

Control of Air Pollution from New Motor Vehicles: Heavy-Duty Engine and Vehicle Standards

Draft Regulatory Impact Analysis

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

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List of Acronyms

Acronym	Definition
°C	Degrees Celsius
µg	Microgram
µm	Micrometers
20xx\$	U.S. Dollars in calendar year 20xx
A/C	Air Conditioning
ABT	Averaging, Banking and Trading
AC	Alternating Current
ACEA	European Automobile Manufacturers Association
ACES	Advanced Collaborative Emission Study
AECD	Auxiliary Emissions Control Device
AEO	Annual Energy Outlook
AES	Automatic Engine Shutdown
AFDC	Alternative Fuels Data Center
AHS	American Housing Survey
Al	Aluminum
Al ₂ TiO ₅	Aluminum Titanate
AMOC	Atlantic Meridional Overturning Circulation
AMT	Automated Manual Transmission
ANL	Argonne National Laboratory
ANPR(M)	Advanced Notice of Proposed Rulemaking
APU	Auxiliary Power Unit
AQ	Air Quality
AQCD	Air Quality Criteria Document
AR4	Fourth Assessment Report
ARB	California Air Resources Board
ARB HHDDT	California Air Resources Board Heavy Heavy-Duty Diesel Test
ASC	Ammonia Slip Catalyst
ASL	Aggressive Shift Logic
ASM	Annual Survey of Manufacturers
ASTM	ASTM International, formerly American Society for Testing and Materials
ASTM	ASTM International, formerly known as American Society for Testing and Materials
AT	Automatic Transmissions
ATA	American Trucking Association
ATIS	Automated Tire Inflation System
ATRI	Alliance for Transportation Research Institute
ATSDR	Agency for Toxic Substances and Disease Registry
ATUS	American Time Use Survey
Avg	Average
B100	1 methyl-ester biodiesel fuel
B20	0.2 biodiesel blended with 0.8 petroleum distillate diesel fuel
BenMAP	Benefits Mapping and Analysis Program
BETP	Bleed Emissions Test Procedure
BEV	Battery Electric Vehicle
bhp	Brake Horsepower
bhp-hr	Brake Horsepower Hour
BLS	Bureau of Labor Statistics
BMEP	Brake Mean Effective Pressure
BSFC	Brake Specific Fuel Consumption
BTS	Bureau of Transportation Statistics
BTS	Bureau of Labor Statistics

BTU	British Thermal Unit
Ca	Calcium
CAA	Clean Air Act
CAAA	Clean Air Act Amendments
CaCO ₃	Calcium Carbonate
CAD/CAE	Computer Aided Design And Engineering
CAE	Computer Aided Engineering
CAFE	Corporate Average Fuel Economy
CAN	Controller Area Network
CARB	California Air Resources Board
CaSO ₄	Calcium Sulfate
CBI	Confidential Business Information
CCP	Coupled Cam Phasing
CCSP	Climate Change Science Program
CDA	Cylinder Deactivation
CDC	Centers for Disease Control
CDPF	Catalyzed Diesel Particulate Filter
CFD	Computational Fluid Dynamics
CFR	Code of Federal Regulations
CH ₄	Methane
CI	Compression-ignition
CILCC	Combined International Local and Commuter Cycle
CIPM	International Committee for Weights and Measures (Bureau International des Poids et Mesures)
CITT	Chemical Industry Institute of Toxicology
CMAQ	Community Multiscale Air Quality
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO ₂	Carbon Dioxide
CO ₂ eq	CO ₂ Equivalent
COFC	Container-on-Flatcar
COI	Cost of Illness
COPD	Chronic Obstructive Pulmonary Disease
CoV	Coefficient of Variation
CPS	Cam Profile Switching
CPSI	Cells per Square Inch
CRC	Coordinating Research Council
CRGNSA	Columbia River Gorge National Scenic Area
CRR	Rolling Resistance Coefficient
CS	Climate Sensitivity
CSI	Cambridge Systematics Inc.
CSS	Coastal Sage Scrub
CSV	Comma-separated Values
Cu	Copper
CuO	Copper(II) oxide or cupric oxide
CVD	Cardiovascular Disease
CVT	Continuously-Variable Transmission
CW	Curb Weight
D/UAF	Downward and Upward Adjustment Factor
DAAAC	Diesel Aftertreatment Accelerated Aging Cycle
DARAP	Diesel Aftertreatment Rapid Aging Protocol
DCP	Dual Cam Phasing
DCT	Dual Clutch Transmission

DE	Diesel Exhaust
DEAC	Cylinder Deactivation
DEER	Diesel Engine-Efficiency and Emissions Research
DEF	Diesel Exhaust Fluid
deSO _x	Removal of sulfur oxide compounds
DF	Deterioration Factor
DHHS	U.S. Department of Health and Human Services
Diesel HAD	Diesel Health Assessment Document
DMC	Direct Manufacturing Costs
DO	Dissolved Oxygen
DOC	Diesel Oxidation Catalyst
DOD	Department of Defense
DOE	Department of Energy
DOHC	Dual Overhead Camshaft Engines
DOT	Department of Transportation
DPF	Diesel Particulate Filter
DPM	Diesel Particulate Matter
DR	Discount Rate
DRIA	Draft Regulatory Impact Analysis
DVVL	Discrete Variable Valve Lift
EAS	Exhaust Aftertreatment System
EC	European Commission
EC	Elemental Carbon
EC	Economic Census
ECM	Electronic Control Module
ED	Emergency Department
EERA	Energy and Environmental Research Associates
EFR	Engine Friction Reduction
EGR	Exhaust Gas Recirculation
EHPS	Electrohydraulic Power Steering
EIA	Energy Information Administration (part of the U.S. Department of Energy)
EISA	Energy Independence and Security Act
EIVC	Early Intake Valve Closing
EMS-HAP	Emissions Modeling System for Hazardous Air Pollution
EO	Executive Order
EPA	Environmental Protection Agency
EPMA	electron probe microanalysis
EPS	Electric Power Steering
ERG	Eastern Research Group
ERM	Employment Requirements Matrix
ESC	Electronic Stability Control
ETC	Electronic Throttle Control
ETW	Estimated Test Weight
EV	Electric Vehicle
F	Frequency
FCEV	Fuel Cell Electric Vehicle
Fe	Iron
FEL	Family Emission Limit
FET	Federal Excise Tax
FEV1	Functional Expiratory Volume
FHWA	Federal Highway Administration
FIA	Forest Inventory and Analysis
FMCSA	Federal Motor Carrier Safety Administration

FOH	Fuel Operated Heater
FR	Federal Register
FRM	Final Rulemaking
FTP	Federal Test Procedure
FVC	Forced Vital Capacity
g	Gram
g/s	Gram-per-second
g/ton-mile	Grams emitted to move one ton (2000 pounds) of freight over one mile
gal	Gallon
gal/1000 ton-mile	Gallons of fuel used to move one ton of payload (2,000 pounds) over 1000 miles
GCAM	Global Change Assessment Model
GCW	Gross Combined Weight
GCWR	Rated Gross-combined Weight (vehicle + trailer)
GDI	Gasoline Direct Injection
GDI	Gasoline Direct Injection
GDP	Gross Domestic Product
GEM	Greenhouse gas Emissions Model
GEOS	Goddard Earth Observing System
GHG	Greenhouse Gas
GIFT	Geospatial Intermodal Freight Transportation
GPF	Gasoline Particulate Filter
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation
GSF1	Generic Speed Form one
GUI	Graphical User Interface
GVWR	Gross Vehicle Weight Rating
GVWR	Rated Gross Vehicle Weight
GWP	Global Warming Potential
H ₂ O	Water
HABs	Harmful Algal Blooms
HAD	Diesel Health Assessment Document
HC	Hydrocarbon
HD	Heavy-Duty
HDDE FTP	Heavy-Duty Diesel Engine Federal Test Procedure
HDE	Heavy-Duty Engine
HDOE FTP	Heavy-Duty Otto-Cycle Engine Federal Test Procedure
HDT	Heavy-Duty Truck
HDUDDS	Heavy Duty Urban Dynamometer Driving Cycle
HDV	Heavy-Duty Vehicle
HEG	High Efficiency Gearbox
HEI	Health Effects Institute
HES	Health Effects Subcommittee
HEV	Hybrid Electric Vehicle
HFC	Hydrofluorocarbon
HFET	Highway Fuel Economy Dynamometer Procedure
HHD	Heavy Heavy-Duty
HHDDT	Highway Heavy-Duty Diesel Transient
HNCO	Iso-cyanic Acid
hp	Horsepower
hrs	Hours
HRV	Heart Rate Variability
HSC	High Speed Cruise Duty Cycle
HTUF	Hybrid Truck User Forum

HWFE	Highway Fuel Economy Drive Cycle
hz	Hertz
IARC	International Agency for Research on Cancer
IATC	Improved Automatic Transmission Control
IC	Indirect Costs
ICCT	International Council on Clean Transport
ICD	International Classification of Diseases
ICF	ICF International
ICM	Indirect Cost Multiplier
ICP	Intake Cam Phasing
ICP-MS	Inductively coupled plasma mass spectrometry
IMAC	Improved Mobile Air Conditioning
IMPROVE	Interagency Monitoring of Protected Visual Environments
IPCC	Intergovernmental Panel on Climate Change
IRAF	infrequent regeneration factor
IRFA	Initial Regulatory Flexibility Analysis
IRIS	Integrated Risk Information System
ISA	Integrated Science Assessment
JAMA	Journal of the American Medical Association
k	Thousand
K	Potassium
kg	Kilogram
KI	kinetic intensity
km	Kilometer
km/h	Kilometers per Hour
kW	Kilowatt
L	Liter
LA92	Inventory development dynamometer driving schedule
lb	Pound
LD	Light-Duty
LDT	Light-Duty Truck
LHD	Light Heavy-Duty
LIVC	Late Intake Valve Closing
LLC	Low Load Cycle
LLNL	Lawrence Livermore National Laboratory's
LPG	Liquified Petroleum Gas
LRR	Lower Rolling Resistance
LSC	Low Speed Cruise Duty Cycle
LT	Light Trucks
LTCCS	Large Truck Crash Causation Study
LUB	Low Friction Lubes
LUC	Land Use Change
m ²	Square Meters
m ³	Cubic Meters
MAGICC	Model for the Assessment of Greenhouse-gas Induced Climate Change
MCF	Mixed Conifer Forest
MD	Medium-Duty
MDPV	Medium-Duty Passenger Vehicle
MECA	Manufacturers of Emissions Control Association
mg	Milligram
Mg	Magnesium
Mg(OH) ₂	Magnesium Hydroxide
mg/hp-hr	Milligrams per horsepower-hour

MHD	Medium Heavy-Duty
MHEV	Mild Hybrid
mi	mile
min	Minute
MM	Million
MMBD	Million Barrels per Day
MMT	Million Metric Tons
Mn	Manganese
MOVES	Motor Vehicle Emissions Simulator
MP-AES	Microwave Plasma Atomic Emission Spectroscopy
mpg	Miles per Gallon
mph	Miles per Hour
MRL	Minimal Risk Level
MSAT	Mobile Source Air Toxic
MT	Manual Transmission
MTS	Maximum Test Speed
MW	Megawatt
MY	Model Year
N ₂	Molecular Nitrogen
N ₂ O	Nitrous Oxide
Na	Sodium
NA	Not Applicable
NAAQS	National Ambient Air Quality Standards
NACFE	North American Council for Clean Freight Efficiency
NAFA	National Association of Fleet Administrators
NAICS	North American Industry Classification System
NAS	National Academy of Sciences
NASTC	National Association of Small Trucking Companies
NATA	National Air Toxic Assessment
NCAR	National Center for Atmospheric Research
NCI	National Cancer Institute
NCLAN	National Crop Loss Assessment Network
NEC	Net Energy Change Tolerance
NEI	National Emissions Inventory
NEMS	National Energy Modeling System
NEPA	National Environmental Policy Act
NESCAUM	Northeastern States for Coordinated Air Use Management
NESCCAF	Northeast States Center for a Clean Air Future
NESHAP	National Emissions Standards for Hazardous Air Pollutants
NH ₃	Ammonia
NHS	National Highway System
NHTSA	National Highway Traffic Safety Administration
NiMH	Nickel Metal-Hydride
NIOSH	National Institute of Occupational Safety and Health
NIST	National Institute for Standards and Technology
Nm	Newton-meters
NMHC	Nonmethane Hydrocarbons
NMMAPS	National Morbidity, Mortality, and Air Pollution Study
NO	Nitric Oxide
NO ₂	Nitrogen Dioxide
NOAA	National Oceanic and Atmospheric Administration
NO _x	Oxides of Nitrogen
NPRM	Notice of Proposed Rulemaking

NPV	Net Present Value
NRC	National Research Council
NRC-CAN	National Research Council of Canada
NREL	National Renewable Energy Laboratory
NTE	Not-to-exceed
NTEA	National Truck and Equipment Association
NTP	National Toxicology Program
NVH	Noise Vibration and Harshness
O&M	Operating and maintenance
O ₃	Ozone
OAQPS	Office of Air Quality Planning and Standards
OBD	Onboard diagnostics
OC	Organic Carbon
OE	Original Equipment
OEHHA	Office of Environmental Health Hazard Assessment
OEM	Original Equipment Manufacturer
OHV	Overhead Valve
OMB	Office of Management and Budget
OOIDA	Owner-Operator Independent Drivers Association
OPEC	Organization of Petroleum Exporting Countries
ORD	EPA's Office of Research and Development
ORNL	Oak Ridge National Laboratory
ORVR	On-Board Refueling Vapor Recovery
ORVR	Onboard refueling vapor recovery
OTAQ	Office of Transportation and Air Quality
P	Phosphorus
Pa	Pascal
PAH	Polycyclic Aromatic Hydrocarbons
PCV	Positive Crankcase Ventilation
PEF	Peak Expiratory Flow
PEMFC	Proton-Exchange Membrane Fuel Cell
PEMS	Portable Emissions Monitoring System
PFI	Port Fuel Injection
PFI	Port Fuel Injection
PGM	Platinum Group Metal
PHEV	Plug-in Hybrid Electric Vehicles
PLT	Production-line testing
PM	Particulate Matter
PM ₁₀	Coarse Particulate Matter (diameter of 10 µm or less)
PM _{2.5}	Fine Particulate Matter (diameter of 2.5 µm or less)
POM	Polycyclic Organic Matter
Ppb	Parts per Billion
Ppm	Parts per Million
Psi	Pounds per Square Inch
PTO	Power Take Off
R&D	Research and Development
RBM	Resisting Bending Moment
REL	Reference Exposure Level
RESS	Rechargeable Energy Storage System
RFA	Regulatory Flexibility Act
RfC	Reference Concentration
RFS2	Renewable Fuel Standard 2
RIA	Regulatory Impact Analysis

RMC-SET	Ramped Modal Cycle Supplementary Emissions Test
RPE	Retail Price Equivalent
RPM	Revolutions per Minute
RSWT	Reduced-Scale Wind Tunnel
S	Second
S	Sulfur
SAB	Science Advisory Board
SAB-HES	Science Advisory Board - Health Effects Subcommittee
SAE	SAE International, formerly Society of Automotive Engineers
SAR	Second Assessment Report
SAV	Submerged Aquatic Vegetation
SBA	Small Business Administration
SBREFA	Small Business Regulatory Enforcement Fairness Act
SCR	Selective Catalyst Reduction
SEA	Selective enforcement audit
SER	Small Entity Representation
SET	Supplemental Emission Test
SGDI	Stoichiometric Gasoline Direct Injection
SHED	Sealed Housing Evaporative Determination
SHEV	Strong Hybrid Vehicles
SI	Spark-Ignition
SiC	Silicon Carbide
SIDI	Spark Ignition Direct Injection
SO ₂	Sulfur Dioxide
SOA	Secondary Organic Aerosol
SOC	State of Charge
SOFC	Solid Oxide Fuel Cells
SOHC	Single Overhead Cam
SO _x	Sulfur Oxides
SO _x	Oxides of Sulfur
SPR	Strategic Petroleum Reserve
SSZ-13	A Chabazite-type Aluminosilicate ABC-6 Zeolite
STB	Surface Transportation Board
Std.	Standard
STP	Scaled Tractive Power
SUV	Sport Utility Vehicle
SVOC	Semi-Volatile Organic Compound
SwRI	Southwest Research Institute
TAR	Technical Assessment Report
TC	Total Costs
TCO	Total Cost of Ownership
TCp	Total Cost package
TDS	Turbocharging And Downsizing
THC	Total Hydrocarbon
TIAX	TIAX LLC
TMC	Technology & Maintenance Council
TOFC	Trailer-on-Flatcar
Ton-mile	One ton (2000 pounds) of payload over one mile
TRBDS	Turbocharging and Downsizing
TRU	Trailer Refrigeration Unit
TSD	Technical Support Document
TSS	Thermal Storage
TW	Test Weight

TWC	Three-Way Catalyst
U.S.	United States
U/DAF	Upward and Downward Adjustment Factor
UBE	Useable battery energy
UCT	Urban Creep and Transient Duty Cycle
UFP	Ultra Fine Particles
ULSD	Ultra-low sulfur diesel
URE	Unit Risk Estimate
USDA	United States Department of Agriculture
USGCRP	United States Global Change Research Program
UV	Ultraviolet
UV-b	Ultraviolet-b
VGT	Variable-geometry Turbine
VIN	Vehicle Identification Number
VIUS	Vehicle Inventory Use Survey
VMT	Vehicle Miles Traveled
VOC	Volatile Organic Compound
VSL	Vehicle Speed Limiter
VTEC-E	Variable Valve Timing & Lift Electronic Control-Economy
VTRIS	Vehicle Travel Information System
VVL	Variable Valve Lift
VVT	Variable Valve Timing
WACAP	Western Airborne Contaminants Assessment Project
WHR	Waste Heat Recovery
WHTC	World Harmonized Transient Cycle
WHVC	World Harmonized Vehicle Cycle
WRF	Weather Research Forecasting
WTP	Willingness-to-Pay
WTVC	World Wide Transient Vehicle Cycle
WVU	West Virginia University
Zn	Zinc
ZSM-5	Zeolite Socony Mobil-5, an Aluminosilicate Pentasil Zeolite within the family of zeolites

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Executive Summary

The Environmental Protection Agency (EPA) is proposing changes to heavy-duty highway engine and vehicle provisions. This draft RIA is generally organized to provide overall background information, methodologies, and data inputs, followed by results of the various analyses. A summary of each chapter of the draft RIA follows.

Chapter 1 describes key technologies that manufacturers could use to meet more stringent emissions standards for oxides of nitrogen (NO_x), particulate matter (PM), hydrocarbons (HC), and carbon monoxide (CO). The chapter introduces technologies specific to compression-ignition engines and spark-ignition engines, and also discusses fuel considerations, advanced powertrain technologies, and emission monitoring technologies that may apply across engine types.

Chapter 2 describes the existing test procedures as well as the development process for the test procedures being proposed for spark and compression ignition engine compliance. This includes the determination of emissions from both engines and hybrid powertrains as well as the development of new duty cycles.

Chapter 3 describes the technology feasibility demonstration programs, including engine technologies and emission control strategies for reducing NO_x, PM, NMHC, and CO. The technologies presented represent potential ways that the industry could meet the proposed stringency levels, and they provide the basis for the technology costs and benefits analyses.

Chapter 4 presents a discussion of the health effects associated with exposure ambient concentrations of ozone, PM, NO₂, CO, and air toxics. The discussion of health impacts is mainly focused on describing the effects of air pollution on the population in general. Additionally, children are recognized to have increased vulnerability and susceptibility related to air pollution and other environmental exposures; this and effects for other vulnerable and susceptible groups are discussed. The chapter also discusses the environmental effects associated with pollutants affected by this proposed rulemaking, specifically PM, ozone, NO_x and air toxics.

Chapter 5 presents our analysis of the national emissions impacts of the proposed and alternative standards for calendar years 2027 through 2045. In this chapter we quantify emissions from NO_x, volatile organic compounds (VOC), PM_{2.5}, CO, and others. The onroad national emissions inventories were estimated using an updated version of EPA's Motor Vehicle Emission Simulator (MOVES) model. Table ES-1 summarizes the projected reductions in heavy-duty emissions from the proposed Options 1 and 2 in 2045. In addition to describing the national emission inventories, this chapter describes the methods used to estimate the spatially and temporally-resolved emission inventories used to support the air quality modeling analysis documented in Chapter 6.

Table ES-1: Projected Heavy-Duty Emission Reductions in 2045 from the Proposed Options 1 and 2 Standards

Pollutant	Percent Reduction in Highway Heavy-duty Emissions	
	Proposed Option 1	Proposed Option 2
NO _x	61%	47%
Primary PM _{2.5}	26%	24%
VOC	21%	20%
CO	17%	16%

Chapter 6 presents information on air quality, including a discussion of current air quality, details related to the methodology used for the air quality modeling analysis, and results from the air quality modeling analysis. Reductions in emissions of NO_x, VOC, PM_{2.5}, and CO from the proposed standards are projected to lead to decreases in ambient concentrations of ozone, PM_{2.5}, NO₂, and CO. Specifically, the proposed standards would significantly decrease ozone design value concentrations across the country, with a population-weighted average decrease of 2 ppb in 2045. Ambient PM_{2.5}, NO₂ and CO concentrations are also predicted to improve in 2045 as a result of the proposed rule. The largest predicted improvements in both ozone and PM_{2.5} are estimated to occur in areas with the worst baseline air quality, where a substantially larger number of people of color are expected to reside. The emission reductions provided by the proposed standards would be important in helping areas attain the National Ambient Air Quality Standards (NAAQS) and prevent future nonattainment. In addition, the proposed standards are expected to result in improvements in nitrogen deposition and visibility but are predicted to have relatively little impact on ambient concentrations of air toxics.

Chapter 7 presents estimates of the costs associated with the emissions-reduction technologies that manufacturers could add in response to the proposed standards. We present these not only in terms of the upfront technology costs per engine as presented in Chapter 3 of this draft RIA, but also how those costs would change in the years following implementation. We present the costs associated with the proposed program elements of extended regulatory useful life and warranty. These technology costs are presented in terms of direct manufacturing costs and associated indirect costs such as warranty and research and development (R&D). The analysis also includes estimates of the possible operating costs associated with the proposed changes--the addition of new technology and extension of warranty and useful life periods. All costs are presented in 2017 dollars consistent with AEO 2018 unless noted otherwise. Table ES-2 presents the technology costs, operating costs and the sum of the two for each proposed option in 2045.

