5,140,250
TOTAL	**32,795,375**	**32,251,799**	**29,612,126**	**27,057,429**	**24,258,178**	**21,656,560**

Table 13-122: Projected GHG Targets (Mg), Proposed Standards - Medium Duty Combined

Manufacturer	2027	2028	2029	2030	2031	2032
Ford	18,961,722	18,546,098	16,985,631	15,402,258	13,863,018	12,314,853
General Motors	16,477,482	16,130,058	14,781,698	13,506,300	12,142,433	10,788,277
Mercedes Benz	1,862,021	1,801,793	1,642,836	1,482,940	1,337,297	1,189,101
Nissan	736,735	713,394	649,703	586,255	528,664	470,130
Stellantis	9,651,295	9,451,702	8,657,728	7,878,111	7,002,492	6,331,720
TOTAL	**47,689,254**	**46,643,046**	**42,717,596**	**38,855,863**	**34,873,904**	**31,094,082**

Table 13-123: Achieved GHG Levels (Mg), Proposed Standards - Medium Duty Vans

Manufacturer	2027	2028	2029	2030	2031	2032
Ford	4,758,966	3,272,901	1,938,968	450,683	98,193	81,273
General Motors	3,168,452	2,178,961	1,290,834	299,867	2,554	11
Mercedes Benz	1,256,139	863,880	453,787	197,712	199,287	201,181
Nissan	494,750	341,090	203,176	74,654	68,336	66,021
Stellantis	1,411,730	998,450	627,699	348,859	96,066	26,512
TOTAL	**11,090,038**	**7,655,283**	**4,514,464**	**1,371,776**	**464,435**	**374,999**

Table 13-124: Achieved GHG Levels (Mg), Proposed Standards - Medium Duty Pickups

Manufacturer	2027	2028	2029	2030	2031	2032
Ford	14,204,434	15,138,319	14,865,910	14,527,658	13,392,450	12,114,910
General Motors	14,037,520	14,960,172	14,713,293	14,129,554	12,977,998	11,447,587
Mercedes Benz	-	-	-	-	-	-
Nissan	50,208	53,672	44,193	55,605	57,198	57,787
Stellantis	8,281,215	8,820,766	8,689,493	8,318,697	7,745,694	6,808,215
TOTAL	**36,573,377**	**38,972,929**	**38,312,889**	**37,031,514**	**34,173,340**	**30,428,499**

Table 13-125: Achieved GHG Levels (Mg), Proposed Standards - Medium Duty Combined

Manufacturer	2027	2028	2029	2030	2031	2032
Ford	18,963,400	18,411,220	16,804,878	14,978,341	13,490,643	12,196,183
General Motors	17,205,973	17,139,133	16,004,127	14,429,421	12,980,551	11,447,598
Mercedes Benz	1,256,139	863,880	453,787	197,712	199,287	201,181
Nissan	544,958	394,762	247,369	130,260	125,534	123,808
Stellantis	9,692,945	9,819,216	9,317,192	8,667,555	7,841,761	6,834,727
TOTAL	**47,663,415**	**46,628,211**	**42,827,353**	**38,403,289**	**34,637,776**	**30,803,498**

Table 13-126: GHG Credits/Debits Earned (Mg), Proposed Standards - Medium Duty Combined

Manufacturer	2027	2028	2029	2030	2031	2032
Ford	(764,771)	(753,048)	(188,764)	(260,367)	(338,464)	(296,675)
General Motors	(575,509)	(353,113)	(821,195)	(143,791)	(155,080)	(357,366)
Mercedes Benz	(29,210)	(119,383)	(63,927)	(28,799)	100,537	210,887
Nissan	1,368,231	1,305,289	1,044,626	125,015	(55,848)	(270,510)
Stellantis	1,406	(79,812)	29,188	307,876	448,783	625,199
TOTAL	**148**	**(67)**	**(72)**	**(66)**	**(71)**	**(88,465)**

13.2.2 Projected Manufacturing Costs per Vehicle

EPA has performed an assessment of the estimated per-vehicle costs for manufacturers to meet the proposed MY 2027-2032 standards, relative to the No Action case. The fleet average costs per vehicle are grouped by vans and pickups. We have included summary tables in this format. The costs in this section represent compliance costs to the industry and are not necessarily the same as the costs experienced by the consumer when purchasing a new vehicle. For example, the costs presented here do not include any state and Federal purchase incentives that are available to consumers. Also, the manufacturer decisions for the pricing of individual vehicles may not align exactly with the production cost impacts for that particular vehicle. EPA's OMEGA model assumes that manufacturers distribute compliance costs through limited cross-subsidization of prices between vehicles in order to maintain an appropriate mix of debit- and credit-generating vehicles that achieves compliance in a cost-minimizing fashion.

13.2.2.1 Proposed Standards

Incremental costs per vehicle for the proposed standards (compared to the No Action case) are summarized by van and truck in Table 13-127.

Table 13-127: Projected Manufacturing Costs Per Vehicle, Proposed Standards - Medium Duty Vehicles

	2027	2028	2029	2030	2031	2032
Vans	$322	$658	$711	$1,184	$1,592	$1,932
Pickups	$386	$31	$67	$374	$603	$1,706
Total	**$364**	**$249**	**$290**	**$654**	**$944**	**$1,784**

Incremental costs per vehicle for the proposed standards, compared to the No Action case, are shown for each OEM in Table 13-128, Table 13-129, and Table 13-130 for vans, pickups, and the medium duty combined fleet, respectively.