Table ES-2: Total Program Costs: Undiscounted Annual Costs in 2045 and Annualized Costs through 2045 at 3% and 7% Discount Rates (Billions of 2017 dollars)

		Total Technology Costs	Total Operating Costs	Sum
Proposed Option 1	2045 Annual	\$1.6	\$0.72	\$2.3
Proposed Option 2	2045 Annual	\$1.4	\$1.5	\$2.9
Proposed Option 1	Present Value, 3%	\$23	\$4.2	\$27
Proposed Option 2	Present Value, 3%	\$21	\$9.2	\$30
Proposed Option 1	Present Value, 7%	\$17	\$2.6	\$19
Proposed Option 2	Present Value, 7%	\$15	\$5.5	\$21
Proposed Option 1	Annualized, 3%	\$1.6	\$0.29	\$1.9
Proposed Option 2	Annualized, 3%	\$1.4	\$0.64	\$2.1
Proposed Option 1	Annualized, 7%	\$1.6	\$0.25	\$1.9
Proposed Option 2	Annualized, 7%	\$1.5	\$0.54	\$2.0

Chapter 8 describes the methods used to estimate health benefits from reducing concentrations of ozone and PM_{2.5}. For the proposed rulemaking, we have quantified and monetized health impacts in 2045, representing projected impacts associated with a year when the program would be fully implemented and when most of the regulated fleet would have turned over. We also discuss unquantified benefits associated with the standards that, if quantified and monetized, would increase the total monetized benefits. Overall, we estimate that the proposed program would lead to a substantial decrease in adverse PM_{2.5}- and ozone-related health impacts in 2045. Table ES-3 presents our estimates of total monetized benefits for proposed Options 1 and 2.

Table ES-3: 2045 Annual Value, Present Value and Equivalent Annualized Value of Benefits of the Proposed Options 1 and 2 (billions, 2017\$)^{a,b}

	Proposed Option 1		Proposed Option 2	
	3% Discount	7% Discount	3% Discount	7% Discount
2045	\$12 - \$33	\$10 - \$30	\$9.1 - \$26	\$8.2 - \$23
Present Value (2027-2045)	\$88 - \$250	\$52 - \$150	\$71 - \$200	\$41 - \$120
Annualized Value	\$6.0 - \$17	\$4.7 - \$13	\$5.0 - \$14	\$4.0 - \$11

^a All benefits estimates are rounded to two significant figures; numbers may not sum due to independent rounding. The range of benefits in this table are two separate estimates and do not represent lower- and upper-bound estimates, though they do reflect a grouping of estimates that yield more and less conservative benefits totals. The benefits in 2045 are presented in annual terms and are not discounted. However, all benefits in the table reflect a 3 percent and 7 percent discount rate used to account for cessation lag in the valuation of avoided premature deaths associated with long-term exposure.

^b The benefits associated with the standards presented here do not include the full complement of health, environmental, and climate-related benefits that, if quantified and monetized, would increase the total monetized benefits.

Chapter 9 compares the estimated range of total monetized health benefits to total costs associated with the proposed criteria pollutant program Options 1 and 2. This chapter also

presents the range of monetized net benefits (benefits presented in Chapter 8 minus costs presented in Chapter 7) associated with the same scenarios (see Table ES-4). EPA expects that implementation of the proposed rule would provide society with a substantial net gain in welfare, notwithstanding the health and other benefits we were unable to quantify (see draft RIA Chapter 8.8 for more information about unquantified benefits).^A

Table ES-4: 2045 Annual Value, Present Value and Equivalent Annualized Value of Costs, Benefits and Net Benefits of the Proposed Options 1 and 2 (billions, 2017\$)^{a,b}

		Proposed Option 1		Proposed Option 2	
		3% Discount	7% Discount	3% Discount	7% Discount
2045	Benefits	\$12 - \$33	\$10 - \$30	\$9.1 - \$26	\$8.2 - \$23
	Costs	\$2.3	\$2.3	\$2.9	\$2.9
	Net Benefits	\$9.2 - \$31	\$8.1 - \$28	\$6.2 - \$23	\$5.3 - \$21
Present Value	Benefits	\$88 - \$250	\$52 - \$150	\$71 - \$200	\$41 - \$120
	Costs	\$27	\$19	\$30	\$21
	Net Benefits	\$61 - \$220	\$33 - \$130	\$41 - \$170	\$21 - \$96
Equivalent Annualized Value	Benefits	\$6.0 - \$17	\$4.7 - \$13	\$5.0 - \$14	\$4.0 - \$11
	Costs	\$1.9	\$1.9	\$2.1	\$2.0
	Net Benefits	\$4.1 - \$15	\$2.9 - \$12	\$2.9 - \$12	\$2.0 - \$9.3

^a All benefits estimates are rounded to two significant figures; numbers may not sum due to independent rounding. The range of benefits (and net benefits) in this table are two separate estimates and do not represent lower- and upper-bound estimates, though they do reflect a grouping of estimates that yield more and less conservative benefits totals. The costs and benefits in 2045 are presented in annual terms and are not discounted. However, all benefits in the table reflect a 3 percent and 7 percent discount rate used to account for cessation lag in the valuation of avoided premature deaths associated with long-term exposure.

^b The benefits associated with the standards presented here do not include the full complement of health, environmental, and climate-related benefits that, if quantified and monetized, would increase the total monetized benefits.

Chapter 10 provides an economic analysis of the impacts of the proposed standards on vehicle sales and employment. This proposed rulemaking is considered economically significant, because it is expected to have an annual impact on the economy of \$100 million or more but is not expected to have measurable inflationary or recessionary effects. This chapter presents a peer-reviewed analysis to develop a relationship between estimated changes in vehicle price due to a new regulation and corresponding changes in vehicle sales (i.e., pre- and low-buy elasticities). We suggest an approach to quantify potential impacts on vehicle sales due to new emission standards; we also provide an example of how the results could be applied to the final regulatory analysis for this rule in draft RIA Chapter 10.1. Our example results for proposed Option 1 suggest pre- and low-buy for Class 8 trucks may range from zero to approximately two percent increase in sales over for a period of up to 8 months before the 2031 standards begin (pre-buy), and a decrease in sales from zero to approximately two percent over a period of up to 12 months after the 2031 standards begin (low-buy). The employment assessment focuses on the motor vehicle manufacturing and the motor vehicle parts manufacturing sectors, with some

^A EPA does not expect the omission of unquantified benefits to impact the Agency's evaluation of regulatory options since unquantified benefits generally scale with the emissions impacts of the proposed Options.

assessment of impacts on additional sectors likely to be most affected by the proposed standards. The employment assessment includes EPA's qualitative and quantitative estimates of the partial employment impacts of this proposed rule on regulated industries and an examination of employment impacts in some closely related sectors.

Chapter 11 presents our analysis of the potential impacts of the proposal on small entities that would be subject to the highway heavy-duty engine and vehicle provisions of this proposed rule. These are: heavy-duty vehicle manufacturers, heavy-duty secondary vehicle manufacturers, and heavy-duty alternative fuel engine converters. Other entities that would be subject to the rule are either not small (e.g., engine and incomplete vehicle manufacturers) or are not expected to incur any burden from the proposed rule (e.g., in sectors other than highway heavy-duty engines and vehicles). Our analysis estimates that no small entities would experience an impact of 3% or more of their annual revenue as a result of our proposal.

Chapter 1 Technology to Control Emissions from Heavy-Duty Engines

This chapter describes key technologies that manufacturers could use to meet more stringent emissions standards for oxides of nitrogen (NO_x), particulate matter (PM), hydrocarbons (HC), and carbon monoxide (CO). The chapter introduces technologies specific to compression-ignition engines and spark-ignition engines, and also discusses fuel considerations, advanced powertrain technologies, and emission monitoring technologies that may apply across engine types.

1.1 Compression-Ignition Engine Technologies

The following sections describe the compression-ignition engine technologies that we are considering for reducing criteria pollutant emissions as part of this proposed rulemaking. Many of the technologies are described with respect to diesel fuel, but they are expected to be broadly applicable to all fuels used in compression-ignition engines. Our compression-ignition engine feasibility demonstration for this proposal is based on some of the technologies presented in this section.

Chapter 3 of this draft RIA describes the existing and proposed test procedures for diesel-ignition engine certification. Chapter 4 describes the compression-ignition engine feasibility demonstration program, including a description of the specific technology package we are evaluating, and the effectiveness of those technologies over our current and proposed test procedures, and our projected cost of those technologies.

1.1.1 Current Catalyst Technologies

This section addresses technologies that, based on our current understanding, would be available in the 2024 to 2030 timeframe to reduce emissions and ensure robust in-use compliance. The following discussion introduces the technologies and emission reduction strategies we are considering for the proposed rulemaking, including thermal management technologies that can be used to better achieve and maintain adequate catalyst temperatures, and next generation catalyst configurations and formulations to improve catalyst performance across a broader range of engine operating conditions.

Modern diesel engines rely heavily upon catalytic exhaust aftertreatment systems (EAS) to meet exhaust emission standards. Current (MY2018-2020) heavy-duty diesel EAS consist of a diesel oxidation catalyst (DOC) followed by a catalyzed diesel particulate filter (CDPF), a urea injector, a urea mixer or other decomposition component, and then one or more selective catalytic reduction (SCR) catalyst substrates (Figure 1-1, Figure 1-2). Such systems are capable of reducing PM emissions by greater than 95% under most operating conditions and are capable of reducing NO_x emissions by 90 to 98% at exhaust temperatures above 250 °C.

Unreacted ammonia downstream of the SCR is typically referred to as "ammonia slip". An ammonia slip catalyst can be zone-coated onto the outlet of the rearmost SCR catalyst substrate (the case for most LHDDE and MHDDE and some HHDDE applications) or can be coated onto a separate catalyst substrate (some HHDDE applications) and uses platinum-group-metal (PGM) exchanged zeolites to promote reaction of ammonia remaining downstream of the SCR catalysts. Ammonia is an important air toxic compound and can also contribute to secondary PM formation. The use of closed-loop feedback electronic control of urea dosing using zirconia NO_x

sensors for NO_x feedback and the use of an ammonia slip catalyst (ASC) together can reduce ammonia emissions from modern EAS-equipped heavy-duty diesel engines to less than 4 mg/bhp-hr.¹ Some LHDDE applications using chassis dynamometer certification place the urea injector and SCR between the DOC and CDPF or combine SCR and CDPF functionality into one catalyst, sometimes referred to as selective catalytic reduction on filter (SCRf).

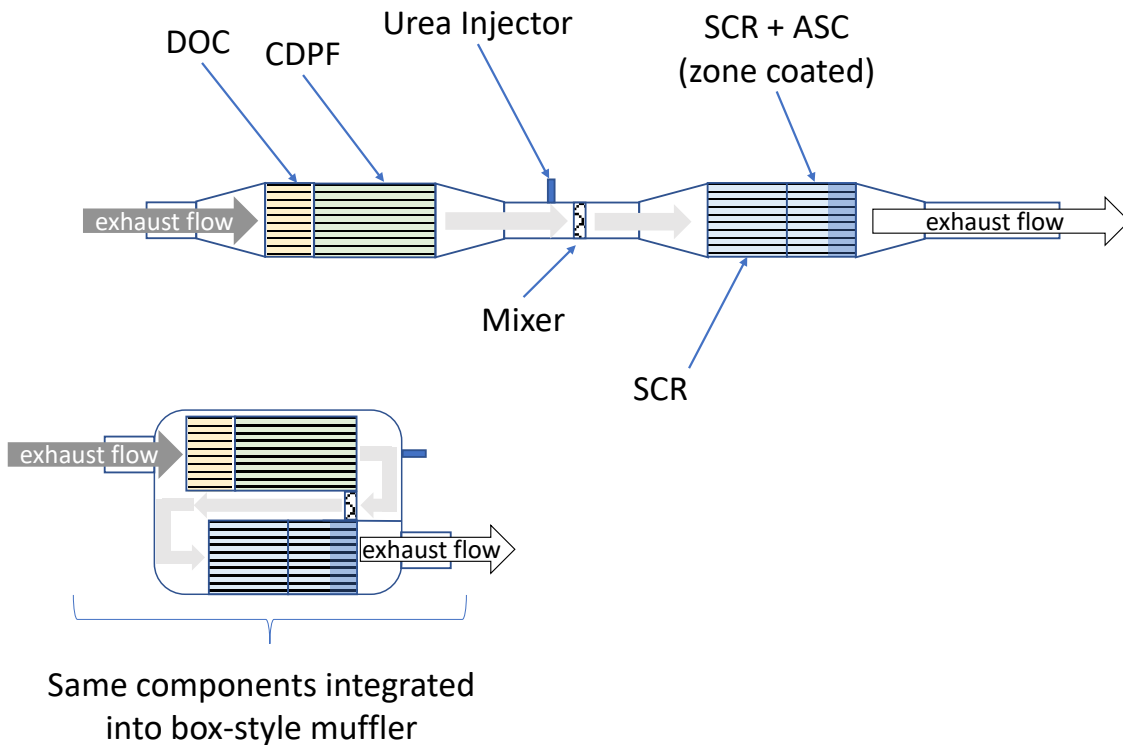


Figure 1-1: Functional schematic showing relative positioning of exhaust emission control components arranged within an in-line exhaust system (top) and integrated into a box-style system (bottom).



Figure 1-2: Integrated series heavy-duty truck exhaust emission control systems from Cummins Emission Solutions (top) and box-style system from Eberspächer (bottom), with cut-away showing some of the internal components (bottom right).^B

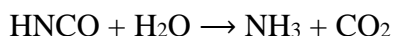
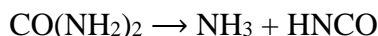
The DOC, SCR, and ASC typically use cordierite ceramic flow-through monolithic substrates that are wash-coated with active materials. The CDPF uses a wall-flow substrate made of either cordierite, silicon carbide (SiC), or aluminum titanate (Al_2TiO_5) for exhaust filtration (or "trapping") of particulate matter that is coated with active materials. Alternating cells of the wall-flow substrate are blocked, forcing the exhaust to flow through the porous substrate wall. The particulate matter, consisting primarily of elemental carbon soot, is filtered from the exhaust flow onto and within the wall of the CDPF and can then be oxidized to CO_2 using either passive regeneration with nitrogen dioxide (NO_2) or active regeneration with excess oxygen in the exhaust. Passive regeneration of the CDPF depends on oxidation of a fraction of nitric oxide (NO) emissions in the exhaust to NO_2 . Soot oxidation using NO_2 occurs at exhaust temperatures

^B Disclaimer: Any mention of trade names, manufacturers or products does not imply an endorsement by the United States Government or the U.S. Environmental Protection Agency. EPA and its employees do not endorse any commercial products, services, or enterprises.

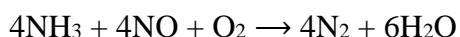
of approximately 250 °C, thus it does not require external heat addition to the exhaust under most operating conditions. Active regeneration using excess oxygen in the exhaust occurs at exhaust temperatures above 500 °C – 600 °C^C, and thus requires adding heat to the exhaust. This can be accomplished using one of several different approaches:

- Late, in-cylinder, post-injection of fuel after the primary combustion event and subsequent heat addition from the exothermic reaction of the excess fuel over the DOC and CDPF
- Direct injection of diesel fuel into the exhaust, with exothermic reaction of the fuel over the DOC and CDPF
- Use of an exhaust-integrated, external combustion burner system

Selective catalytic reduction (SCR) reduces nitrogen oxides NO_x (consisting of both NO and NO₂) to N₂ and water by using ammonia (NH₃) as the reducing agent. The SCR catalyst coatings used for post-2010 model-year heavy-duty diesel applications in the U.S. are typically copper (Cu) exchanged or iron (Fe) exchanged zeolites, (e.g., Fe-ZSM-5), and most SCR coatings for recent (MY2018-2020) applications are one of several different Cu and/or Fe-exchanged chabazite zeolite structures (e.g., Cu-SSZ-13). The method for supplying ammonia to the SCR catalyst is to inject a mixture of 32.5% urea in water solution into the exhaust stream. In the presence of high temperature exhaust gasses (> 180 - 250 °C)^D, the urea decomposes to form both NH₃ and iso-cyanic acid (HNCO) by thermolysis, with subsequent hydrolysis of the HNCO to form additional NH₃:



The “standard SCR reaction” of NO (the predominant NO_x species from diesel combustion) over transition-metal zeolite or vanadium SCR catalysts can be represented as:



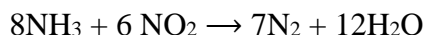
Improved reaction kinetics can be achieved at low exhaust temperatures (<300 °C) by oxidizing a portion of the NO in exhaust using a platinum-group-metal (PGM) coated diesel oxidation catalyst (DOC) to achieve a 1:1 molar ratio of NO:NO₂. The resulting “fast SCR reaction” is:



^C The temperature at which soot oxidation temperature occurs differs depending on the catalytic coating used on the CDPF.

^D Note that the urea decomposition temperature is dependent upon spray atomization, exhaust flow turbulence, and exhaust flow rate.

An NO₂ SCR reaction with limited NO availability also occurs, but at a significantly slower reaction rate than the standard SCR reaction and is sometimes referred to as the "slow SCR reaction":



The details of SCR reactions for NO_x reduction over transition-metal zeolite SCR can be better represented as a series of interrelated reactions that are part of a more complex redox cycle, such as the one proposed by Rudolf and Jacob.²

Urea dosing control takes into account a number of different factors, including:

- The stoichiometry of NO_x reduction by NH₃ (1:1 or 4/3:1 molar ratio)
- Molar ratio of NO:NO₂ at the inlet of the SCR catalyst
- The amount of NH₃ stored and released from the zeolites
 - Thermal desorption of stored NH₃ can allow NO_x reduction to occur at exhaust temperatures that are often too low for urea injection and decomposition
- The degree of urea/exhaust mixture preparation of the system design
 - Droplet formation and evaporation
 - Induced turbulent mixing of aqueous urea and exhaust to aid droplet breakup
- The efficiency of urea decomposition to NH₃ (> 95-98% at >250 °C is typical for modern injector/mixer designs)
- The probability forming solid deposits at low exhaust temperatures from partially decomposed urea
 - Urea injection at exhaust temperatures below approximately 180 to 200 °C can result in significantly increased deposit formation depending on mixture preparation and other factors
 - Urea injector fouling can occur from deposit build up on the urea injector tip and other exhaust system surfaces
 - Deposits can temporarily deactivate active catalytic surfaces, requiring higher temperature operation in order to remove the deposits

Copper (Cu) exchanged chabazite zeolites such as Cu-SSZ-13 have demonstrated good hydrothermal stability, good low temperature performance, and represent a large fraction of the transition-metal zeolite SCR catalysts used in heavy-duty applications.³ Improvements to both the coating processes and the substrates onto which the zeolites are coated have improved the low-temperature and high-temperature NO_x conversion, improved selectivity of NO_x reduction to N₂ (i.e., reduced selectivity to N₂O), and improved the hydrothermal stability. Improvements in SCR catalyst coatings over the past decade have included:^{4,5,6,7,8}

- Increased washcoat thickness

- Optimization of Silicon/Aluminum (Al) and Cu/Al ratios
- Increased Cu content and Cu surface area
- Optimization of the relative positioning of Cu^{2+} ions within the zeolite structure
- The introduction of specific co-cations
- Co-exchanging of more than one type of metal ion into the zeolite structure

In the absence of more stringent NO_x standards, these improvements have been realized primarily as reductions in SCR system volume, reductions in system cost, and improvements in durability since the initial introduction of metal-exchanged zeolite SCR in MY2010. Sales-weighted average engine-displacement-specific catalyst volumes for MY2019 MHDDE and HHDDE are shown in Table 1-1.

Table 1-1: Engine-displacement specific catalyst substrate volume for MY2019 MHDDE and HHDDE.

Component	MHDDE Specific Volume*	HHDDE Specific Volume*
DOC	0.61	0.74
CDPF	1.39	1.49
SCR	2.11	2.24
ASC	0.38	0.40
Notes: *Specific Volume = (catalyst total substrate volume) / (engine's piston swept displacement)		

NO_x reductions greater than 95% are possible with modern SCR systems over a broad range of operating conditions and at relatively high hours of operation, however SCR functionality is particularly reduced at lower exhaust temperatures due to difficulties with low-temperature urea decomposition and due to slower SCR reaction kinetics (Figure 1-3). In the figure, the initial data point at 140 °C SCR inlet temperature reflects NO_x reduction with stored ammonia only (no urea injection). The hours in the legend represent of operation over an accelerated aging cycle that included both thermal and chemical effects. The 1,430 hours of aging represented approximately 8,000 hours of equivalent engine operation. Reduced oxidation of NO to NO_2 over the DOC and DPF at low exhaust temperatures (e.g., 200 to 250 °C) reduces the ability to take advantage of the "fast SCR reaction". As previously mentioned, current SCR systems limit urea injection to temperatures above 180 °C to 200 °C to prevent urea injector and catalyst deposits. NO_x reduction reactions at temperatures below approximately 200 °C are thus reliant on use of NH_3 stored within the zeolite structure. During extended operation at low exhaust temperatures, stored NH_3 is eventually depleted and if exhaust temperatures cannot be increased sufficiently to allow initiation of urea injection and effective decomposition to NH_3 , then NO_x reduction eventually ceases.

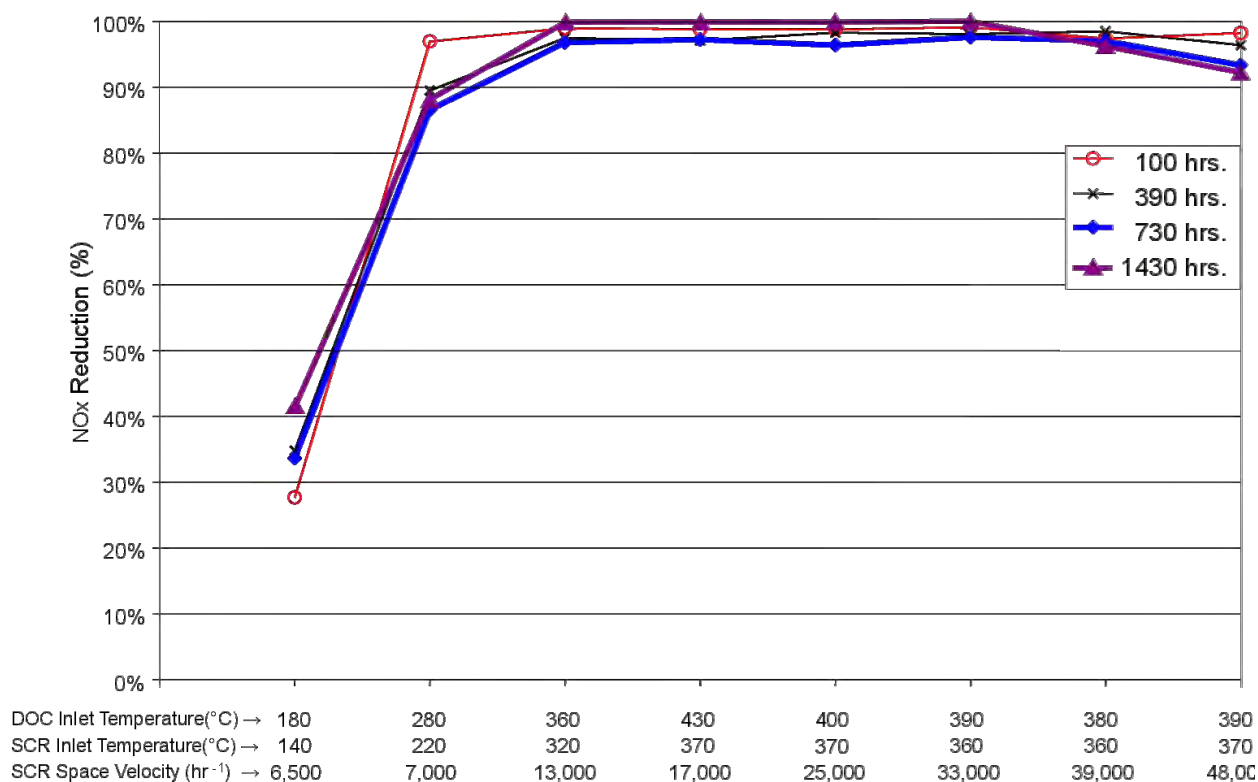


Figure 1-3: NO_x reduction efficiency of an early, developmental Cu-zeolite SCR formulation relative to DOC and SCR inlet temperatures and SCR space velocity (adapted from McDonald et al. 2011⁹).

Compression-ignition engine exhaust temperatures are relatively low following cold starts, during coasting downhill, during sustained idle, or at low vehicle speeds and during light load operation. Technologies that accelerate warm-up from a cold-start and maintain catalyst temperature above 200°C can help achieve further NO_x reduction from SCR systems under those types of operation. Technologies that improve urea decomposition to NH₃ at temperatures below 200°C can also be used to reduce NO_x emissions under cold start, coasting, light load, and low speed conditions.

1.1.2 Catalyst Durability

The regulatory full-useful-life for HHDDE emissions compliance with the fully-phased-in 2007 Heavy-duty Standards is 435,000 miles, ten years, or 22,000 hours of operation. Zeolite-based SCR systems have demonstrated high levels of NO_x reduction efficiency at the end of regulatory useful life. The aging mechanisms of diesel exhaust aftertreatment systems are complex and include both chemical and hydrothermal changes. Aging mechanisms on a single component can also cascade into impacts on multiple catalysts and catalytic reactions within the system due to the interrelated nature of catalytic reactions over upstream components on other aftertreatment components further downstream. Some aging impacts are fully reversible (i.e., conditions occur that can fully mitigate the aging impact). Other aging impacts are only partially reversible, irreversible, or can only be reversed with some form of intervention (e.g., changes to engine calibration to alter exhaust temperature and/or composition).

DOCs undergo reversible aging due to adsorption of hydrocarbons, soot and sulfur species; and irreversible aging due to phosphorus (P) poisoning^E and thermal sintering of platinum group metals (PGM) and other active materials. The catalytic materials on DPFs undergo similar aging impacts, and also continuously accumulate metallic ash, which typically accumulates towards the rear of the DPF channels. As accumulated ash migrates towards the front of the DPF channels, exhaust backpressure increases. Heavy-duty diesel exhaust systems, particularly those of HHDDE, are designed to allow CDPF removal for ash maintenance, often at approximately 250,000- to 350,000-mile intervals. Systems for LHDDE and MHDDE are typically designed with sufficient CDPF capacity to forgo ash maintenance within the current regulatory requirements for full useful life. Ash maintenance involves removal of the CDPF and application of either a dry cleaning process (e.g., reverse flushing of the CDPF with compressed air) or a wet cleaning process (e.g. reverse flushing of the CDPF with water or with a specific aqueous cleaning solution).

Aging of zeolite SCR is more complex. Hydrothermal aging of Cu-SSZ-13 SCR catalysts impacts both catalyst acidity and NH₃ adsorption, transforms active Cu sites into less active species, and causes Cu migration from exchanged positions within the zeolite structure and subsequent formation of aggregated CuO.¹⁰ The severity of hydrothermal aging increases in the presence of sulfur.¹¹

Chemical poisoning of SCR can occur from fuel and lubricant contaminants, or via degradation of upstream components. Sources of chemical poisoning include:

- Lubricant consumption
 - Zinc dialkyldithiophosphate anti-wear, antioxidant, and corrosion inhibiting additives
 - Phosphorus (P)
 - Zinc (Zn)
 - Sulfur (S)
- Fuel
 - S
 - Trace contaminants from biodiesel blending (alkali metals, e.g. Na, K)
 - Adsorption of hydrocarbon species into zeolite structure and subsequent blockage of pores through soot formation¹²
- Migration of metals from upstream components
 - PGM from the DOC and CDPF
 - Transition metal (e.g. Fe, Cu) oxides from upstream SCR components or along SCR substrates in series

Hydrothermal and chemical aging impacts on the DOC can also impact SCR NO_x reduction, particularly at low temperatures, via inhibition of NO to NO₂ oxidation necessary for the fast SCR reaction. The potential for future SCR durability improvements fall into the following categories:

^E The sources of P poisoning are from lubricating oil consumption and P-containing lubricating oil additives, such as zinc dithiophosphate.

- Designing excess capacity into the catalyst (e.g., increased catalyst volume, increased catalyst cell density, increased active material content and surface area)
- Use of a small-volume initial “sacrificial” substrate to adsorb chemical catalyst poisons upstream of the initial DOC or SCR substrate
- Continued improvements to zeolite materials
 - Further optimization of Silicon/Aluminum (Al) and Cu/Al ratios
 - Exchange of beneficial co-cations
 - Co-exchanging of more than one type of transition metal into the zeolite structure
 - Reducing pore size to inhibit HC adsorption and pyrolysis
- Direct hydrocarbon dosing downstream of the light-off SCR during active CDPF regeneration to reduce exposure of the light-off SCR to hydrocarbons and fuel contaminants
- Use of washcoat additives, changes to substrate porosity, and other improvements to increase PGM dispersion, reduce PGM particle size, reduce PGM mobility and reduce agglomeration within the DOC and CDPF washcoatings,
- Improvements to catalyst housings and substrate matting material to minimize vibration and prevent exhaust gas leakage around the substrate
- Reducing SCR and DOC sectional density, either through increased porosity or decreased cell wall thickness, thus lowering substrate mass and improving warm-up characteristics.
- Adjusting engine calibration and emissions control system design to minimize operation that would damage the catalyst (e.g., improved control of CDPF active regeneration, increased passive CDPF regeneration, HC dosing downstream of initial light-off SCR, direct temperature sensor feedback control of active regeneration and chemical deSOx)
- Use of specific engine calibration strategies for chemical deSOx of SCR (e.g., high temperature operation with urea dosing)¹³ to remove strongly-bound sulfur compounds from zeolite SCR
- Diagnosis and prevention of upstream engine malfunctions that can potentially damage exhaust aftertreatment components

Increased SCR catalyst capacity, along with incremental improvements to current zeolite coatings would be primary strategies for improving NO_x control over a longer regulatory useful life requirement. SCR capacity can be increased by approximately 40 to 50% with the use of a light-off SCR substrate combined with a downstream substrate with a moderate volume increase and with moderately increased catalytic activity from continued incremental improvements to chabazite and other zeolite coatings used for SCR. Total SCR volume would thus increase by approximately 50% to 80% relative to today’s systems. SCR capacity can also be increased in the downstream SCR system using thin-wall (4 to 4.5 mil), high cell density (600 cells-per-square-inch) substrates.

Chemical aging of the DOC, CDPF, and SCR can be reduced by the presence of an upstream light-off SCR or use of a small “sacrificial” substrate to adsorb chemical poisons. Transport and adsorption of sulfur (S), P, calcium (Ca), zinc (Zn), sodium (Na), and potassium (K) compounds and other catalyst poisons are more severe for the initial catalyst within an emissions control system and tend to reduce in severity for catalysts positioned further downstream. Chemical deSO_x strategies can be used to remove strongly-bound sulfur from zeolite SCR¹³. This involves

creating a strongly reducing environment via dosing of urea in excess of the typical 1:1 NH_3 to NO_x ratio at temperatures of approximately 500 °C to 550 °C. Further evolutionary improvements to the DOC washcoating materials to increase PGM dispersion and reduce PGM mobility and agglomeration are also anticipated for meeting increased useful life requirements.

The primary strategy for maintaining CDPF function to a longer useful life would be through design of integrated systems that facilitate easier removal of the CDPF for ash cleaning at regular maintenance intervals. Accommodation of CDPF removal for ash maintenance is already incorporated into many existing diesel exhaust system designs.^F Incremental improvements to catalyst housings and substrate matting material are also expected to be necessary for all catalyst substrates within the system. Integration into a box-muffler type system, is currently being used by a number of manufacturers and this approach is expected to continue for all catalyst components (except possibly for an initial close-coupled/light-off SCR) in order to improve passive thermal management and improve access to the DPF for ash maintenance.

1.1.3 Improving SCR NO_x Reduction at Low Exhaust Temperatures

The improvement of SCR NO_x reduction under low-speed (<1200 rpm) light-load (< 5-bar BMEP) conditions or immediately following cold starts will require improvements to both active and passive thermal management of the EAS.

1.1.3.1 Active Thermal Management

Active thermal management involves using engine hardware and associated control systems to maintain and/or increase exhaust temperatures. This can be accomplished through a variety of means, including engine throttling, heated aftertreatment systems, and exhaust flow bypass systems. Later combustion phasing can also be used for active thermal management.

Diesel engines operate at very low fuel-air ratios (i.e., with considerable excess air), and particularly so at low load (<5-bar BMEP) conditions. This causes relatively cool exhaust to flow through the exhaust system at low loads, which cools the catalyst substrates. This is particularly the case at idle. It is also significant at moderate-to-high engine speeds with little or no engine load, such as when a vehicle is coasting down a hill. Air flow through the engine can be reduced by induction and/or exhaust throttling. All modern heavy-duty diesel engines are equipped with an electronic throttle control (ETC) within the induction system and most are equipped with a variable-geometry-turbine (VGT) turbocharger, and these systems can be used to throttle the induction and exhaust system, respectively, at light-load conditions. However, throttling reduces volumetric efficiency^G, and thus has a trade-off relative to CO_2 emissions and fuel consumption.

Heat can be added to the exhaust and the EAS by burning fuel in the exhaust system or by using electrical heating, both of which can increase the SCR efficiency. Burner systems use an additional diesel fuel injector in the exhaust to combust fuel and create additional heat energy in the exhaust flow. Electrically heated catalysts use electric current applied to a metal foil monolithic structure in the exhaust to add heat to the exhaust flow. In addition, heated and higher-pressure urea dosing systems improve the decomposition of urea at low exhaust

^F Video by Eberspaecher demonstrating DPF removal for ash cleaning maintenance: https://youtu.be/lf_vysKbfaA

^G Relative efficiency of the air-exchange process in an internal combustion engine

temperatures and thus allow urea injection to occur at lower exhaust temperature (i.e., at approximately 135 °C to 140 °C). At light-load conditions with relatively high flow/low temperature exhaust, considerable fuel energy or electric energy would be needed for these systems. This would likely cause a considerable increase in CO₂ emissions and fuel consumption with conventional designs.

Exhaust flow bypass systems can be used to manage the cooling of exhaust during cold start and low load operating conditions. For example, significant heat loss occurs as the exhaust gases flow through the turbocharger turbine. Turbine bypass valves allow exhaust gas to bypass the turbine and avoid this heat loss at low loads when turbocharger boost requirements are low. In addition, an EGR flow bypass valve would allow exhaust gases to bypass the EGR cooler when EGR cooling is not required, such as immediately following a cold start or under cold ambient conditions. EGR cooler bypass is currently used in light-duty diesel and LHDDE applications.

Variable valve actuation (VVA) systems can also be used for active thermal management. VVA includes a family of valvetrain designs that alter the timing and/or lift of the intake and exhaust valves. Use of VVA can reduce pumping losses, increase specific power, and control the level of residual gases in the cylinder.

VVA has been adopted in light-duty vehicles to increase an engine's efficiency and specific power. It has also been used as a thermal management technology to open exhaust valves early to increase heat rejection to the exhaust and heat up exhaust catalysts more quickly. This VVA strategy, called early exhaust valve opening (EEVO), has been applied to the Detroit DD8¹⁴ to aid in CDPF regeneration, but a challenge with this strategy for maintaining aftertreatment temperature is that it reduces cycle thermal efficiency, and thus can contribute to increased CO₂ emissions.

Cylinder deactivation (CDA), late intake valve closing (LIVC), and early intake valve closing (EIVC) are three VVA strategies that can also be used to reduce airflow through the exhaust system at light-load conditions, and have been shown to reduce the CO₂ emissions and fuel consumption trade-off compared to use of the ETC and/or VGT for throttling.^{15,16,17,18}

Since we are particularly concerned with catalyst performance at low loads, EPA will be evaluating two valvetrain-targeted thermal management strategies that reduce air aspiration of engines at light-load conditions (i.e., less than 3-4 bar BMEP): CDA and LIVC. Both strategies force engines to operate at a higher fuel-air ratio in the active cylinders for a given load demand, which increases exhaust temperatures, with the benefit of little or no fuel consumption increase and with potential for fuel consumption decreases under some operating conditions. The key difference between these two strategies is that CDA completely removes airflow from one or more deactivated cylinders with the potential for exhaust temperature increases of up to 80 °C at light loads, while LIVC reduces airflow from all cylinders with up to 40 °C hotter exhaust temperatures.^{16,17,18}

One of the challenges of CDA is that it requires proper integration with the rest of the vehicle's driveline. This can be difficult in the vocational vehicle segment where an engine is often sold by the engine manufacturer (to a chassis manufacturer or body builder) without knowing the type of transmission or axle used in the vehicle or the precise duty cycle of the vehicle. The use of CDA requires fine tuning of the engine calibration as the engine moves into and out of deactivation to achieve acceptable noise, vibration, and harshness (NVH). Mitigation

strategies include changes to driveline dampening, motor mount and/or chassis dampening, and the use of dynamic CDA with individual cylinder deactivation control.

LIVC may provide emission reductions similar to fixed CDA, with the added benefits of no significant NVH concerns. A production-level LIVC system may also be cost-competitive or lower in cost compared to CDA, depending on how LIVC is implemented and depending on specific engine valvetrain design characteristics.

1.1.3.2 Passive Thermal Management

Passive thermal management involves changes or modifications to component designs to increase and maintain the exhaust gas temperatures without the use of active thermal management. It is done primarily through insulation and/or reducing the mass of EAS and other exhaust system components so that less exhaust energy input is required to reach catalyst light-off temperatures and/or the exhaust temperatures at which urea dosing can commence.¹⁹ Passive thermal management strategies generally have little to no impact on CO₂ emissions or can improve CO₂ emissions if used to replace an active thermal management strategy. The use of passive thermal management strategies for improving catalyst light-off in light-duty gasoline applications has led to significant reductions in cold-start exhaust emissions.²⁰ Passive thermal management design elements can be equally applied to EAS systems used in heavy-duty applications.

More specifically, using a smaller sized, initial SCR catalyst within the EAS with a high-porosity, lower density substrate reduces its mass and reduces catalyst warmup time. Moving the SCR catalyst nearer to the turbocharger outlet effectively reduces the available mass prior to the SCR inlet, minimizing heat loss and reducing the amount of energy needed to warm components up to normal operating temperatures. Reducing the mass of the exhaust system and insulating between the turbocharger outlet and the inlet of the SCR system using an air-gap or other insulation would reduce the amount of thermal energy lost through the walls. Close coupling of catalysts is near ubiquitous in modern light-duty EAS. The use of air-gap construction is also common in light-duty applications.

Dual-walled manifolds and exhaust pipes utilizing a thin inner wall and an air gap separating the inner and outer wall may be used to simultaneously insulate the exhaust system and reduce the thermal mass, minimizing heat lost to the walls and decreasing the time necessary to reach operational temperatures after a cold start. Mechanical insulation applied to the exterior of exhaust components, including exhaust catalysts, is readily available and can minimize heat loss to the environment and help retain heat within the catalyst as operation transitions to lighter loads and lower exhaust temperatures. Integrating the DOC, DPF, and SCR substrates into a single exhaust assembly can also assist with retaining heat energy.

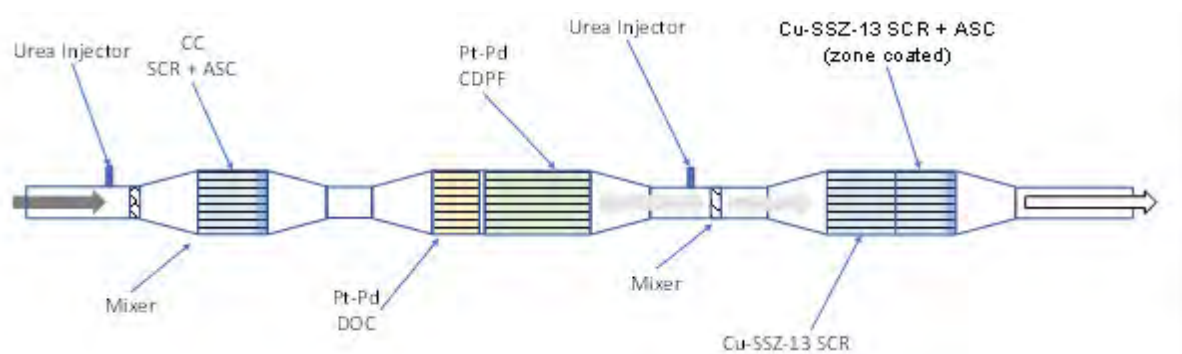
EPA is evaluating several passive thermal management strategies in the diesel technology feasibility demonstration program, including a light-off SCR located closer to the exhaust turbine (see draft RIA Chapter 1.1.3.3), use of an air-gap exhaust manifold and downpipe, use of lower mass, high-porosity and/or thin-wall substrates for the DOC and light-off SCR substrates, and use of an insulated and integrated single-box system for the DOC, DPF, and downstream SCR/ASC. We will evaluate their combined ability improve catalyst warmup and maintain higher exhaust temperatures under light-load conditions, which are anticipated to significantly reduce NO_x emissions during both in-use operation and over the regulatory engine dynamometer

test cycles used for engine certification (see draft RIA Chapter 4.1 for detailed discussion of our diesel technology demonstration programs).

1.1.3.3 Advanced SCR System Development

A recent development in SCR system architecture is the development of light-off or dual SCR systems, which is a variation of passive thermal management.^{16, 21, 22} This system maintains a layout similar to the conventional SCR configuration discussed earlier, but integrates an additional small-volume SCR catalyst, which is in some cases also close-coupled to the turbocharger's exhaust turbine outlet (Figure 1-4). This small SCR catalyst may be configured with or without an upstream DOC, and with or without a small sacrificial substrate to adsorb chemical poisons upstream of an initial SCR substrate. A recent example of this system's architecture was demonstrated as part of "Stage 3" of the California Air Resources Board (CARB) – Heavy-duty Low-NO_x Test Program.²³ The CARB Stage 3 research program is summarized within Chapter 4.1.1.1. EPA is evaluating dual-SCR catalyst system technology similar to the CARB "Stage 3" system as part of a diesel technology feasibility demonstration program (see Chapter 4.1.1.2 for more detail).

The benefits of this design result from its ability to warm up the initial light-off SCR substrate faster as a result of it being relatively low mass and being the first catalyst downstream of the turbocharger with the EAS. Such light-off SCR catalysts can also be designed to have smaller substrates with lower bulk density. The reduced mass reduces thermal inertia and allows faster warmup. The design also positions the urea injection and mixing as the very first components in the system, thus allowing faster heat up of the urea injector and urea mixer when implementing active thermal management measures. These designs also require less input of heat energy into the exhaust to maintain exhaust temperatures during light-load operation. Urea injection to the close-coupled light-off SCR can also be reduced or terminated once the second, downstream SCR reaches operational temperature, thus allowing additional NO_x to reach the DOC and CDPF to promote passive regeneration (soot oxidation) on the CDPF, reducing fuel consumption and CO₂ emissions. Very close-coupling of the light-off SCR to the exhaust turbine is possible when using heated urea dosing system since such systems enable a relatively short mixing length between the urea dosing system and the inlet of the light-off SCR (see Chapter 4.1.1.2 for more detail).



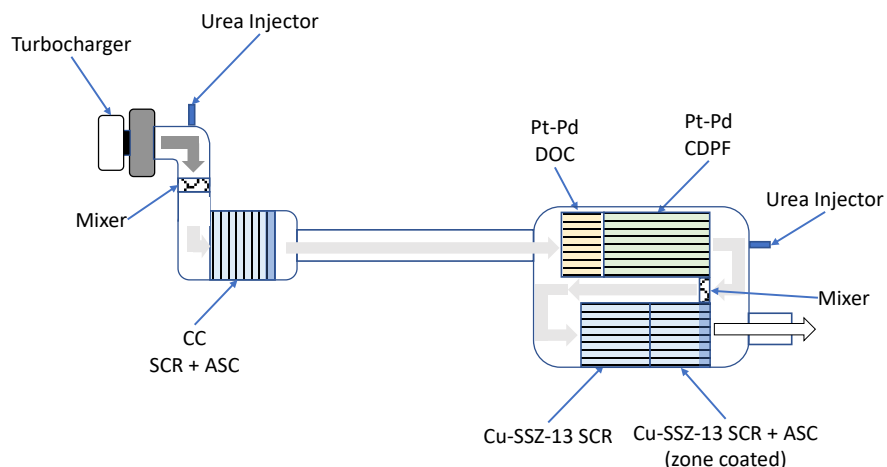


Figure 1-4: Potential layout of a 2027+ dual-SCR system in an in-line configuration (top) and comparable components integrated to improve passive thermal management (bottom).

One potential concern about this technology is the durability challenge associated with placing an SCR catalyst upstream of the CDPF. To address this concern, two light-off SCR system designs will be hydrothermally and chemically aged to an equivalent of 850,000 miles as part of the EPA Heavy-duty Diesel Low NO_x Demonstration Program. Please refer to Chapter 4.1.1.2 for additional information regarding this test program.