Table 13-128: Projected Manufacturing Costs Per Vehicle, Proposed Standards - Medium Duty Vans

Manufacturer	2027	2028	2029	2030	2031	2032
Ford	$392	$785	$873	$1,478	$1,836	$2,166
General Motors	$236	$607	$584	$1,053	$1,576	$1,903
Mercedes Benz	$344	$413	$602	$663	$911	$1,260
Nissan	$342	$497	$431	$856	$1,032	$1,325
Stellantis	$230	$599	$602	$1,009	$1,586	$2,000
TOTAL	**$322**	**$658**	**$711**	**$1,184**	**$1,592**	**$1,932**

Table 13-129: Projected Manufacturing Costs Per Vehicle, Proposed Standards - Medium Duty Pickups

Manufacturer	2027	2028	2029	2030	2031	2032
Ford	$387	$23	$66	$137	$579	$1,408
General Motors	$353	$19	$47	$250	$523	$1,652
Mercedes Benz	-	-	-	-	-	-
Nissan	$592	-$178	$963	-$226	-$317	-$348
Stellantis	$435	$67	$95	$964	$778	$2,296
TOTAL	**$386**	**$31**	**$67**	**$374**	**$603**	**$1,706**

Table 13-130: Projected Manufacturing Costs Per Vehicle, Proposed Standards - Medium Duty Combined

Manufacturer	2027	2028	2029	2030	2031	2032
Ford	$389	$316	$376	$650	$1,058	$1,696
General Motors	$322	$177	$191	$465	$804	$1,719
Mercedes Benz	$344	$413	$602	$663	$911	$1,260
Nissan	$358	$453	$465	$786	$944	$1,216
Stellantis	$389	$185	$208	$974	$956	$2,231
TOTAL	**$364**	**$249**	**$290**	**$654**	**$944**	**$1,784**

13.2.3 Technology Penetration Rates

Presented below are the projected technology penetration rates, by manufacturer, for vans and pickups, for the No Action case and the proposed standards. Tables are summarized by body style for BEV penetrations, with the remainder of the fleet being ICE vehicles.

13.2.3.1 No Action Case

Table 13-131 summarizes medium duty vehicle BEV penetrations for the No Action case.

Table 13-131: Projected BEV Penetrations, No Action - Medium Duty Vehicles

	2027	2028	2029	2030	2031	2032
Vans	25%	24%	24%	22%	21%	22%
Pickups	0%	0%	0%	0%	0%	0%
Total	**9%**	**8%**	**8%**	**8%**	**7%**	**8%**

13.2.3.2 Proposal

Table 13-132 summarizes medium duty vehicle BEV penetrations for the proposed standards.

Table 13-132: Projected BEV Penetrations, Proposed Standards - Medium Duty Vehicles

	2027	2028	2029	2030	2031	2032
Vans	35%	55%	73%	92%	97%	98%
Pickups	7%	1%	3%	4%	15%	19%
Total	**17%**	**20%**	**28%**	**34%**	**43%**	**46%**

13.2.4 Medium-Duty Vehicle Sensitivities

The tables below summarize the projected average GHG targets and average achieved compliance, in g/mi, BEV penetrations, and incremental vehicle cost vs the No Action case, for medium duty vehicles. They are prepared for both the Low Battery Cost and the High Battery Cost sensitivities.

13.2.4.1 Low Battery Costs

Table 13-133. Projected targets with Low Battery Costs for No Action case and proposed standards (CO_2 grams/mile) - Medium Duty Combined

	2027	2028	2029	2030	2031	2032
No Action	479	478	478	480	481	481
Proposed	437	423	386	349	312	275

Table 13-134. Projected achieved levels with Low Battery Costs for No Action case and proposed standards (CO_2 grams/mile) - Medium Duty Combined

	2027	2028	2029	2030	2031	2032
No Action	478	478	478	480	480	480
Proposed	436	423	385	350	307	273

Table 13-135. BEV penetrations with Low Battery Costs for No Action case and proposed standards - Medium Duty Combined

	2027	2028	2029	2030	2031	2032
No Action	9%	8%	7%	7%	8%	7%
Proposed	17%	18%	26%	33%	38%	44%

Table 13-136. Average incremental vehicle manufacturing cost vs. No Action case for Low Battery Costs, proposed standards - Medium Duty Combined

	2027	2028	2029	2030	2031	2032	6-yr avg
Proposed	$118	$4	-$142	$5	$564	$1,094	$274

13.2.4.2 High Battery Costs

Table 13-137. Projected targets with High Battery Costs for No Action case and proposed standards (CO_2 grams/mile) - Medium Duty Combined

	2027	2028	2029	2030	2031	2032
No Action	482	482	482	482	483	483
Proposed	439	428	390	355	316	276

Table 13-138. Projected achieved levels with High Battery Costs for No Action case and proposed standards (CO_2 grams/mile) - Medium Duty Combined

	2027	2028	2029	2030	2031	2032
No Action	482	482	482	481	482	483
Proposed	439	428	389	352	313	273

Table 13-139. BEV penetrations with High Battery Costs for No Action case and proposed standards - Medium Duty Combined

	2027	2028	2029	2030	2031	2032
No Action	5%	5%	5%	5%	3%	3%
Proposed	14%	17%	25%	27%	36%	43%

Table 13-140. Average incremental vehicle manufacturing cost vs. No Action case for High Battery Costs, proposed standards - Medium Duty Combined

	2027	2028	2029	2030	2031	2032	6-yr avg
Proposed	$810	$640	$919	$1,648	$2,191	$3,072	$1,547