1.1.4 Closed Crankcases

During combustion, gases can leak past the piston rings sealing the cylinder and into the crankcase. These gases are called blowby gases and generally include unburned fuel and other combustion products. Blowby gases that escape from the crankcase are considered crankcase emissions (see 40 CFR 86.402-78). Current regulations restrict the discharge of crankcase emissions directly into the ambient air, and blowby gases from gasoline engine crankcases have been controlled for many years by sealing the crankcase and routing the gases into the intake air through a positive crankcase ventilation (PCV) valve. However, in the past there have been concerns about applying a similar technology for diesel engines. For example, high PM emissions venting into the intake system could foul turbocharger compressors. As a result of this concern, diesel-fueled and other compression-ignition engines equipped with turbochargers (or other equipment) were not required to have sealed crankcases (see 40 CFR 86.007-11(c)). For these engines, manufacturers are allowed to vent the crankcase emissions to ambient air as long as they are measured and added to the exhaust emissions during all emission testing to ensure compliance against the emission standards.

Because all new highway heavy-duty diesel engines on the market today are equipped with turbochargers, they are not required to have closed crankcases under the current regulations. Manufacturer compliance data show approximately one-third of current highway heavy-duty diesel engines have closed crankcases, indicating that some heavy-duty engine manufacturers have developed systems for controlling crankcase emissions that do not negatively impact the turbocharger. EPA is proposing provisions to require a closed crankcase ventilation system for all highway compression-ignition engines to prevent crankcase emissions from being emitted directly to the atmosphere (See Preamble Section III). These emissions could be routed upstream of the aftertreatment system or back into the intake system.

1.1.4.1 Emissions from Open Crankcases

EPA conducted emissions testing of open crankcase systems on two low mileage, modern heavy-duty diesel trucks.²⁴ The testing was conducted at EPA's National Vehicle and Fuel Emissions Laboratory. The two vehicles were tested on a heavy-duty chassis dynamometer where the crankcase flow and emissions were measured separately from the tailpipe exhaust emissions. The vehicles were tested over a variety of operating conditions. The cycles included the ARB Transient cycle with a cold start, repeat ARB Transient cycles, a 10 minute idle cycle, and a highway cycle at 55 mph and 65 mph.

The crankcase emission rates were calculated for THC, NMHC, CH₄, NO_x, CO₂, and CO using the densities found in 40 CFR 86.144-94. The average crankcase and tailpipe emission rates for each of the two trucks (NVFEL 1 and NVFEL 2) by test phase are shown in Figure 1-5. The error bars represent the standard error of the mean. As shown, the crankcase THC and CO emissions are a notable fraction of the tailpipe exhaust emissions. Table 1-2 includes the average crankcase emission rates across the cycles for each truck.

Table 1-2: Average Crankcase Emission Rates (gram/hour)

	THC	CH₄	NO_x	CO
Truck 1	0.305	0.001	1.19	0.212
Truck 2	0.067	0.026	1.09	0.832

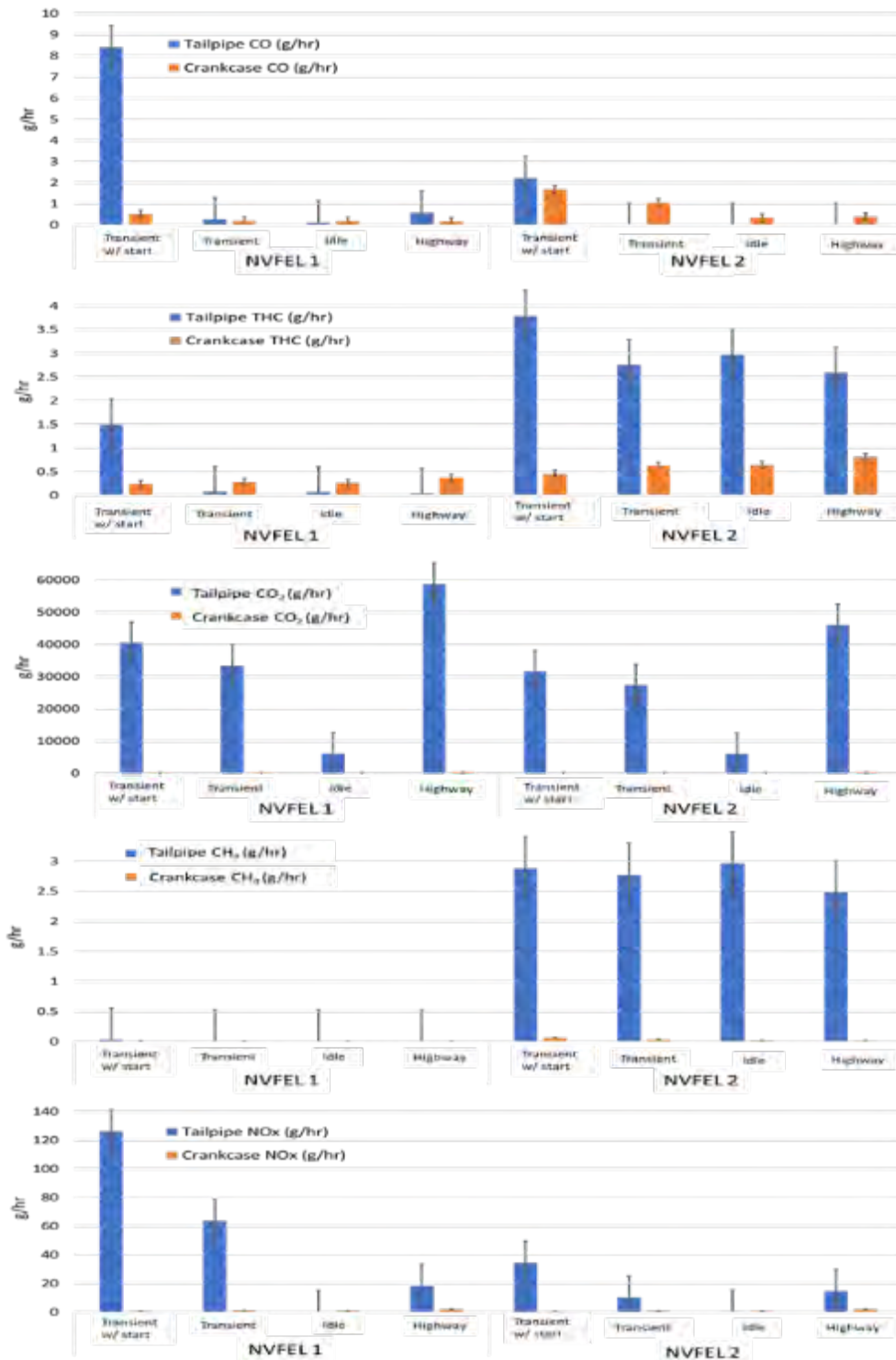


Figure 1-5: Tailpipe Exhaust and Crankcase Emission Rates from Two Heavy-Duty Diesel Trucks

We were unable to measure PM emissions from the crankcase as part of the EPA test program. Therefore, in our MOVES model we will continue to use the PM emission rates measured in the Advanced Collaborative Emissions Study (ACES) Phase 1 test program.²⁵ The average PM emission rate of the four 2007 MY heavy-duty diesel engines was 32.1 mg/hour.

1.1.4.2 Description of Closed Crankcase Technologies

Crankcase emissions are controlled through the use of closed crankcase filtration systems or by routing unfiltered blow-by gases directly into the exhaust system upstream of the emission control equipment. Closed crankcase filtration systems work by separating oil and particulate matter from the blow-by gases through single or dual stage filtration approaches, routing the blowby gases into the engine's intake manifold and returning the filtered oil to the oil sump. These systems are required for new heavy-duty diesel vehicles in Europe starting in 2000. Oil separation efficiencies in excess of 90 percent have been demonstrated with production ready prototypes of two stage filtration systems. By eliminating 90 percent of the oil that would normally be vented to the atmosphere, the system works to reduce oil consumption and to eliminate concerns over fouling of the intake system when the gases are routed through the turbocharger.

An alternative approach would be to route the blow-by gases into the exhaust system upstream of the catalyzed diesel particulate filter which would be expected to effectively trap and oxidize the engine oil and diesel PM. This approach may require the use of low sulfur engine oil to ensure that oil carried in the blow-by gases does not compromise the performance of the sulfur-sensitive emission control equipment.

Our feasibility analysis is based on the use of closed crankcase system that includes technologies designed to filter crankcase gases sending the clean gas to the engine intake for combustion and returning the oil filtered from the gases to the engine crankcase. These systems are proven in use.

1.1.5 Opposed-Piston Diesel Engines

While not part of EPA's planned technology demonstration program for the this rulemaking, the agency is tracking ongoing work to develop opposed-piston diesel engine technology for heavy-duty on-highway vehicle applications.^{26,27} One example of work with this technology is a project to develop and demonstrate a 10.6 liter, 450 hp opposed-piston diesel engine and related aftertreatment technologies for Class 8 line-haul tractors operating at certified emission performance levels of 0.02 g NO_x/bhp-h (90 percent below US 2010) and 432 g CO₂/bhp-h (2027 HD Phase 2 engine standard).²⁸ In addition to the emissions demonstration work, a high level cost study has been conducted by FEV that indicates the direct and indirect cost of an opposed-piston engine are less than that of a conventional HD diesel engine.²⁹ This project is supported by a variety of public and private sector partners including: Achates Power, Aramco Services Company, BASF, CALSTART, CARB, Corning, Delphi, Eaton, Faurecia, Federal Mogul, PACCAR/Peterbilt, Sacramento Metropolitan Air Quality Management District, San Joaquin Valley Air Pollution Control District, South Coast Air Quality Management District, Southwest Research Institute, Tyson Foods, and Walmart.³⁰

Opposed-piston engine technology has not yet been proven feasible in Class 8 on-highway applications, but if feasibility is shown, then the technology could provide another pathway to ultra-low NO_x, high efficiency engine technology for heavy-duty vehicle fleets. If the demonstration project cited above is successful, then it may lead to early-commercial deployment of opposed-piston diesel engines for heavy-duty on-highway applications in the near-term. As such, it may be reasonable to anticipate commercialization of heavy-duty opposed-piston diesel engine technology by model year 2027.

1.2 Spark-Ignition Engine Technologies

The following sections describe the spark-ignition engine technologies we considered to reduce criteria pollutant emissions (NMHC, CO, NO_x, and PM) as part of this rulemaking. Many of the technologies are described with respect to gasoline fuel, but they are expected to be broadly applicable to all fuels used in spark-ignition engines. Our spark-ignition engine feasibility demonstration for this proposal is based on some of the technologies presented in this section.

Chapter 2.3 of this draft RIA describes the existing and proposed test procedures for spark-ignition engine certification. Chapter 3.2 describes the spark-ignition engine feasibility demonstration program, including a description of the specific technology packages we evaluated, the effectiveness of those technologies over our current and proposed test procedures, and our projected cost of those technologies.

1.2.1 Technology Description for NMHC, CO, and NO_x Control

A range of technology options exist to reduce NMHC, CO, and NO_x emissions from both heavy-duty highway gasoline fueled spark ignition and diesel engines to levels below the current EPA 2007/2010 standards. Available options include modifications to the engine calibration, engine design, exhaust system, and aftertreatment system design. The different available options each contain specific benefits and limitations. This section describes the technical challenges to reducing emissions from current levels, describes available technologies for reducing emissions, estimates the potential emissions reduction of the different technologies, describes if there are other ancillary benefits to engine and vehicle performance with the technology, and reviews the limits of each technology. Except where noted, these technologies are applicable to all spark-ignition engines covered by this rule. Unique compression-ignition technologies are addressed in Section 1.1.

1.2.1.1 Summary of the Technology Challenge for NMHC, CO, and NO_x Control

Historically, heavy-duty spark-ignition engine FTP tests have shown that the majority of NMHC, CO, and NO_x emissions occur during the cold start phase; however, emissions during warmed-up and hot operation, specifically during high-load operation, can significantly contribute to emissions. Additionally, as described in Chapter 3.2, in-vehicle testing has indicated that sustained low load conditions such as prolonged idling can result in emission increases due to reduced aftertreatment temperatures (i.e. cool-off). The proposed standards in this rulemaking target high-load NMHC, CO and NO_x emission control performance. Specifically, significant quantities of NMHC and CO emissions can be produced if enrichment events occur regularly during high-load operation. Control of NO_x emissions during high-load operation requires designs that provide sufficient catalyst volume to handle the higher exhaust gas flow rates and also precise control of closed loop fuel biasing for the catalyst to maintain peak NO_x efficiency.

In order to achieve significantly lower NMHC, CO and NO_x emissions over the FTP, manufacturers can change the design of their exhaust and catalyst systems, as well as adopt calibration strategies to reduce catalyst light-off times and reduce warmed-up and hot running emissions. Design changes to reduce catalyst light-off time (e.g. closer catalyst placement) can

also result in higher catalyst temperatures during high-load operation. To achieve lower NMHC and NO_x levels, manufacturers will need to develop and implement technologies and calibration strategies to manage catalyst temperatures during high-load operation while minimizing fuel enrichment.

For the catalyst to effectively reduce NMHC, CO and NO_x emissions it must reach a light-off temperature of approximately 350 °C. Emissions during the catalyst warm up period can be reduced by reducing the emissions produced by the engine during the catalyst warm up phase. Emissions can also be reduced by shortening the time period required for the catalyst to reach the light-off temperature and maintaining sufficient catalyst temperature during low load and idle operation. Reducing warmed-up NO_x emissions requires improving the efficiency of the catalyst system using improved catalyst loading and washcoat technologies in addition to more precise calibration and software controls. NO_x emissions performance will also generally be reduced from a reduction in the sulfur content of the fuel.

To achieve the proposed heavy-duty emission standards, it is anticipated that engine manufacturers will focus on four areas to reduce emissions:

- Minimizing the emissions produced by the engine before the catalyst reaches the light-off temperature
- Reducing the time required for the catalyst to reach the light-off temperature and staying above the light-off temperature throughout all operation
- Improving the NO_x efficiency of the catalyst during warmed-up operation at medium and high loads
- Minimizing or eliminating enrichment in high-load operation.

We describe strategies to address these four areas in the following sections.

1.2.1.2 Reducing Engine-Out Emissions

During the first minutes of the cold start FTP, the engine is operating either at idle or low speed and load. The engine start temperature is between 20 and 30 °C (68 and 86 °F). At these temperatures and under these low loads the cold engine produces lower concentrations of NO_x than NMHC. As the engine warms up and as the load increases the concentration of NO_x produced by the engine increases and the concentration of NMHC decreases.

The design of the air induction system, combustion chamber, spark plug, and fuel injection system determine the quantity of fuel required for stable combustion to occur in the cold engine. Optimizing the performance of these components can provide reductions in the amount of fuel required to produce stable combustion during these cold operating conditions. Reductions in the amount of fuel required leads to reductions in cold start NMHC emissions.

The design considerations to minimize cold start emissions are also dependent on the fuel injection method. Port fuel injected (PFI) engines have different design constraints than gasoline direct injection (GDI) spark ignition engines. For both PFI and GDI engines, however, attention to the details affecting the in-cylinder air/fuel mixture can reduce cold start NMHC emissions.

For example, it has been shown that cold start NMHC emissions in PFI engines can be reduced by reducing the size of the fuel spray droplets and optimizing the spray targeting. Fuel impinging on cold engine surfaces in the cylinder does not readily vaporize and does not combust.³¹ Improving injector targeting to reduce the amount of fuel reaching the cylinder walls reduces the amount of fuel needed to create a combustible air fuel mixture. Reducing the size of the spray droplets improves the vaporization of the fuel and the creation of a combustible mixture. Droplet size can be reduced by modifying the injector orifice plate and by increasing the fuel pressure. Reducing droplet size and improving fuel vaporization during cold start has been shown to reduce cold transient emissions by up to 40 percent during the cold start phase of the light-duty FTP emission test.

The mixture formation process in a GDI engine is different than a PFI engine. In a PFI engine the fuel can be injected prior to or during the intake valve opening to prepare the fuel in an optimal manner for emission controls. The fuel generally has time to evaporate during the intake stroke as the fuel and air are drawn into the cylinder and is mixed with the incoming air. In addition, as the engine combustion heat from the previous firing events warms the intake valve and other surfaces in the area, the fuel can be injected into the intake runner and engine heat can assist in evaporating the fuel prior to the intake valve opening. The GDI engine injects fuel at higher fuel pressures than PFI engines directly into the combustion chamber. In a GDI engine, the fuel droplets need to evaporate and mix with the air in the cylinder in order to form a flammable mixture. Injecting directly into the cylinder reduces the time available for the fuel to evaporate and mix with the intake air in a GDI engine compared to a PFI engine. An advantage of the GDI design is that the fuel spray does not impinge on the walls of the intake manifold or other surfaces in the cylinder.

GDI systems stagger the injection timing event. At least one study has indicated that significant reductions in hydrocarbon emissions can be achieved by splitting the injections during the cold start of a GDI engine. An initial injection occurs during the intake stroke and a second injection is timed to occur during the compression stroke. This injection method reduced unburned hydrocarbon emissions 30 percent compared to a compression stroke only injection method.³²

These are two examples of specific engine design characteristics, fuel injector design and fuel system pressure on PFI engines and injection timing on GDI engines, which can be used to reduce cold start NMHC emissions significantly during the engine warm up prior to the catalyst reaching the light-off temperature.

Optimizing the fuel injection system design and calibration is anticipated to be used in all vehicle classes, including heavy-duty vehicles. It is anticipated that these described improvements, along with improvements to other engine design characteristics, will be used to reduce cold start emissions for passenger cars, LDTs, MDPVs, and HDTs in coming model years, which would pave the way for them to be applied to heavy-duty engines.

Because the engine is relatively cold and the operating loads are low during the first 50 seconds of operation, the engines typically do not produce significant quantities of NO_x emissions during this time. In addition, manufacturers tend to retard the combustion timing during the catalyst warm up phase. Retarding combustion timing has been shown also to reduce the concentration of NMHC in the exhaust. This calibration method further reduces peak combustion temperatures while increasing the exhaust gas temperature compared to optimized

combustion timing. The increased exhaust gas temperature leads to improved heating of the catalyst and reduced catalyst light-off times. Retarding combustion and other technologies for reducing catalyst light-off time are discussed in the following section.

1.2.1.3 Reducing Catalyst Light-Off Time

The effectiveness of current engine emission control systems depends in large part on the time it takes for the catalyst to light-off, which is typically defined as the catalyst reaching a temperature of 350°C. In order to reduce catalyst light-off time, it is expected manufacturers will use technologies that will improve heat transfer to the catalyst during the cold start phase and improve catalyst efficiency at lower temperatures. Technologies to reduce catalyst light-off time include calibration changes, thermal management, close-coupled catalysts, catalyst PGM loading, and secondary air injection. The technologies are described in greater detail below.

1.2.1.3.1 *Calibration Changes*

Engine calibration changes may be employed to increase the temperature and mass flow of the exhaust with the goal of reducing the amount of time required for the catalyst to reach the critical light-off temperature. By reducing the time required for the catalyst to light-off, these changes can effectively reduce NMHC, CO and NO_x emissions. Since the catalyst system in an SI engine is the predominant method to control emissions and is responsible for over a 95% reduction from the engine out emissions, any acceleration in the warm-up of the catalyst system translates into immediate emission reductions at the tailpipe.

Retarding combustion in a cold engine by retarding the spark advance is a well-known method for reducing the concentration of NMHC emissions in the exhaust and increasing the exhaust gas temperature.^{33,34} The reduction in NMHC concentrations is due to a large fraction of the unburned fuel within the cylinder combusting before the flame is extinguished at the cylinder wall. Reductions of total hydrocarbon mass of up to 40 percent have been reported from these studies evaluating the effect of spark retard on exhaust emissions.

In addition to reducing the NMHC exhaust concentration, retarding the spark advance reduces the torque produced by the engine. In order to produce the same torque and maintain the engine speed and load at the desired level when retarding the spark advance, the air flow into the engine is increased causing the manifold pressure to increase which can also improve combustion stability. Retarding the combustion process also results in an increase in the exhaust gas temperature. The retarded ignition timing during the cold start phase in addition to reducing the NMHC emissions increases the exhaust mass flow and exhaust temperature. These changes lead to a reduction in the time required to heat the catalyst.

The torque produced by the engine will begin to vary as the spark retard amount reaches engine combustion limits. As the torque variations increase, the combustion process is deteriorating, and the engine performance begins to degrade due to the partial burning. It is the level of this variability which defines the absolute maximum reduction in spark advance that can be utilized to reduce NMHC emissions and reduce the catalyst light-off time.

Retarding combustion during cold start can be applied to spark-ignition engines in all vehicle classes. The exhaust temperatures and NMHC emission reductions will vary based on engine design. This calibration methodology is anticipated to be used to improve catalyst warm-up times and reduce cold start NMHC emissions for all vehicle classes.

With the penetration of variable valve timing technology increasing in gasoline-fueled engines, additional work is being performed to characterize the impact of valve timing on cold start emissions. Calibration changes to the valve timing during the cold start phase can lead to additional reductions in cold start NMHC emissions.³⁵

1.2.1.3.2 *Exhaust System Thermal Management*

This category of technologies includes all design attributes meant to conduct combustion heat into the catalyst with minimal cooling. This includes insulating the exhaust piping between the engine and the catalyst, reducing the wetted area of the exhaust path, reducing the thermal mass of the exhaust system, and/or using close-coupled catalysts (i.e., the catalysts are packaged as close to the engine cylinder head as possible to mitigate the cooling effects of longer exhaust piping). By reducing the time required to achieve catalyst light-off, thermal management technologies reduce NMHC, CO and NO_x emissions.

Moving the catalyst closer to the cylinder head is a means that manufacturers have been using to reduce both thermal losses and the catalyst light-off time. Many vehicles today use close-coupled catalysts, a catalyst which is physically located as close as possible to the cylinder head. Moving the catalyst from an underbody location closer to the cylinder head reduces the light-off time significantly.

Another means for reducing heat losses is to replace cast exhaust manifolds with thin-wall stamped manifolds. Reducing the mass of the exhaust system reduces the heat losses of the system. In addition, an insulating air gap can be added to the exhaust system which further reduces the heat losses from the exhaust system. Insulating air gap manifolds are also known as dual-wall manifolds.

With thin- and dual-wall exhaust manifolds, close-coupled catalyst housings can be welded to the manifold. This reduces the needed for manifold to catalyst flanges which further reduces the thermal inertia of the exhaust system. Close coupling of the catalyst and reducing the thermal mass of the exhaust system significantly reduces the light-off time of the catalyst compared to an underbody catalyst with flanges and pipes connected to a cast exhaust manifold.

Using close-coupled catalysts reduces the heat losses between the cylinder head and catalyst. While reducing the time required to light-off the catalyst the close-coupled catalyst can be subject to higher temperatures than underbody catalysts during high-load operating conditions. To ensure the catalyst does not degrade, manufacturers currently use fuel enrichment to maintain the exhaust temperatures below the levels which would damage the catalyst. It is anticipated that to meet the proposed heavy-duty emission standards, manufacturers will ensure that fuel enrichment is minimized on the FTP. Calibration measures, other than fuel enrichment, may therefore be needed to ensure the catalyst temperature does not exceed the maximum limits.

Another technology beginning to be used for both reducing heat loss in the exhaust and limiting exhaust gas temperatures under high-load conditions is integrating the exhaust manifold into the cylinder head. Honda utilized this technology on the Insight's 1.0 L VTEC-E engine. The advantage of this technology is that it minimizes exhaust system heat loss during warm-up. In addition, with the exhaust manifold integrated in the cylinder head, the cooling system can be used to reduce the exhaust temperatures during high-load operation. It is anticipated that

manufacturers will further develop this technology as a means to both quickly light-off the catalyst and reduce high-load exhaust temperatures.

We expect thermal management to be an effective strategy for manufacturers to lower NMHC, CO and NO_x emission levels. Our feasibility demonstration described in Chapter 3.2 evaluates catalysts located closer to the engine as a method of thermal management. We expect that manufacturers will further optimize the thermal inertia of the exhaust system to minimize the time needed for the catalyst to achieve the light-off temperature, while ensuring the high-load performance does not cause thermal degradation of the catalyst system. It is expected that methods and technologies will be developed to reduce the need to use fuel enrichment to reduce high-load exhaust temperatures.

Optimizing the catalyst location and reducing the thermal inertia of the exhaust system are design options manufacturers can apply to all vehicle classes for improving engine cold start emission performance. It is not anticipated that heavy-duty vehicles with spark-ignition engines will utilize catalysts that are very close-coupled to the exhaust manifold (i.e., will not use a strategy similar to close-coupled catalyst locations found on passenger cars and light-duty trucks). The higher operating loads of these heavy-duty engines results in durability concerns due to high thermal loading. It is expected that manufacturers will work to optimize the thermal mass of the exhaust systems to reduce losses along with optimizing the underbody location of the catalyst. These changes are expected to improve the light-off time while not subjecting the catalysts to the higher thermal loadings from a close coupled location.

1.2.1.3.3 *Catalyst Design Changes*

There are several different catalyst design changes that can be implemented to reduce the time for the catalyst to light-off. Changes include modifying the substrate design, replacing a large volume catalyst with a cascade of two or more catalysts, and optimizing the loading and composition of the platinum group metals (PGM).

Progress continues to be made in the development of the catalyst substrates which provide the physical support for the catalyst components, which typically include a high surface area alumina carrier, ceria used for storing oxygen, PGM catalysts, and other components. A key design parameter for substrates is the cell density. Today, catalyst substrates can be fabricated with cell densities up 1,200 cells per square inch (cps) with wall thicknesses approaching 0.05 mm.

Increasing the surface area of the catalyst improves the performance of the catalyst. Higher substrate cell densities increase the surface area for a given catalyst volume. Higher surface areas improve the catalyst efficiency and durability reducing NMHC and NO_x emissions.

The key limitation of the higher cell density substrates is increased exhaust system pressures at high-load conditions. The cell density and substrate frontal area are significant factors that need to be considered to optimize the catalyst performance while limiting flow loss at high-load operation.

Engine speeds and load are low during the first 50 seconds of the FTP test and it is a challenge to achieve catalyst light-off during the cold start operation. One method for reducing the catalyst light-off time is to replace a single catalyst with two catalysts which when combined total the same volume as the single catalyst. Having a two-catalyst system that includes a close-coupled, front catalyst with comparatively reduced-volume reduces the heat needed to reach the

light-off temperature for the front catalyst due to its location and reduced thermal mass. The front catalyst of the two-catalyst system will reach operating temperature before the individually larger volume single catalyst, reducing the light-off time of the system.

All other parameters held constant, increasing the PGM loading of the catalyst also improves the efficiency of the catalyst. The ratio of PGM metals is important as platinum, palladium, and rhodium have different levels of effectiveness promoting oxidation and reduction reactions. Therefore, as the loading levels and composition of the PGM changes, the light-off performance for both NMHC and NO_x need to be evaluated. Improved catalyst substrates and PGM loadings designs additional effective approaches to reduce emissions and we anticipate manufacturers will incorporate advanced catalyst designs in their future emission strategies.³⁶ We used an advanced catalyst formulation in our HD SI feasibility demonstration for this rule (see Chapter 3.2).

1.2.1.3.4 *Secondary Air Injection*

By injecting air directly into the exhaust stream, close to the exhaust valve, combustion (hydrocarbon oxidation) can be maintained within the exhaust, creating additional heat and thereby further increasing the catalyst temperature. The air/fuel mixture must be adjusted to provide a richer exhaust gas for the secondary air to be effective.

Secondary air injection systems are used after the engine has started and once exhaust port temperatures are sufficiently high to sustain combustion in the exhaust port. When the secondary air pump is turned on the engine control module increases the amount of fuel being injected into the engine. Sufficient fuel is added so that the air/fuel ratio in the cylinder is rich of stoichiometric. The exhaust contains significant quantities of CO and hydrocarbons. The rich exhaust gas mixes with the secondary air in the exhaust port and the combustion process continues, increasing the temperature of the exhaust and rapidly heating the manifold and close-coupled catalyst.^{37,38}

Engines which do not use secondary air injection can only operate rich of stoichiometry for a minimal amount of time after a cold start as the added enrichment would cause increased NMHC emissions. The richer cold start calibration used with vehicles that have a secondary air injection system provides a benefit, as combustion stability is improved. In addition, the richer calibration is not as sensitive to changes in fuel volatility. Less volatile fuels found in the market may result in poor start and idle performance on engines calibrated to run lean during the cold operation. Engines which use secondary air and have a richer warm up calibration would have a greater combustion stability margin. Manufacturers may perceive this to be a benefit for the operation of their vehicles during the cold start and warm up phase.

Historically, secondary air injection has also been used to control CO and NMHC emissions during high load rich operation. These designs incorporated a mechanically driven air pump that would continuously inject air into part of the catalyst to oxidize the CO and NMHC emissions, a particularly important emission control technology used during enrichment operation. With the improvements in electronic engine controls, all manufacturers discontinued the use of secondary air injection for the purpose of high load enrichment and instead used software models and other algorithms that maintain stoichiometric operation for slightly longer periods of operation than previously. These newer strategies however were designed to only provided a temporary emission control benefit of stoichiometric operation since the engines eventually go into

enrichment modes for either power improvement or thermal protection at which point the CO and NMHC emissions are no longer controlled.

1.2.1.4 Improving Catalyst NO_x Efficiency during Fully Warmed-up Operation

For engines certified to the EPA 2007/2010 emission standards, significant quantities of NO_x emissions are produced by engines during warmed-up engine operation on the FTP. The stabilized NO_x emission levels will need to be reduced to achieve the proposed heavy-duty NMHC, CO and NO_x emission standards. Improving the NO_x performance of the engine can be achieved by improving the catalyst efficiency during warmed-up operation. As previously described, the performance of the catalyst can be improved by modifications to the catalyst substrate, increasing cell density, increasing PGM loadings, and, particularly important, reducing the sulfur level of gasoline. Three-way catalyst efficiency is also affected by frequency and amplitude of the air/fuel ratio. For some engines warmed-up catalyst NO_x efficiency can be improved by optimizing the air/fuel ratio control and limiting the amplitude of the air fuel ratio excursions. It is anticipated that a combination of changes will be made by manufacturers, including further improvements to air/fuel ratio calibration and catalyst changes including cell density and PGM loadings.

1.2.1.5 Reducing Enrichment

Heavy-duty vehicles tend to operate at high loads and catalyst durability can be a concern due to the increased thermal loading as the catalyst is moved closer to the cylinder head. Moving the catalyst closer to the exhaust manifold could result in increasing the time spent in fuel enrichment modes to ensure the catalyst temperatures are maintained below design thresholds, which if allowed to operate too hot could reduce the durability of the catalyst. Using fuel enrichment to control catalyst temperature while effective, causes significant increases in criteria pollutant emissions and also significant increases in fuel consumption.

1.2.1.5.1 *Exhaust Gas Temperature Measurement*

The methodology for determining when temperatures in the exhaust and in the catalyst are high enough to initiate thermal protection (i.e., enrichment) is almost exclusively done using software modeling of the thermally-limited components. This methodology can be effective at triggering enrichment when needed; however, if it is implemented in an excessively conservative manner where the temperature prediction is higher than the actual critical component temperature, it can result in unnecessary enrichment episodes which lead to substantial increases in all the emissions. Since the gasoline heavy-duty engines are designed for work and are expected to operate regularly at high loads where the exhaust temperatures become important concerns for component durability, any improvement in the accuracy of the methodology to provide enrichment protection will result in both reductions in emissions and improvements to durability.

A potential improvement over the current practice of using temperature modeling is use of hardware in the form of temperature measurement sensors in the exhaust at the most critical locations, generally at the catalyst inlet. While some light-duty variations are available, currently, only one gasoline HD product, the Nissan NV series of cargo vans with the 5.6L V8 has implemented temperature sensors.³⁹ However, temperature measurement sensors are very common in all diesel applications. While this improvement to the accuracy of temperature

measurements in the exhaust may not result in emission reductions during the limited operation range of today's certification test cycles, it will likely provide "real world" emission reductions compared to modeled temperature strategies that may conservatively trigger enrichment episodes prematurely.

1.2.1.5.2 *Continuous Stoichiometric Operation*

One concept that has been used in other non-road sectors (e.g., large SI engines operating indoors or confined areas) is requiring the engine to always operate at stoichiometry where the three-way catalyst is generally at peak efficiency for all emissions. To apply this strategy to heavy-duty highway SI engines, manufacturers would have to prevent the engine from entering enrichment. Enrichment could be avoided with upgrades to materials of specific components that are currently limited by high temperature constraints, or using the large degree of modern engine control authority to prevent the engine from entering areas of operation that require enrichment. Modern gasoline engines have several engine hardware components and calibration strategies that could be used to reduce temperatures by modifying combustion or load characteristics, such as EGR, valve timing, electronic throttle airflow, cylinder deactivation, and other available methods. Some of these methods to remain in stoichiometric air-fuel control may result in a governing or detuning of the engine after a period of time to avoid prolonged high power operation where stoichiometric operation cannot be maintained due to increasing exhaust component temperatures; however, this may be an acceptable approach for a sector where sustained absolute engine power may not be necessary or as important as lower emissions and better fuel economy.

While we were unable to directly control enrichment in our HD SI feasibility demonstration, in Chapter 3.2 we show that emissions can be well-controlled when an engine maintains stoichiometric operation. We expect engine manufacturers will continue to optimize their engine calibrations and limit enrichment as an effective means of reducing NMHC and CO emissions to meet future standards.

1.2.1.6 Additional Emission Control Strategies

A strategy that may provide some degree of emission reductions involves down-speeding or governing of the engine operating range to keep the engine speeds and loads in areas where engine hardware and exhaust temperatures minimize needed enrichment for thermal protection. This strategy will allow the emission controls to remain in stoichiometric air-fuel control (i.e. closed loop) where the catalysts can maintain peak efficiency for NMHC, CO and NO_x for a broader range of operation.

The down-speeding approach was a technology discussed to reduce CO₂ emissions for the HD Phase 2 GHG rule⁴⁰ and has been successfully implemented in both gasoline and diesel applications to reduce GHG emissions. With the advent of modern electronic controls of both engine and transmission, the opportunity exists to precisely keep the engine in the optimal operating areas for reduced GHG and criteria emissions. Multi-speed automatic transmissions available in recent years in HD applications with wide ratios containing 6 or more forward gears have provided the opportunity to operate the engine in a more optimal fashion with little or no loss of vehicle performance and capabilities. This strategy is currently used by at least one HD gasoline engine manufacturer as indicated by its advertised maximum rated test speed (i.e. peak horsepower) of approximately 4000 RPM compared to the much higher speeds, over 4700 RPM

of other HD applications.⁴¹ This lower speed is made possible by transmission strategies preventing over-speeding, which allows the emission controls to operate in a much more desirable and lower emitting area of engine operation. We evaluated engine down-speeding as part of the HD SI feasibility demonstration presented in Chapter 3.2.

1.2.2 **Technology Description for PM Control**

Particulate matter emitted from internal combustion engines is a multi-component mixture composed of elemental carbon (or soot), semi-volatile organic compounds (SVOC), sulfate compounds (primarily sulfuric acid) with associated water, nitrate compounds and trace quantities of metallic ash. At temperatures above 1,300 K, fuel hydrocarbons without access to oxidants can pyrolyze to form particles of elemental carbon. Fuel pyrolysis can occur as the result of operation at richer than stoichiometric air-to-fuel ratio (primarily PFI gasoline GDI engines), direct fuel impingement onto surfaces exposed to combustion (primarily GDI and diesel engines), and non-homogeneity of the air-fuel mixture during combustion (primarily diesel engines). Elemental carbon particles that are formed can be oxidized during later stages of combustion via in-cylinder charge motion and reaction with oxidants.

SVOCs are composed primarily of organic compounds from lubricant and partial combustion products from fuel. PM emissions from SVOC are typically gas phase when emitted from the engine and contribute to PM emissions via particle adsorption and nucleation after mixing with air and cooling. Essentially, PM-associated SVOC represent the condensable fraction of NMHC emissions. Sulfur and nitrogen compounds are emitted primarily as gaseous species (SO_2 , NO and NO_2). Sulfate compounds can be a significant contributor to PM emissions from stratified lean-burn gasoline engines and diesel engines, particularly under conditions where PGM containing exhaust catalysts used for control of gaseous and PM emissions oxidize a large fraction of the SO_2 emissions to sulfate (primarily sulfuric acid). Sulfate compounds do not significantly contribute to PM emissions from spark-ignition engines operated at near stoichiometric air-fuel ratios due to insufficient availability of oxygen in the exhaust for oxidation of SO_2 over PGM catalysts.

Elemental carbon PM emissions can be controlled by:

- Reducing fuel impingement on piston and cylinder surfaces
- Inducing charge motion and air-fuel mixing via charge motion (e.g., tumble and swirl) or via multiple injection (e.g., GDI and diesel/common rail applications)
- Injection strategies that eliminate opportunity for PM forming conditions (open valve injection on PFI)
- Reducing or eliminating operation at net-fuel-rich air-to-fuel ratios (PFI gasoline and GDI applications)
- Use of wall-flow or partial-wall-flow exhaust filters (GPF)

SVOC PM emissions can be controlled by:

- Reducing lubricating oil consumption

- Improvements in exhaust catalyst systems used to control gaseous NMHC emissions (e.g., increased PGM surface area in the catalyst, improvements in achieving catalyst light-off following cold-starts, etc.)

1.2.3 Technologies to Address Evaporative 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. To evaluate the evaporative emission performance of current production heavy-duty gasoline vehicles, EPA tested two heavy-duty vehicles over running loss, hot soak, three-day diurnal, on-board refueling vapor recovery (ORVR), and static test procedures. These engine-certified “incomplete” vehicles meet the current heavy-duty evaporative running loss, hot soak, and three-day diurnal emission requirements. However, as they are certified as incomplete vehicles, they are not required to control refueling emissions and do not have ORVR systems. Results from the refueling testing confirm that these vehicles have much higher refueling emissions than gasoline vehicles with ORVR controls.^{42,43} The results for the ORVR tests are shown in Table 1-3. A discussion on the test procedure limitations and estimated modeled results from this test program is in Section 2.3.2.

Table 1-3: ORVR results with modeled values for test procedure limitations

	SHED (grams)	Modeled SHED (grams)	Average (g/gal)	Modeled Average (g/gal)	Current Refueling Standard (g/gal)
Ford E-450	114	168	2.3	3.34	0.2
	108		2.2		
Isuzu NPR	72	86	2.8		
	71		2.8		

Opportunity exists to extend the usage of the refueling evaporative emission control technologies already implemented in complete heavy-duty gasoline vehicles to the engine-certified incomplete gasoline vehicles in the over-14,000 lb. GVWR category. The primary technology we are considering is the addition of ORVR, which was first introduced to the chassis-certified light-duty and heavy-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 over-14,000 pound GVWR incomplete heavy-duty gasoline vehicles are similar to complete heavy-duty vehicles that are already required to incorporate ORVR. These incomplete vehicles may have slightly larger fuel tanks than most chassis-certified (complete) heavy-duty gasoline vehicles and are somewhat more likely to have dual fuel tanks. These differences may require 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 1-6 presents a schematic of a standard ORVR system.

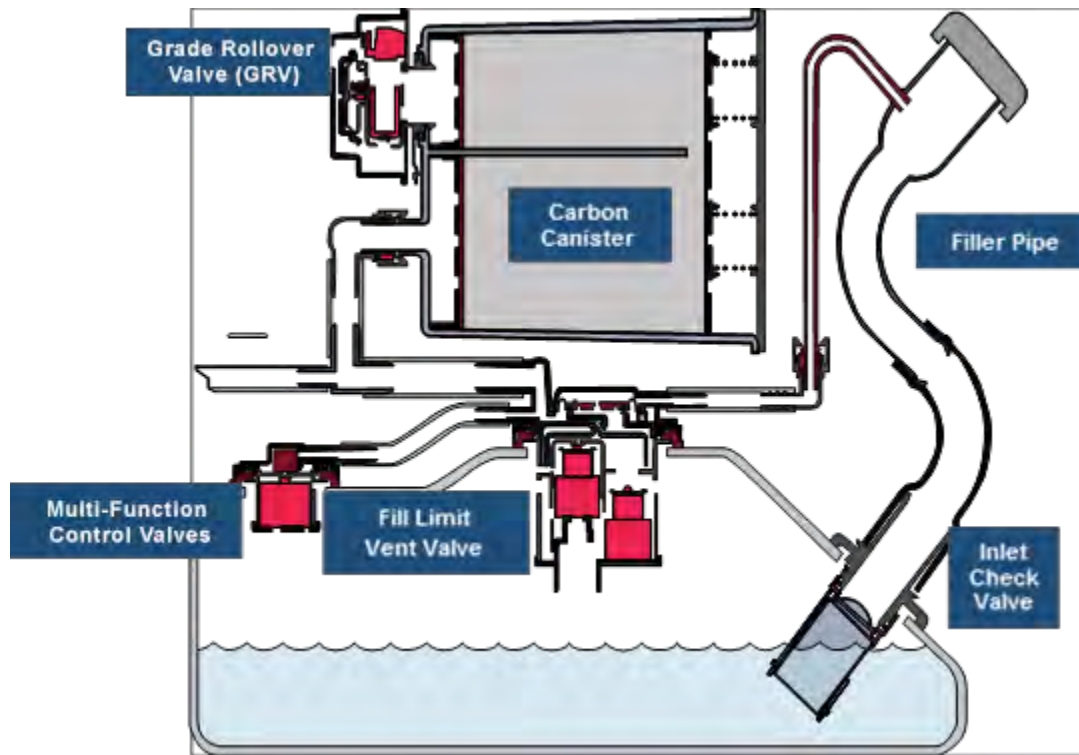


Figure 1-6: Schematic of an ORVR system^H

1.2.3.1 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.

^H Stant ORVR System <https://www.stant.com/>

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.

1.2.3.2 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 1-6) 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.

1.2.3.3 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.

1.2.3.4 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.

1.2.3.5 Design considerations for Unique Fuel Tanks

The commercial truck market gasoline applications 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 (50 to 70 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.

A small portion of the commercial truck market gasoline applications have fuel tanks that are similar in design to diesel fuel tanks located on the outside of the frame. These tanks are typically cylindrical or rectangular in shape with the gas cap directly on the top of the tank and do not have a fill neck. These type of fuel tanks may require unique approaches such as a mechanical seal built into the fuel tank filling location where the fuel cap is normally located, or they may require a design that adds a filler pipe for a liquid seal approach.

1.3 Fuels Considerations

Both the compression- and spark-ignition engine technologies discussed above are capable of running on alternative fuels (e.g., natural gas, biodiesel). We have typically applied the gasoline- and diesel-fueled engine standards to alternatively-fueled engines based on the combustion cycle of the alternatively-fueled engine: applying the gasoline-fueled engine standards to spark-ignition engines and the diesel-fueled engine standards to compression-ignition engines. This approach is often called “fuel neutral.” The sections below discuss some of the available alternative fuels in more depth.

1.3.1 Natural gas

With relatively low natural gas prices (compared to their peak values) in recent years, the heavy-duty industry has become increasingly interested in engines that are fueled with natural gas. It has some emission advantages over diesel, with lower engine-out levels of both NO_x and

PM. Several heavy-duty CNG engines have been certified with NO_x levels better than 90 percent below US 2010 standards. However, because natural gas must be distributed and stored under pressure, there are additional challenges to using it as a heavy-duty fuel.

Liquified Petroleum Gas (LPG) is also used in certain lower weight-class urban applications, such as airport shuttle buses, school buses, and emergency response vehicles. LPG use is not extensive, nor do we project it to grow significantly in the proposed rulemaking timeframe.

1.3.2 **Biodiesel**

Over the last decade, biodiesel content in diesel fuel has increased under the Renewable Fuels Standard. In 2010, less than 400 million gallons of biodiesel were consumed in the U.S., whereas in 2018, over 2 billion gallons of biodiesel were being blended into U.S. diesel fuel. While the biodiesel content in diesel fuel averaged around 3.5 percent in 2018, biodiesel levels range from 0 to 20 volume percent in highway diesel fuel. As discussed further below, with increasing volumes of biodiesel in the fuel stream, greater attention has been given to the influence of biodiesel on highway diesel fuel quality. The following sub-sections discuss how biodiesel is produced and the importance of purification processes for removing potential metal containments, standards for biodiesel fuel quality, potential impacts of metals in biodiesel fuel on diesel engines, aftertreatment systems, and emissions, as well as efforts by EPA and others to test the metal content of biodiesel samples across the country.

1.3.2.1 **Biodiesel Production and a Potential for Metals**

Biodiesel can be made from various renewable sources, such as vegetable oil, animal fat, or waste cooking oil. It is produced through transesterification of the oil or fat with methanol, which results in mono-alkyl esters and the co-product glycerin. The process occurs in the presence of a catalyst, typically sodium or potassium methoxide or hydroxide.⁴⁴ Following transesterification and separation of the glycerin, the biodiesel must be purified, which is usually done by extracting, distilling, or filtering the impurities into water.

The purification process is essential to address the potential for metal and other impurities in biofuel. There are number of potential sources of metal contamination in biofuel production. These include:

- 1) Vegetable oil seeds used to produce feedstock contain high concentrations of sodium (Na), potassium (K), calcium (Ca), magnesium (Mg), and potassium (P), as well as aluminum (Al), iron (Fe), manganese (Mn), zinc (Zn), and smaller concentrations of other metals.⁴⁵

- 2) The potassium and sodium methoxide catalysts which break down triglycerides to methyl esters (NaOH and KOH can also be used) can contribute metals to biodiesel. These metals can form soaps with free fatty acids, and the soaps in both the metal esters and glycerine forms are reacted with acid (hydrochloric acid) to convert the soaps to free fatty acids so they can be more easily removed. Sodium hydroxide is added to neutralize any acid added to eliminate soaps.

- 3) Methyl esters are washed, distilled or filtered to remove the metals added as catalysts. The wash water is recycled, and metal ions can accumulate in the wash water. Hard wash water containing CaCO₃, Mg(OH)₂, CaSO₄ is found in Rocky Mountain states and the Midwest, and these water-soluble compounds can accumulate in the residual water found in biodiesel.

4) The medium used to filter methyl esters could also contribute to metals in the biodiesel. The filter material is typically made up of diatomaceous earth which is primarily silica containing alumina, iron oxide and calcium oxide. In addition, small amounts of calcium or magnesium can be added to the fuel from the purification process.^{46,47}

1.3.2.2 Standards for Biodiesel Fuel Quality

Biodiesel quality, including metal content, is regulated by ASTM D6751-19 for B100 fuels. ASTM D6751-19 sets a limit of 5 ppm for combined Na and K (group 1A metals) and a limit of 5 ppm for combined Ca and Mg (group 2A metals) using the EN14538 inductively coupled plasma optical emission spectroscopy (ICP-OES) measurement method.⁴⁸ ASTM D6751-18 also places a 10-ppm limit on P (group 5 metal) using the ASTM D4951 inductively coupled plasma atomic emission spectroscopy (ICP-AES) measurement method.⁴⁹ The limits on metals in ASTM D6751 are meant to be protective when biodiesel is used in blends (e.g., B20, B10). Fuel quality for biodiesel blends in the B6 to B20 range is regulated by ASTM D7467-19.⁵⁰ This specification does not contain a metal limit for these biofuel blends because, as the method states, the concentration would likely be too low to measure using the ICP-OES method specified (EN 14538). Similarly, D975 regulates B0 to B5 and does not have a metals specification (just a total ash % limit of 0.01%).⁵¹ Thus, the basis for control of metals in biodiesel blends is control of the B100 blend stock. The thought being that if the B100 fuel is under the ASTM D6751-19 limit, the combined Na + K and Mg + Ca will be below 1 ppm respectively for B20 and lower blends. Yet, the actual metal content of today's fuels can be challenging to quantify when it is lower than the 1 ppm level specified for B20 and lower blends, because of the detection limit of the current test methods. The detection limit of the EN14538 is 1 ppm for each metal, and the method includes a statement if the metal is below the limit of detection of the method, then it is not included in the reporting calculation. Efforts to quantify biodiesel metal contents below 1 ppm are discussed in 1.3.2.5 below.

1.3.2.3 Potential Impacts of Metals on Engine and Emission Control Devices

Across a range of concentrations, metals in biodiesel can be present as ions, abrasive solids or soluble metallic soaps. Abrasive solids can contribute to wear of fuel system components, pistons and rings, as well as contribute to engine deposits. Soluble metallic soaps have little impact on wear but may contribute to diesel particulate filter plugging and engine deposits. Metal accumulation in diesel particulate filters can increase pressure drops and result in shorter times between maintenance intervals.^{52,53} A level of 1 mg/kg (1 part per million) of trace metal in the fuel result in an estimated accumulation of about 22 g of trace metal in diesel particulate filters per 100,000 miles (assuming a fuel economy of 15 mpg and 100% trapping efficiency).⁵²

Metallic fuel contaminants can also accumulate on fuel injectors, or be converted to oxides, sulfates, hydroxides or carbonates in the combustion process, which forms an inorganic ash that can deposit onto the exhaust emission control devices found in modern diesel engines.⁵⁴ Alkali metals are well known poisons for catalysts used in emission control devices, and have been shown to negatively impact the mechanical properties of ceramic substrates.^{55,56} Alkali metal hydroxides such as Na and K are volatilized in the presence of steam and can, therefore, penetrate the catalyst washcoat or substrate.

1.3.2.4 Potential for Emissions Impacts of Metals in Biodiesel

Numerous studies have collected and analyzed emission data from diesel engines operated on biodiesel blended diesel fuel with controlled amounts of metal content.^{53,57,58,59,60,61,62,63,64} Some of these studies show an impact on emissions, while others do not. However, four factors need to be considered when reviewing these studies:

1. These studies were conducted using accelerated aging protocols and exposure to these metals from the fuel consumed in a more conventional manner could cause different effects (the effects could be greater or less) than what these studies show,
2. The emissions testing studies were designed to test the effect of metal content in biodiesel if the metal content was at the ASTM limit, however, as shown below, biodiesel likely contains a lower metal content than the standard.
3. Different manufactures use different catalyst formulations and different physical layouts for emission aftertreatment systems, and while one manufacturer might be less susceptible to metals contamination, others may be more affected. This issue relates to factor #4:
4. When these studies examined the effect of metals on heavy-duty engines, they studied the impact of these metals based on current engine and aftertreatment configurations over the current regulatory useful life. This proposed rule would require heavy-duty engines to comply with a more stringent NO_x standard and a longer useful life. Certainly, a longer useful life would expose the aftertreatment devices to increased amounts of metals (many of today's engines often operate beyond the current regulatory useful life and would already be exposed to more metals than during their regulatory useful life). Also, the engine manufacturers may change the composition and configuration of their aftertreatment devices to comply with the proposed standards, which could affect how fuel metals would affect the aftertreatment devices.

Brookshear et al. 2012 studied the impact of Na on heavy-duty diesel engine aftertreatment devices.^{59,I} In this accelerated aging study, they doped a B20 fuel to 5,000 ppm each of Na and S and aged to an equivalent 435,000 miles. They found impacts on SCR function if the SCR was positioned before the DPF. There was no impact on the DOC or DPF.

Lance et al. 2016 also studied the effect of Na on heavy-duty diesel engine aftertreatment.^{61,J} They doped their B20 fuel with Na to a level of 14 ppm or 14 times the pseudo 1 ppm limit of a B20 fuel and accelerated aged the aftertreatment out to 435,000 miles. The results indicated an acceleration of DPF ash buildup and platinum group metal migration from the DOC/CDPF to the SCR. The results of the system performance, including degradation in performance, are shown in Figure 1-7. The results indicated that the degradation in NO_x performance can be attributed to degradation of all aftertreatment components.

^I Author affiliations: University of Tennessee and Oak Ridge National Lab

^J Author affiliations: Oak Ridge National Lab, Cummins, and National Renewable Energy Lab

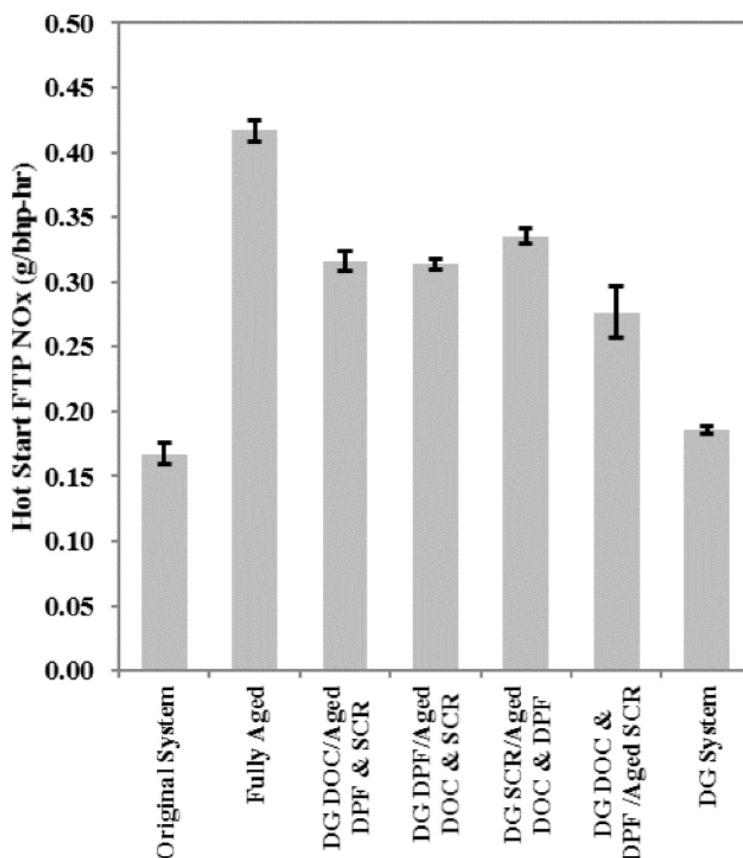


Figure 1-7: SCR performance over the hot start HDDE FTP^{61, K}

Williams et al. 2011 studied the effect of Na and Ca on a 2008 non-road 8.8L Caterpillar diesel engine, a MAN D2066 10.5 L diesel engine, and a 2008 Cummins 8.3L diesel engine.^{64, L} They doped their B20 fuel to 27 times the pseudo 1 ppm Na and Ca limit of a B20 fuel and accelerated aging of the emission control systems out to 150,000 and 435,000 miles. The results showed no significant degradation in the thermo-mechanical properties of cordierite, aluminum titanate, or silicon carbide DPFs after exposure to 150,000-mile equivalent biodiesel ash and thermal aging. It is estimated that the additional ash from 150,000 miles of biodiesel use would also result in moderate increases in exhaust backpressure for a DPF. A decrease in DOC activity was seen after exposure to 150,000-mile equivalent aging, resulting in higher HC slip and a reduction in NO₂ formation. The exposure of a cordierite DPF to 435,000-mile equivalent aging resulted in a 69% decrease in the thermal shock resistance parameter. The metal-zeolite SCR catalyst experienced a slight loss in activity after exposure to 435,000-mile equivalent aging. This catalyst, placed downstream of the DPF, showed a 5% reduction in overall NO_x conversion activity over the HDDT test cycle.

^K Note that DG indicates that the specific component is not an aged part, but a new degreased part

^L Author affiliations: National Renewable Energy Lab, Manufacturers of Emission Controls, BASF, Caterpillar, and Umicore AG

Williams et al. 2013 studied the effect of Na, K and Ca on a 2011 LD 6.7L diesel engine aftertreatment.^{54,M} They doped their B20 fuel to 14 times the pseudo 1 ppm Na and Ca limit of a B20 fuel and accelerated aged the emission control systems out to 150,000 miles. The authors aged sets of production exhaust systems that included a DOC, SCR catalyst, and DPF. Four separate exhaust systems were aged, each with a different fuel: ULSD containing no measurable metals, B20 containing sodium, B20 containing potassium, and B20 containing calcium. Analysis of the aged catalysts included Federal Test Procedure emissions testing with the systems installed on a Ford F250 pickup, bench flow reactor testing of catalyst cores, and electron probe microanalysis (EPMA). The thermo-mechanical properties of the aged DPFs were also measured.

EPMA imaging of aged catalyst parts found that both the Na and K penetrated into the washcoat of the DOC and SCR catalysts, while Ca remained on the surface of the washcoat. Bench flow reactor experiments were used to measure the standard NO_x conversion, NH₃ storage, and NH₃ oxidation for each of the aged SCR catalysts. Flow reactor results showed that the first inch of the SCR catalysts exposed to Na and K had reduced NO_x conversion through a range of temperatures (Figure 1-8 and Figure 1-9) and also had reduced NH₃ storage capacity. The SCR catalyst exposed to Ca had similar NO_x conversion and NH₃ storage performance compared to the catalyst aged with ULSD.

Chassis dynamometer vehicle emissions tests were conducted with each of the aged catalyst systems installed onto a Ford F250 pickup. Regardless of the evidence of catalyst deactivation seen in flow reactor experiments and EPMA imaging, the vehicle successfully passed the 0.2 gram/ mile NO_x emission standard with each of the four aged exhaust systems. This indicates that if catalyst volumes are chosen to account for degradation, the emission control system can accommodate some loss in catalyst activity since deactivation occurred only in the first inch of the catalyst and did not affect overall NO_x emissions.⁵⁴

^M Author affiliations: National Renewable Energy Lab, Oak Ridge National Lab, Manufacturers of Emission Controls, BASF, Ford, and University of Tennessee

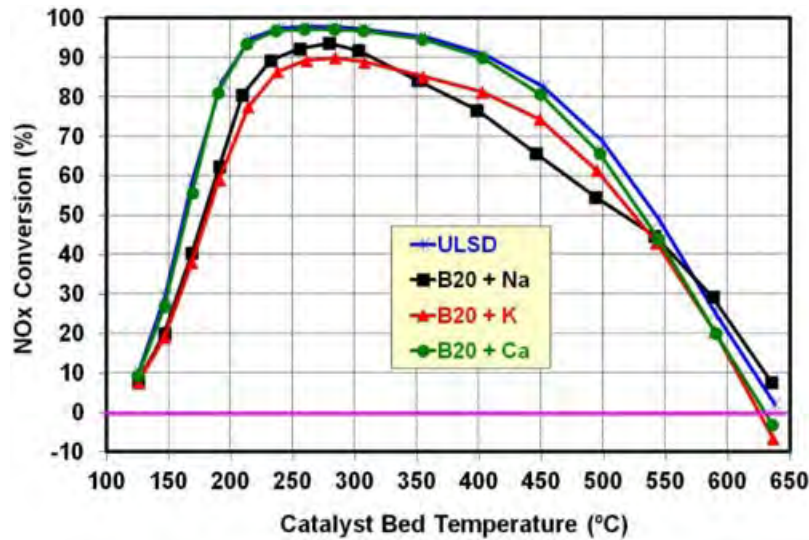


Figure 1-8: SCR NO_x conversion for the first inch of aged SCR catalysts.⁵⁴

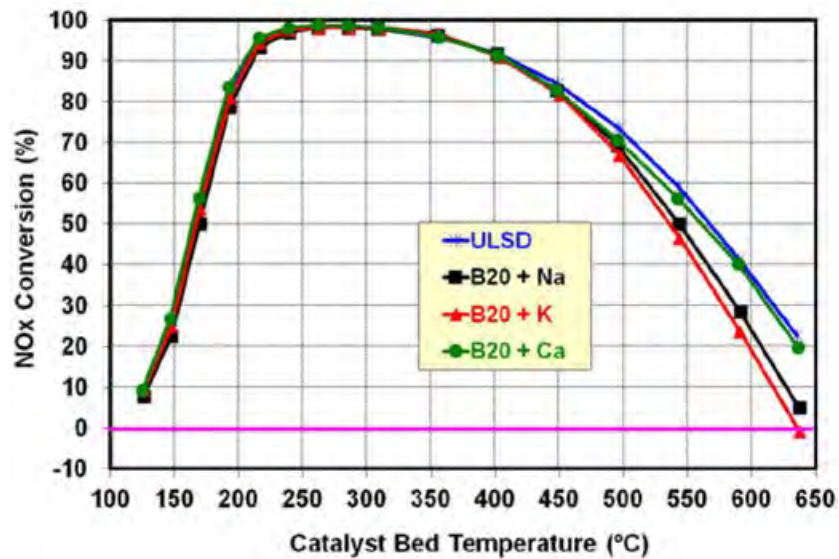


Figure 1-9: SCR NO_x conversion for the seventh inch of aged SCR catalysts.⁵⁴

1.3.2.5 Testing for Metals in Biodiesel

The National Renewable Energy Laboratory (NREL) has conducted several studies on the metal content of biodiesel. The NREL studies generally look at the fuel quality in fuel samples taken across from the country. In some cases, samples are taken at the refinery where B100 was sampled and in other cases they are taken at the pump. These studies provided analysis of metal content for fuel samples collected and analyzed in the 2006, 2007, 2008, 2011, and 2016 timeframes. The 2006, 2007, and 2011 studies analyzed the metal content of B100 fuel, while the 2008 and 2016 studies analyzed the metal content of biodiesel blends up to approximately B20. Some samples taken during the 2006 study were acquired prior to the finalization of the combined Na + K limit in ASTM D6751 (May 2006).^{46,47,65,66,67,68,69}

These results indicate that over the 2006 to 2018 time frame the incidence of off specification biofuel decreased over time. A summary of the off-specification samples can be found in Table 1-4.

Table 1-4: NREL Fuel Samples off Specification for ASTM D6751 (or equivalent B20) limit for Na + K and Ca + Mg.

NREL Fuel Study Year	Biodiesel Content	Number of Samples off spec for Na + K	Number of Samples off spec for Ca + Mg	Total Number of Samples
2006 (pre-D6751)	B100	7	1	24
2006 (post-D6751)	B100	0	1	15
2007	B100	3	3	55
2008	B0.2 to B90	6	0	34
2011	B100	1	0	67
2016	B0 to B22	0	1	35
2017	B100	1	0	459
2018	B100	0	0	491

The NREL studies prior to 2016 focused on identifying gross exceedances of the blends and blend stocks. As noted above, the analytical method specified in ASTM D6751-18 (EN 14538) affords a detection limit of 1 ppm, which is adequate to ensure whether or not biofuel blend stocks (B100) are compliant with the Na + K and Ca + Mg limits. In addition to determining compliance with the ASTM D6751-18 limit, it is also important to determine the actual metal content of these fuels in order to assess the levels that aftertreatment systems will be exposed to over their full useful life. The 2016 NREL study used measurement equipment and procedures capable of testing down to lower metal levels, which is useful for understanding the actual metal content of biodiesel blends. Table 1-5 summarizes the test procedures and level of detection (LOD) levels for each year of the NREL studies.

Table 1-5: Test procedure LODs for NREL studies.

Year of NREL Study	Test Procedure	Level of Detection (ppm)			
		Na	K	Ca	Mg
2006	ASTM D5185	?	?	?	?
2007	ASTM D7111	1	1	0.1	0.1
2008	ASTM D7111	0.5	0.5	0.5	0.1
2011	ASTM D7111	1	1	0.1	0.1
2016	UOP-389	0.1	0.1	0.1	0.1
2016	ICP-MS	0.029	0.001	0.0005	0.001
2017	EN 14538	1	1	1	1
2018	EN 14538	1	1	1	1

In the 2016 study, NREL took steps to improve their understanding of testing accuracy and improve the testing resolution of the analysis by utilizing three different measurement methods, two of which afforded very low detection limits. In this study, biodiesel blends were analyzed for metal content using the Universal Oil Products Method 389 (UOP-389), Microwave Plasma Atomic Emission Spectroscopy (MP-AES), and Inductively Coupled Plasma Mass Spectroscopy (ICP-MS) methods.⁷⁰ This allowed for comparisons of metal content from the three different testing methods. Almost all the results for the MP-AES testing method were below the LOD, though, so this method will not be further discussed. The results of the study for UOP-389 and the ICP-MS are presented in Table 1-6.

Table 1-6: NREL 2016 Metals results for UOP-389 and ICP-MS⁷⁰

State	Biodiesel Content	Error	UOP-389 ICP-AES				ICP-MS				
	Vol %	Vol %	Na	K	Ca	Mg	Na	K	Ca	Mg	Fe
			ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
FL-1 (fleet)	22.01	1.76	0.14	0.04	0.08	0.01	(0.029)	0.021	0.008	0.026	0.065
FL-2	18.38	1.59	0.04	0.01	0.05	0.01	(0.029)	0.033	0.002	0.014	0.146
GA	19.36	1.63	0.06	0.02	0.06	0.01	(0.029)	0.034	0.002	0.011	1.44
NC-1 (fleet)	20.4	1.68	0.06	0.01	0.09	0.02	(0.029)	0.02	0.002	0.01	0.004
NC-2	0	0.71	0.02	0.01	0.02	0.01	No Data	No Data	No Data	No Data	No Data
PA-1	17.73	1.56	0.09	0.01	0.05	0.02	(0.029)	0.014	0.002	0.009	0.012
PA-2 (fleet)	20.31	1.68	0.08	0.02	0.04	0.03	(0.029)	0.031	0.002	0.019	0.017
MA	21.35	1.73	0.04	0.01	0.04	0.01	(0.029)	0.02	0.002	0.015	0.016
VA (fleet)	18.56	1.6	0.08	0.02	0.06	0.02	(0.029)	0.028	0.012	0.011	0.086
IA (fleet)	16.1	1.48	0.09	0.03	0.04	0.01	(0.029)	0.1	0.017	0.014	0.249
IL	15.3	1.44	0.07	0.01	0.03	0.01	(0.029)	0.02	0.007	0.019	0.005
IN	20.34	1.68	0.2	0.07	0.1	0.03	(0.029)	0.237	0.106	0.031	0.075
KS	17.27	1.53	0.09	0.02	0.53	0.06	(0.029)	0.11	1.366	0.166	1.557
KY	20.11	1.67	0.05	0.01	0.03	0.01	(0.029)	0.022	0.002	0.015	0.069
MI	20.51	1.69	0.11	0.02	0.06	0.01	(0.029)	0.045	0.122	0.025	3.117
MN-1	10.68	1.22	0.04	0.01	0.04	0.01	(0.029)	0.016	0.002	0.025	0.172
MN-2	10.61	1.22	0.02	0.01	0.03	0.01	(0.029)	0.016	0.002	0.048	0.003
MO	19.44	1.64	0.09	0.01	0.05	0.01	(0.029)	0.034	0.01	0.012	0.019
OH-1	20.4	1.68	0.05	0.01	0.05	0.01	(0.029)	0.013	0.002	0.011	0.033
OH-2	8.84	1.13	0.01	0.01	0.03	0.01	(0.029)	0.015	0.002	0.007	0.003
TN-1	20.24	1.68	0.1	0.01	0.06	0.01	(0.029)	0.019	0.003	0.006	0.085
TN-2 (fleet)	20.02	1.67	0.24	0.02	0.08	0.01	(0.029)	0.029	0.012	0.009	0.361
LA	12.26	1.3	0.04	0.01	0.03	0.01	No Data	No Data	No Data	No Data	No Data
TX-1	17.14	1.53	0.06	0.01	0.08	0.01	(0.029)	0.01	0.002	0.005	0.003
TX-2	1.4	0.78	0.07	0.01	0.04	0.01	(0.029)	0.012	0.002	0.006	0.004
TX-3	1.2	0.77	0.04	0.01	0.03	0.01	(0.029)	0.011	0.002	0.005	0.004
CO	21.99	1.76	0.09	0.01	0.05	0.01	(0.029)	0.023	0.094	0.035	0.037
ID (fleet)	19.64	1.65	0.22	0.03	0.12	0.03	(0.029)	0.085	0.065	0.034	0.044
AZ (fleet)	20.39	1.68	0.07	0.01	0.04	0.01	(0.029)	0.085	0.065	0.034	0.044
CA-1	18.84	1.61	0.05	0.02	0.03	0.01	(0.029)	0.016	0.002	0.019	0.009
CA-2	22.12	1.77	0.07	0.01	0.04	0.01	(0.029)	0.016	0.002	0.011	0.03
CA-3 (fleet)	19.9	1.66	0.06	0.01	0.04	0.01	(0.029)	0.033	0.002	0.018	0.005
NM	19.61	1.65	0.1	0.02	0.05	0.01	(0.029)	0.025	0.002	0.005	0.284
OR-1	20.1	1.67	0.06	0.02	0.03	0.02	(0.029)	0.012	0.002	0.005	0.009
OR-2	20.15	1.67	0.05	0.01	0.05	0.01	(0.029)	0.021	0.002	0.005	0.011
Average			0.079	0.016	0.064	0.014	(0.029)	0.037	0.058	0.021	0.243
Average Na + K and Ca + Mg			0.047		0.039		0.033		0.040		

Note: Values in parenthesis are below the detection limit and are reported at the detection limit.

Differences in the results between the two methods could be due to interferences by other metals, or other aspects of the molecules, with the measuring method. The measurement

differences could also be due to the unique ionization efficiency of each element and how well the instrument ionizes the element of interest. Even small differences could impact the results at sub 1-ppm levels. The difference in sample preparation techniques can also have a significant effect on the results. The UOP-389 method uses acid digestion followed by ashing, while the ICP-MS method used a simpler preparation of sample dilution and direct analysis. The UOP-389 method was developed for the analysis of petroleum products and blending components, including biodiesel blends, and uses a wet ashing method that is unique to this procedure, which is why it was selected for this project.

Although several samples contained elevated amounts of Ca and Mg (KS, MI, IN, and CO) that were well above the level of other samples, these trace levels would still be very low in the B100 blend stock, with the exception of one sample (KS). Overall, the NREL data suggest that metal contents in biodiesel have decreased over time and, as of 2018, are generally very low across samples. Nevertheless, small sample sizes could be biasing the results.^{44,45,65,66,67,68,69}

To that end, in 2019 an engine manufacturer raised concerns to EPA that biodiesel is the source of high metal content in highway diesel fuel, and that higher biodiesel blends, such as B20, are the principal problem.⁷¹ The engine manufacturer observed higher than normal concentrations of alkali and alkaline earth metals (Na, K, Ca, and Mg) in their highway diesel fuel samples, and observed fouling of the aftertreatment control systems of their engines, which caused an associated increase in emissions. The engine manufacturer sampled the ash that was fouling their fuel injectors and aftertreatment devices and determined the ash to be composed of sodium sulfate, sodium carboxylates, and sodium chloride, which they claimed were from biodiesel. The engine manufacturer recommends limiting biodiesel blends to 5 percent biodiesel (B5). After hearing engine manufacturer concerns about the metal content in biodiesel in early 2019, EPA began to focus a previously developed fuel sampling program on biodiesel metal content. Below, we summarize the information that we obtained through that sampling program.

Separate from hearing about engine manufacturer concerns with biodiesel metal content, EPA began a process to determine the metal content of different fuels in early 2016. The most prominent concern to EPA at that time was the blending of less refined natural gas liquids with ethanol to produce E85 blends; however, EPA recognized the need to understand the metal content of all fuels. EPA initiated a sampling effort in late 2016 to obtain samples of diesel fuel, gasoline, natural gas liquids, jet fuel, biodiesel and ethanol. The samples were collected in acid-washed glass bottles using a clean hands/dirty hands sampling procedure to reduce the chance for contamination during the sampling process. Fuel samples were collected from both small and large fuel production plants, in the case that facility size plays a role in the amount of metals which ends up in the fuel. Samples were also taken in different geographical regions. Fuel production facilities likely use different feedstocks based on their geographical region, and the different feedstock types could affect the fuels metal content. Because of the cost and effort involved in obtaining these fuel samples, a limited number of samples of each fuel type were obtained. Thus, this was a screening study, which could be expanded later on if high metal contents were detected in any of the fuels.

Approximately 100 samples were obtained across the various fuel types. A subset of these samples (27 B100 samples) were recently sent to the California Department of Food and Agriculture (CDFA) laboratory. These samples were analyzed for biodiesel regulated metals, including Na, K, Ca, Mg and P, and also tested for Molybdenum (Mo), Boron (B), Barium (Ba),

Copper (Cu), Manganese (Mn), Silica (Si), Titanium (Ti), Vanadium (V) and Zinc (Zn). The California lab utilized the ASTM D7111-16 ICP-AES method that returned detection limits of 0.023 (Na), 0.052 (K), 0.013 (Ca), 0.004 (Mg), 0.001 (P), 0.006 (Mo), 0.013 (B), 0.001 (Ba), 0.005 (Cu), 0.001 (Mn), 0.017 (Si), 0.003 (Ti), 0.002 (V), and 0.005 (Zn) ppm.⁷² The results of the analysis are shown in Table 1-7 and

Table 1-8.

Na was above the detection limit for 22 of the samples, with the highest result at 564 ppb. K was only above the detection limit for 3 of the samples, with the highest result at 660 ppb. Ca was above the detection limit for 9 of the samples, with the highest result at 551 ppb. Mg was only above the detection limit for 5 of the samples, with the highest result at 133 ppb. The highest result for combined Na and K was 744 ppb, while the highest result for combined Ca and Mg was 662 ppb.

All of the 27 B100 fuel samples from this test program were compliant with the ASTM D6751-18 limit of 5 ppm for Na + K and Ca + Mg respectively, and the results showed that levels were at less than 20% of the limit for two of the samples, while the rest were at less than 10% (and in most cases well below that) of the limit. A reduction of 80% in metal content for B20 and a reduction of 95% in metal content for B5 fuel blends would result in a maximum Na + K content of 149 ppb and 37 ppb respectively for the B100 fuel with the highest Na + K content. Ca + Mg would be 132 ppb and 33 ppb respectively.^N

^N This assumes no contribution from the diesel fuel used to formulate the blends.

Table 1-7: EPA 2017 Metals results for ICP-AES analysis of Na, K, Ca, and Mg performed by CDFA.

Sample ID	Area of US	Na (ppm)	K (ppm)	Ca (ppm)	Mg (ppm)	Na + K (ppm)	Ca + Mg (ppm)
25982	East	0.171	0.211	0.131	0.133	0.382	0.264
25988	East	0.084	0.660	(0.013)	0.018	0.744	[0.031]
25998	Midwest	0.241	(0.052)	(0.013)	0.005	[0.293]	[0.018]
26004	Midwest	(0.023)	(0.052)	(0.013)	(0.004)	(0.075)	(0.017)
26006	Midwest	0.081	(0.052)	(0.013)	(0.004)	[0.133]	(0.017)
26083	Midwest	0.181	(0.052)	0.026	(0.004)	[0.233]	[0.030]
26084	Midwest	0.188	(0.052)	0.025	(0.004)	[0.240]	[0.029]
26088	Midwest	0.111	(0.052)	(0.013)	(0.004)	[0.163]	(0.017)
26090	Midwest	0.135	(0.052)	(0.013)	(0.004)	[0.187]	(0.017)
26092	Midwest	0.201	(0.052)	(0.013)	(0.004)	[0.253]	(0.017)
26095	Midwest	0.378	(0.052)	(0.013)	(0.004)	[0.430]	(0.017)
26164	South	0.193	(0.052)	0.040	(0.004)	[0.245]	[0.044]
26165	South	0.044	(0.052)	(0.013)	(0.004)	[0.096]	(0.017)
26166	South	(0.023)	(0.052)	(0.013)	(0.004)	(0.075)	(0.017)
26217	West	0.108	(0.052)	(0.013)	(0.004)	[0.160]	(0.017)
26218	West	0.564	(0.052)	0.027	(0.004)	[0.616]	[0.031]
26219	West	0.278	(0.052)	0.143	0.031	[0.330]	0.174
26248	West	0.303	(0.052)	0.551	0.111	[0.355]	0.662
26250	South	0.031	0.186	(0.013)	(0.004)	0.217	(0.017)
26253	South	(0.023)	(0.052)	(0.013)	(0.004)	(0.075)	(0.017)
26254	South	(0.023)	(0.052)	(0.013)	(0.004)	(0.075)	(0.017)
26256	South	(0.023)	(0.052)	(0.013)	(0.004)	(0.075)	(0.017)
26283	South	0.331	(0.052)	(0.013)	(0.004)	[0.383]	(0.017)
26830	South	0.379	(0.052)	0.016	(0.004)	[0.431]	[0.020]
26833	East	0.290	(0.052)	(0.013)	(0.004)	[0.342]	(0.017)
27581	East	0.226	(0.052)	0.044	(0.004)	[0.278]	[0.048]
27955	West	0.270	(0.052)	(0.013)	(0.004)	[0.322]	(0.017)
Average		0.182	0.085	0.046	0.014	0.267	0.060

*Values in (parenthesis) are below the detection limit and are reported at the detection limit.

**Na + K and Ca + Mg values in [square brackets] include one element that is below the detection limit and is included in the calculation at the detection limit.

Table 1-8: EPA 2017 Metals results for ICP-AES analysis of Mo, P, B, Ba, Cu, Mn, Si, Ti, V, and Zn performed by CDFA.

Sample ID	Area of US	Mo (ppm)	P (ppm)	B (ppm)	Ba (ppm)	Cu (ppm)	Mn (ppm)	Si (ppm)	Ti (ppm)	V (ppm)	Zn (ppm)
25982	East	0.070	0.301	2.577	0.057	0.157	0.141	2.364	0.138	0.134	0.041
25988	East	0.012	0.305	1.220	0.006	0.032	0.014	2.896	0.004	0.010	(0.005)
25998	Midwest	(0.006)	0.207	0.126	0.002	0.006	0.002	0.927	(0.003)	0.003	(0.005)
26004	Midwest	(0.006)	0.073	0.154	(0.001)	(0.005)	(0.001)	0.034	(0.003)	(0.002)	(0.005)
26006	Midwest	0.008	0.138	0.081	(0.001)	(0.005)	(0.001)	0.100	(0.003)	(0.002)	(0.005)
26083	Midwest	(0.006)	0.188	0.062	0.003	0.022	0.004	0.241	(0.003)	(0.002)	(0.005)
26084	Midwest	(0.006)	0.182	0.053	0.002	0.023	0.004	0.233	(0.003)	(0.002)	(0.005)
26088	Midwest	(0.006)	0.735	0.029	(0.001)	(0.005)	(0.001)	0.020	(0.003)	(0.002)	(0.005)
26090	Midwest	0.008	0.226	0.017	(0.001)	0.019	(0.001)	0.172	(0.003)	(0.002)	(0.005)
26092	Midwest	0.010	0.165	0.038	(0.001)	0.046	(0.001)	1.168	(0.003)	0.004	(0.005)
26095	Midwest	(0.006)	0.100	0.029	(0.001)	0.054	(0.001)	1.043	(0.003)	0.004	(0.005)
26164	South	0.022	0.232	0.022	(0.001)	0.024	0.003	0.220	(0.003)	(0.002)	(0.005)
26165	South	(0.006)	0.949	(0.013)	(0.001)	(0.005)	(0.001)	0.046	(0.003)	(0.002)	(0.005)
26166	South	(0.006)	0.019	0.014	(0.001)	(0.005)	(0.001)	0.032	(0.003)	(0.002)	(0.005)
26217	West	0.011	0.101	0.024	(0.001)	0.035	(0.001)	0.350	(0.003)	0.021	(0.005)
26218	West	(0.006)	(0.001)	(0.013)	(0.001)	0.025	(0.001)	(0.017)	(0.003)	(0.002)	0.049
26219	West	(0.006)	0.302	0.014	(0.001)	0.035	(0.001)	0.104	(0.003)	(0.002)	(0.005)
26248	West	(0.006)	0.365	(0.013)	0.004	0.037	(0.001)	1.776	(0.003)	(0.002)	(0.005)
26250	South	(0.006)	(0.001)	(0.013)	(0.001)	(0.005)	(0.001)	0.130	(0.003)	(0.002)	(0.005)
26253	South	(0.006)	0.025	0.023	(0.001)	(0.005)	(0.001)	1.077	(0.003)	(0.002)	(0.005)
26254	South	(0.006)	0.021	0.027	(0.001)	(0.005)	(0.001)	1.239	(0.003)	(0.002)	(0.005)
26256	South	(0.006)	(0.001)	(0.013)	(0.001)	(0.005)	(0.001)	0.306	(0.003)	(0.002)	(0.005)
26283	South	(0.006)	0.133	(0.013)	(0.001)	0.193	(0.001)	0.592	(0.003)	0.020	(0.005)
26830	South	(0.006)	0.193	(0.013)	(0.001)	0.066	(0.001)	1.516	(0.003)	0.004	(0.005)
26833	East	0.012	0.237	(0.013)	(0.001)	0.035	0.007	0.397	(0.003)	0.013	(0.005)
27581	East	(0.006)	0.038	(0.013)	(0.001)	(0.005)	(0.001)	0.461	(0.003)	0.004	(0.005)
27955	West	(0.006)	(0.001)	(0.013)	(0.001)	(0.005)	(0.001)	0.115	(0.003)	(0.002)	(0.005)
Average		0.010	0.194	0.172	0.004	0.032	0.007	0.651	0.008	0.009	0.008

*Values in parenthesis are below the detection limit and are reported at the detection limit.

The California Air Resources Board (ARB) CDFA inspectors carried out a biodiesel sampling campaign throughout California during the spring and fall of 2019 collecting three hundred fifty-five (355) biodiesel and diesel fuel samples from both #2 diesel labeled pumps and biodiesel labeled pumps in the state of California.⁷³

These samples were analyzed by the same lab as the 27 EPA samples mentioned above and afforded the same detection limits. The primary focus of analysis was to examine the average and observed range of concentration for Na, K, Ca, Mg and P of the biodiesel samples and the diesel samples.

Statistical analysis of the samples showed that the Na, K, Ca, Mg and P concentrations in all of the 355 collected fuel samples across California were significantly lower than the worst case expected concentrations for a B20 fuel blended from B100 blend stock that is at the ASTM

D6751-18 limit. Only three P samples, one Mg + Ca sample, and thirteen Na + K samples across the entire sample set exceeded worst case expected absolute concentrations for a B5 blended from B100 blend stock that is at the ASTM D6751-18 limit.

Na was the most abundant metal observed and was above the detection limit for 273 of 355 samples with sample 30077 exhibiting the highest result at 837 ppb. The rest of the metals were largely below detection limits. K was only above the detection limit for 14 of 355 samples with sample 15162 exhibiting the highest result at 172 ppb. Ca was above the detection limit for 24 of 355 samples with sample 30062 exhibiting the highest result at 168 ppb. Mg was only above the detection limit for 32 of 355 samples with sample 15162 exhibiting the highest result at 238 ppb. Sample 30077 exhibited the highest result for combined Na and K at 889 ppb, while sample 30062 exhibited the highest result for combined Ca and Mg at 353 ppb. P was above the detection limit for 92 of 355 samples, with sample 30077 exhibiting the highest result at 862 ppb. Tables containing the maximum and average concentrations with standard deviation can be found in the ARB comments to the ANRPM in the docket.⁷³

A review of the NREL, EPA, and ARB data sets indicate that biodiesel fuel is compliant with the ASTM D6751-18 limits for Na, K, Ca, and Mg. While the test results indicate that there is an occasional B100 blend stock that is off specification with respect to the ASTM D6751-18 limits, and occasional BXX blends that are off specification to the pseudo limits, these occurrences are the exception. The NREL 2016, EPA, and ARB data sets all use measurement methods that afford low levels of detection (sub-100 ppb), and these data sets further indicate that the Na, K, Ca, and Mg content of biodiesel blends is extremely low in general, on the order of less than 100 ppb. While these metals are present in biodiesel blends and testing has shown that exposure to metals can adversely affect emission control system performance, data suggest that the low levels measured in today's fuels are not enough to adversely affect system performance out to full regulatory useful life, provided that the engine manufacturer properly sizes the catalysts to account for the low-level exposure.

1.4 Advanced Powertrain Technologies

This section discusses powertrain technologies capable of reducing NO_x emissions from heavy-duty vehicles. In particular, we provide a technology description and emissions performance discussion, as well as an overview of current and future markets for heavy-duty hybrid electric vehicles (HEVs), battery electric vehicles (BEVs), and fuel cell electric vehicles (FCEVs). These powertrain technologies (HEVs, BEVs, FCEVs) are collectively referred to as advanced powertrain technologies where appropriate in this discussion.

1.4.1 Hybrid

1.4.1.1 Technology Description

Heavy-duty HEVs are those that are propelled by both an on-board engine using a consumable fuel (e.g., diesel internal combustion engine, hydrogen fuel cell) and an energy storage device (e.g., battery, capacitor). HEV technologies that recover and store braking energy using a driveline-coupled electric machine and battery storage have been used extensively in light-duty applications as fuel saving features and are being adopted in certain heavy-duty applications. Heavy-duty hybrid technologies can be described along a continuum of "mild" to "strong" in terms of the extent to which they utilize an energy source other than a combustion

engine; they also differ in the coupling and placement of the electric machine within the powertrain. The specific definitions of "mild" and "strong" hybrids can be challenging to solidify given variation in how different manufacturers employ individual and combinations of hybrid technologies. The purpose of this discussion is to provide an overview of the types of technologies employed across the mild to strong hybrid spectrum, rather than focus on defining the technologies per say.^o

For instance, North American Council for Clean Freight Efficiency (NACFE) defines "mild" hybrids as those that use a starter or generator combined with a small battery pack to supplement main engine power in select circumstances; most mild hybrids use 48V electrical batteries or batteries with lower voltage and can provide fuel economy benefits in the range of 10% or less.⁷⁴ The 48V battery is a lithium-ion battery that pairs with an electric motor to supplement the typical combustion engine and 12V battery in conventional vehicles; the 48V battery and associated network can power a variety of components (e.g., electric turbos, EGR pumps, AC compressors, heated catalysts, cooling fans, oil pumps, coolant pumps), along with supplying power to active chassis systems and regenerative braking.⁷⁹ In contrast, NACFE defines "strong" hybrids as those that utilize a larger electric machine paired with a smaller engine and larger battery pack (relative to mild hybrids); strong hybrids generally use 300 to 500V electrical batteries, and thus can propel the vehicle down the roadway at moderate speeds without engine power.⁷⁴ Across the spectrum of hybrid technologies, there is a wide variety of powertrain configurations that can range from electrifying an axle or adding a 48V battery for accessory loads (mild hybrids) to a powertrain designed such that the electrical propulsion is able to meet the duty-cycle demands in nearly all driving conditions (strong, plug-in hybrid).⁷⁴ Mild hybrid configurations that may be of growing interest in the industry include the use of an electric motor/generator, regenerative braking, electric boosts and advanced batteries, as well as advanced stop-start systems that employ a 48V belt-driven starter-generator.⁷⁹ Detailed descriptions of different hybrid configurations and components is available in the National Academies of Sciences report, "Reducing Fuel Consumption and Greenhouse Gas Emissions of Medium- and Heavy-Duty Vehicles, Phase Two: Final Report".⁷⁵

1.4.1.2 Emissions Performance

Emissions impacts of heavy-duty hybrids vary across this spectrum of mild to strong, as well as with the level of integration and design of the technology. Heavy-duty hybrid technologies have the potential to decrease or increase NO_x emissions depending on how they are designed. For example, a hybrid system can reduce NO_x emissions if it eliminates idle operation or uses the recovered electrical energy to heat aftertreatment components. In contrast, data show that some hybrid technologies can produce higher engine-out NO_x emissions due to higher engine speeds combined with lower torque relative to a conventional engine; lowering the torque (load) on the engine can also reduce the engine's ability to maintain sufficiently high aftertreatment temperatures during low-load operation.⁷⁶ The combination of higher engine out NO_x with lower aftertreatment efficiency resulted in up to 50% higher NO_x emissions in MY2010 to 2012 heavy-duty hybrid vehicles.⁷⁶ Improvements in integration and design of hybrid powertrain and engine components can address the potential for elevated NO_x emissions from hybrid vehicles. EPA

^o EPA defines "mild hybrid" as a hybrid engine or powertrain with regenerative braking capability where the system recovers less than 20 percent of the total braking energy over the transient cycle defined in Appendix I of 40 CFR part 1037. (40 CFR 1036.801)

recently worked with stakeholders to adapt a test procedure that was initially developed for HD vehicles such that it now allows hybrid powertrains to be certified to the HD GHG engine standards; this powertrain test procedure was finalized in the HD GHG Phase 2 technical amendments rule (86 FR 34321, June 29, 2021). Under this proposed rulemaking, EPA is proposing that this powertrain test procedure can also be to meet the criteria pollutant engine standards. See preamble Section III.B.2.v for additional discussion on this proposal, and Chapter 2.1.1.1.3 details on the powertrain test procedure.

We did not include heavy-duty hybrid technologies in the proposed rulemaking's emissions inventory analysis. Hybrids were excluded for two reasons: 1) the variability in heavy-duty hybrid emissions based on design, integration, and use of the technology (outlined above), and 2) uncertainty in the which types of hybrids will grow in which segments of the heavy-duty market (discussed further below).

1.4.1.3 Current and Future Markets

As noted above mild heavy-duty hybrid powertrain options such as 48V battery systems to electrify certain components or electrified axles are of increasing interest to heavy-duty vehicle market.⁷⁹ According to a recent NACFE report, there were no Class 3 through 8 HEV models available in late 2019, but at least one HEV Class 5 delivery truck is now available.^{74,77} A variety of hybrid transit buses are available and have been in production since the early 2000s.⁷⁴

The choice to use a hybrid technology in heavy-duty delivery vehicles will depend on a variety of factors that fall into several categories, including: duty cycle (e.g., length of typical route, freight weight requirements), regional requirements (e.g., zero emissions zones, weather and terrain conditions), and costs (e.g., capital costs, operational costs of fuel and equipment).⁷⁴ Some data suggest that these and other factors may be leading fleets to use and plan for hybrid heavy-duty vehicles. In 2019, more than 30% of fleets responding to the National Truck and Equipment Association (NTEA) fleet purchasing survey stated that they currently operate alternative-fuel trucks, with electric hybrid being one of the predominate alternative-fuel options.⁷⁸ In 2019, 19% of survey respondents indicated that they are electrifying their systems, with 77% of those respondents indicating that they intend to expand their use of electrification.⁷⁸ Of fleets electrifying their vehicles, the telecom/utility market shows a higher electrification penetration rate than other markets according to NTEA 2019 survey responses. Truck mounted equipment (e.g., bucket and crane operations) are the most commonly electrified systems, although that may be shifting towards “environmental control” systems.^{P,78} Idle reduction is another area of growth within the use of heavy-duty hybrid technology, with 56% of NTEA survey respondents indicating they are incorporating idle reduction technology in 2019. Fleets choose to purchase vehicles with idle reduction, electrification, or other alternative fuel options based primarily on reductions in operating and life cycle costs compared to conventional vehicles.⁷⁸ Tax or grant incentives, payback period, and the ability to lease vehicles also play a role in fleets’ purchasing decisions on alternatively fueled trucks.^{Q,78}

^P The category “environmental control systems” is not defined in NTEA survey results.

^Q Note that “automation/advanced technology features” were also included in the survey question on purchasing drivers for alternatively fueled trucks (NTEA 2019)

Hybrid technology in the heavy-duty industry is projected to increase significantly over the next several years as a result of the HD Phase 2 GHG standards, as well as higher electrical demands from safety and entertainment features.⁷⁹ Members of the Manufacturers of Emissions Control Association (MECA) project that 48V systems as potentially feasible by 2024 for some engine families, with a wider range of offerings available by 2027.⁷⁹ Mild-hybridization with a 48V system could provide a synergistic benefit with the CDA technology discussed in Section 1.1.3 above, as well as other engine management strategies (e.g., start-stop capability).⁷⁹ The total cost of ownership (TCO) for hybrid technologies, and its relation to diesel vehicles, will vary based on the specifics of the hybrid system (e.g., battery size, battery voltage, motor power and level of integration).

1.4.2 Battery-Electric and Fuel Cell

1.4.2.1 Technology description

Similar to light-duty battery-electric vehicles, heavy-duty battery electric vehicles (BEVs) utilize a traction battery pack to store electricity for use by an electric traction motor, which transfers mechanical energy to an electric transmission in order to drive the wheels of the vehicle.⁷⁴ Fuel cell electric vehicles (FCEV) utilize a proton-exchange membrane fuel cell (PEMFC) stack that converts hydrogen and oxygen to electricity for use by an electric traction motor, which transfers mechanical energy to an electric transmission in order to drive the wheels. The FCEV is similar to a BEV in that it utilizes all-electric drive, but that electricity is derived via an electrochemical reaction of hydrogen with oxygen in air across a membrane electrolyte assembly.^{74,80} FCEVs are often similar to strong hybrids since a lithium-ion battery pack is required in order to buffer power demand to the PEMFC and to provide regenerative braking. FCEV powertrain architectures similar to a BEV using a PEMFC as a range extender are also possible.^{81,82,83} High voltage electric machines are necessary to provide sufficient torque for the full range of vehicle operation; thus bus voltage is also similar to BEV applications.^RHEVs

Battery technology is rapidly evolving with different battery chemistries and battery pack designs coming into the market.⁷⁴ While manufacturers can build off experience with light-duty electric vehicle batteries, there are differences in battery design for heavy-duty vehicles. Considerations for heavy-duty vehicle battery design include: the energy-to-weight ratio, energy-to-volume ratio, specific power (amount of current acceptable), battery lifetime (calendar years and charge cycles), recharging time, temperature management (both cooling and heating), and safety (both during use and at end-of-life).^{74,84,92} Detailed discussion of battery design is outside the scope of this document, but we will briefly discuss a few key aspects of these considerations. The energy to weight or volume ratios impact vehicle weight and the amount of cargo a vehicle can carry, whereas specific power can influence charging time. Information on expectations for battery lifetime in heavy-duty applications is nascent, but data from light-duty vehicles suggests that batteries can operate at greater than 90% of the original capacity after approximately 150,000 miles (80% original capacity is a general target for end of useful life in a commercial vehicle battery; total lifetime mileage of heavy-duty trucks varies by weight class and application but can range from 250,000 to more than 800,000 miles [see Chapter 3 for more discussion on mileage accumulation and Regulatory Useful Life]).⁹² Ambient temperatures can influence

^R A number of PEMFC concepts under consideration for future HD truck applications use a larger battery pack and are technically PHEVs, so they would, in that case, use grid electricity.

battery life and performance, where increases in auxiliary power demand for cabin heating or cooling combined with lower efficiency in battery chemistry result in reduced driving range.⁸⁵ Once depleted, the amount of time required to recharge a battery will vary based not only on battery specific power, but also the battery size (e.g., 100 kWh, 550 kWh), battery state of charge (e.g., 20%, 50%), battery type, and type of charging equipment available.^{74,92} The current SAE J1772 standard defines multiple charging levels. These include AC Level 1 (1.92 kW), AC Level 2 (19.2kW, provisionally 22 kW), DC Level 1 (up to 48 kW) and DC Level 2 (up to 400 kW), all of which use the CCS1 connector within North America. With these variables in mind, charging times for a medium duty electric truck would be longer on an AC Level 2 Charger (e.g., 1 hour of AC Level 2 charging to go 10 to 20 mi) than on a fast charger at DC Level 2 (e.g., 20 minutes or less to go at least 60 mi).^{104,86,87}

Within the EU, ACEA has developed recommended specifications for opportunity charging, or "OppCharge" using 150 kW to 600 kW automated overhead charging for urban bus applications.⁸⁸ The OppCharge system is already in service for urban bus charging in the EU. Comparable overhead charging systems may also be applied to other BEV applications. In the U.S., SAE has established a new standard, J3105, for overhead charging of heavy-duty vehicles, including urban buses and heavy-duty trucks.⁸⁹ The SAE J3105 standard provides two levels of DC charging: J3105 Level 1 at up to 600 kW and J3105 Level 2 at up to 1.2 MW. Tesla additionally claims a charge rate of up to 1.6 MW for their proprietary "Megacharger", which is currently in development.⁹⁰

The analogous infrastructure for a FCEV is a hydrogen refueling station, which can offer refueling in time periods similar to filling a diesel fuel tank.^{8,74} The extent to which refueling/recharging time matters will vary for different applications of heavy-duty vehicles (e.g., delivery vans parked in a distribution center overnight versus a long-haul truck that refuels/recharges en route to a destination).

The choice between a BEV or FCEV powertrain technology for a particular heavy-duty vehicle application will likely depend on the specifics of an array of factors relevant to the particular duty-cycle and operations of an individual owner-operator or fleet.⁷⁴ For instance, considerations such as charging/refueling infrastructure access, charging/refueling time, energy conversion efficiency, vehicle weight, payload capacity, operational range, safety, noise levels, and other driver preferences may influence the extent to which individual fleets select a BEV or FCEV.^{91,92,74} Within each of these considerations there can be a spectrum of actual vehicle characteristics that an individual fleet or purchaser would want to consider.^T For instance, for vehicle weight, BEVs are generally expected to be heavier than diesel trucks or FCEVs due to the larger, heavier battery; however, ICE, FCEV, and BEV weight all vary based on the specific configuration of a model and the duty cycle it is intended to serve.⁷⁴ In urban delivery applications where a relatively smaller, lighter weight battery-pack could be used to drive a BEV 100 miles before charging, the additional vehicle weight from a battery-pack in a BEV may

^SIn 2019, refueling a FCEV to go 350 miles was estimated as taking 15 minutes compared to 5 minutes to refill a diesel fuel tank for the same trip length; note that hydrogen refilling stations can supply hydrogen at 350 or 700 bar, which can significantly impact the amount of time required to refill (NACFE 2019)

^T Further discussion on factors such as noise levels, vehicle weight, payload capacity, operational range, charging/refueling time, energy conversion efficiency, safety, and other driver preferences is available in guidance reports by NACFE (NACFE Class7/8Report, BEVs where they make sense, MD TCO report).

matter less, particularly when the purchaser takes into account the lack of weight from diesel fuel, diesel exhaust fluid, emissions control technology, exhaust systems, and other components that are not needed in a BEV.^{74,92} The duty cycle of urban delivery vehicles can also fit well with the operational characteristics of a BEV, where trucks could charge at the same location after completing their delivery route for the day and additional energy is recovered throughout the day from regenerative braking in stop-and-go traffic.^{74,92} For similar reasons, regional haul applications in which a truck travels 300 miles or less per day may also be well-suited for BEV technology.^{93,74} Transit and school buses are other applications that may be well-suited for BEV technology given frequent regenerative braking opportunities and well-defined routes.¹⁰⁴ In contrast, FCEVs may be more well-suited for long-haul applications due the higher percentage of time in steady-state highway operations and longer-range capabilities at a vehicle weight comparable to an ICE.⁷⁴ The specificity with which BEVs and FCEVs may be built for certain applications (e.g., smaller, lighter battery packs in urban delivery trucks compared to larger battery packs in regional haul trucks; better steady-state performance of fuel cell technology in long-haul applications) may be seen as continuation of the trend towards greater specialization of heavy-duty diesel trucks over the past several years (e.g., optimizing aerodynamics for long haul); however, greater vehicle specialization for a particular application may limit the sale of the vehicle to second and third owners.⁷⁴ On the other hand, technology improvements, such as decreases in battery costs and greater availability of DC Fast chargers, could minimize differences between BEV models, as well as between BEVs and conventionally fueled trucks. Improvements in fuel cell technology could similarly minimize cost differences between FCEVs and diesel trucks.

1.4.2.2 Emissions Performance

BEVs and FCEVs do not have internal combustion engines (ICEs), and thus have zero tailpipe emissions of NO_x.^U The absence of tailpipe emissions means that the emissions performance of these heavy-duty vehicles are not dependent on the maintenance and repair of emissions control systems, as is the case for most types of hybrids, and all ICEs. Nevertheless, emissions from producing electricity to recharge the vehicle battery, in the case of BEVs, or emissions from producing hydrogen, in the case of FCEVs, are part of the emissions profile for these vehicles.^V Comparisons of lifecycle emissions from BEVs, FCEVs, and ICEs vary in terms of assumptions and conclusions, but generally suggest lower lifecycle emissions associated with BEVs and FCEVs relative to ICEs, particularly if electricity or hydrogen fuel is generated from renewable sources (e.g., wind, solar, biomethane, hydroelectric).^{W,74,104}

The emissions impacts of BEVs and FCEVs are not included in the proposed rulemaking's emissions inventory analysis because we anticipate that manufacturers will meet the proposed standards with diesel and gasoline engine technologies. However, we recognize that BEV or

^U Note that there have also been experimental bus applications using solid oxide fuel cells (SOFC) instead of PEMFCs; SOFCs reform liquid or gaseous fossil fuels and do have tailpipe emissions.

^V Other lifecycle emissions, such as those due to producing battery packs, hydrogen fuel cells, and other vehicle components are also important to consider when looking at emissions performance over the life a vehicle, but these factors are considered outside the scope of this analysis.

^W The source and production process used to supply energy for powering BEV charging or FCEV hydrogen production have large impacts on lifecycle emissions. For instance, hydrogen production through grid electrolysis is very energy intensive, which could result in higher emissions. BEV charging powered by coal-driven power plants could similarly increase lifecycle NO_x emissions relative to ICEs.

FCEV technologies are increasingly being introduced into the heavy-duty market. As such, we were interested in evaluating the emissions impacts of BEV and FCEV technologies entering the heavy-duty market due to market forces alone (i.e., not due to manufacturers changing their production plans due to a change in criteria pollutant standards). As discussed in Section 0 below, there is a wide range of projections for BEV and FCEV sales in the 2027 through 2045 timeframe. Due to the wide range, we conducted a sensitivity analysis to evaluate the potential impacts of BEV and FCEV on our emissions estimates. This sensitivity analysis is briefly described here, with results presented in Chapter 5 Appendix 5.

The BEV and FCEV sensitivity analysis was conducted through post-processing MOVES emissions inventories for the Baseline, the proposed Option 1 and 2, and the Alternative (i.e., each scenario). Specifically, we used a ratio of BEV and FCEV sales over total sales in calendar years 2027 and 2045 to adjust each scenario in the proposed rulemaking using Equation 1-1. For vehicle sales data we used estimates from the 2018 Energy Information Administration (EIA) and a 2017 National Energy Laboratory (NREL) study.^{94,95} The EIA data is consistent with what is used in our main MOVES emissions inventory analysis, and likely reflects a conservative estimate of future BEV and FCEV sales. The NREL study includes "Low", "Medium", and "High" adoption scenarios for BEVs; we used the "Medium" adoption scenario to reflect a more moderate estimate of future BEV sales relative to the EIA data. The NREL data does not include FCEV sales data, and we were unable to identify a comparable data source for FCEV sales volume projections in 2027 through 2045. If additional data on FCEV sales is available when we are conducting analyses for the final rulemaking, then we would likely evaluate using those data. Similarly, if EPA receives feedback that the NREL "High" scenario may be more appropriate for reflecting BEV market adoption, then we would consider that for the final rule.

Equation 1-1

$$Emissions_adjusted_{i,j} = Emissions_{i,j} \times (1 - BEV_FCEV_Ratio_j)$$

Where:

i: pollutant

j: sourcetype

BEV_FCEV_Ratio: Ratio of BEV and FCEV to total vehicle population

In both the EIA and NREL datasets, vehicle sales are categorized by light-, medium-, or heavy-heavy-duty vehicles, or buses. We apportioned vehicle sales in each of these categories to MOVES sourcetypes based on Table 3-3 in the MOVES Population and Activity Technical Report.⁹⁶ In general, light- and medium-heavy duty vehicle sales were assigned to vocational sourcetypes in MOVES (e.g., refuse [51], single-unit short-haul truck [52], single-unit short-haul truck [53]), while heavy-heavy-duty vehicle sales were assigned to long-haul sourcetypes (i.e., combination short-haul truck [61], combination long-haul truck [62]). For buses, the NREL dataset provided transit bus sales, so no re-assignment was needed; however, EIA does not provide explicit data for buses and thus total heavy-duty vehicles are typically used to map buses MOVES sourcetypes. We recognize that using total heavy-duty vehicle sales is likely a significant underestimate of BEV transit bus sales, but since we are using EIA data as a conservative, lower bound, estimate we did not adjust the EIA data. Table 1-9 provides a comparison of BEV sales in 2027 and 2045 from EIA and NREL data sources. Emissions inventory results of the sensitivity analysis are provided in draft RIA Chapter 5, Appendix 5.

Additional discussion on BEV and FCEV emissions performance, as it relates to the potential for emissions credits, along with a request for comment on this topic is discussed in Section IV.I of the Preamble.

Table 1-9: BEV & FCEV Sales Percentages

	2027	2045
EIA Medium-heavy Duty (BEV & FCEV)	1%	2%
NREL Medium-heavy Duty (BEV only)	5%	28%
EIA Heavy-heavy Duty (BEV & FCEV)	0.4%	0.7%
NREL Heavy-heavy Duty (BEV only)	2%	10%
EIA Buses (BEV & FCEV only)	0.8%	1%
NREL Transit Buses (BEV only)	9%	48%

1.4.2.3 Current and Future Markets

In 2019, there were approximately 60 makes and models of BEVs available for purchase, with additional product lines in prototype or other early development stages.^{104,X,Y} The FCEV market in 2019 included three commercially available models, again with additional options in prototype or other early development stages.^{74,104} Current production volumes of both BEVs and FCEVs are small with the NACFE estimating fewer than 50 FCEVs and fewer than 100 BEVs Class 7/8 trucks in production in the US in 2019.⁷⁴ While a number of prototypes and demonstration projects are underway, particularly in ports in the state of California, they are generally in early stages of establishing feasibility and durability of the technology, as well as building out necessary infrastructure.⁷⁴ Nevertheless, some manufacturers are building off of a wealth of experience in battery-electric passenger car and/or transit bus production, which suggests the potential for rapid adaptation and growth of BEVs in the heavy-duty market.⁷⁴ Indeed, larger numbers of BEVs are in production the medium-heavy duty market (relative to Class 7/8) since urban delivery is seen as a duty-cycle well-suited for BEV performance.^{92,92,97} BEV technology is also increasingly used in the transit bus market, with electric buses growing from 300 to 650 in the US between 2018 to 2019.^{98,Z} Table 1-10 and Table 1-11 provide a snapshot of BEVs in the medium- and heavy-duty truck, and bus markets as of 2019, according to one source; however, given the dynamic nature of the BEV and FCEV market, the number and types of vehicles available is changing fairly rapidly.⁹⁹ Similar efforts to inventory available BEV and FCEV

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

^Y Note that there are varying estimates of BEV and FCEV models in the market; NACFE 2019 provided slightly lower estimates than the those included here from Nadel and Jung 2020. A recent NREL study suggests that there may be more models available, but it is unclear how many are no longer on the market since the inventory includes vehicles introduced and used in commerce starting in 2012 (Smith et al. 2019).

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

vehicles are available in recent reports by NREL, ACEEE, and ICCT, as well as an interactive webtool developed by CALSTART.^{84,104,100,101}

Table 1-10: BEV Truck Offerings or Planned Offerings in the US (as November 2019)^{AA}

Manufacturer	Model	Range	Battery, H2 Capacity	Availability
Delivery Vans, Shuttles, and Straight Trucks				
BYD	6F	124 miles	221 kWh	Today
Chanje	V8100	150 miles	100 kWh	Today
Freightliner (Daimler)	eM2	230 miles	325 kWh	Production in 2021
GreenPower	EV Star Cargo	150 miles	118 kWh	Today
International (Navistar)	eMV	250 miles	321 kWh	Production in 2021
Lightning Systems	Ford Transit 350HD	120 miles	86 kWh	Today
	Ford E-450	110 miles	129 kWh	Today
	Ford F-59	110 miles	128 kWh	Today
	Chevy 6500XD	130 miles	192 kWh	Today
Lion	Lion8	Unknown	480 kWh	TBD
Mitsubishi Fuso (Daimler)	eCanter	80 miles	83 kWh	Demonstration
Motiv	Ford E-450	100 miles	127 kWh	Today
	Ford F-53	125 miles	127 kWh	Today
	Ford F-59	90 miles	127 kWh	Today
Peterbilt (Paccar)	Model 220EV	100 miles	148 kWh	Demonstration
Phoenix Motor Cars	Ford E-450	100 miles	105 kWh	Today
Rivian	Unknown	Unknown	Unknown	Deployment in 2021
Workhorse	C1000	125 miles	70 kWh	TBD
Xos	Medium Duty	200 miles	Unknown	Today
Tractor Trucks				
BYD	8TT	125 miles	409 kWh	Today
Freightliner (Daimler)	eCascadia	250 miles	550 kWh	Production in 2021
Nikola	Nikola One (sleeper)	750 miles	80 kg H2	Production in 2022
	Nikola Two (day)	400 miles	1,000 kWh	Production in 2022
Peterbilt (Paccar)	Model 579	250 miles	352 kWh	Demonstration
Tesla	Semi	500 miles	Unknown	Production in 2020
Toyota/Kenworth (Paccar)	T680	300 miles	60 kg H2	Demonstration
Volvo Group	VNR	Unknown	Unknown	Production in 2020
Xos	ET One	300 miles	Unknown	Demonstration
Refuse Trucks				
BYD	6R	125 miles	221 kWh	Today
	8R	56 miles	295 kWh	Today
Mack (Volvo Group)	LR	Unknown	Unknown	Demonstration
Peterbilt (Paccar)	Model 520EV	80 miles	315 kWh	Demonstration
Street Sweepers				
Global Environmental Products	M4 – electric	240 kWh	11 hours	Today
	M4 – fuel cell	20 kg	10 hours	Today

Note: Ranges represent the maximum values reported by manufacturers. Models available “today” are defined as vehicles eligible for California’s Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project incentive funding, if not otherwise commercially available for purchase. Parent companies are listed in parentheses. Manufacturer partnerships are designated with a slash.

^{AA} Table adapted from UCS (2019)⁹⁹

Table 1-11: BEV Bus Offerings or Planned Offerings in the US (as November 2019)^{BB}

Manufacturer	Model	Range	Battery , H2 Capacity	Availability
School Buses				
Blue Bird	MicroBird (Type A)	100 miles	88 kWh	Today
	Vison (Type C)	120 miles	160 kWh	Today
	All American (Type D)	120 miles	160 kWh	Today
GreenPower	Synapse 72 (Type D)	140 miles	200 kWh	Today
IC (Navistar)	chargE (Type C)	120 miles	260 kWh	TBD
Lion	Type A	150 miles	129 kWh	Today
	Type C	155 miles	220 kWh	Today
Motiv	Type A	75 miles	106 kWh	Today
	Type C	90 miles	127 kWh	Today
Thomas Built (Daimler)	Jouley (Type C)	120 miles	220 kWh	Today
Transit Buses				
BYD	K7 (30')	135 miles	196 kWh	Today
	K9 (35')	215 miles	266 kWh	Today
	K9 (40')	177 miles	352 kWh	Today
	K11 (60')	230 miles	Unknown	Today
Complete Coach Works	ZEPS	150 miles	311 kWh	Today
El Dorado National	AXESS Fuel Cell (35')	260 miles	50 kg of H2	Today
	AXESS Fuel Cell (40')	260 miles	50 kg of H2	Today
Gillig	ePlus (29')	Unknown	296 kWh	Today
	ePlus (35')	Unknown	444 kWh	Today
	ePlus (40')	Unknown	444 kWh	Today
GreenPower	EV250 (30')	175 miles	210 kWh	Today
	EV300 (35')	175 miles	260 kWh	Today
	EV350 (40')	185 miles	320 kWh	Today
	EV400 (45')	185 miles	320 kWh	Today
Lightning Systems	City Transit Bus Repower	200 miles	320 kWh	Today
Lion	LionM (26')	150 miles	160 kWh	Today
New Flyer	Xcelsior (35')	260 miles	545 kWh	Today
	Xcelsior (40')	225 miles	466 kWh	Today
	Xcelsior (60')	135 miles	466 kWh	Today
	Xcelsior Fuel Cell (40')	300 miles	37.5 kg of H2	Today
	Xcelsior Fuel Cell (60')	300 miles	60 kg of H2	Today
Proterra	Catalyst (35')	234 miles	440 kWh	Today
	Catalyst (40')	328 miles	660 kWh	Today
Coach Buses				
BYD	C6M (23')	124 miles	121 kWh	Today
	C8M (35')	200 miles	353 kWh	Today
	C9M (40')	200 miles	353 kWh	Today
	C10M (45')	230 miles	446 kWh	Today
MCI (New Flyer)	D45 CRTe LE CHARGE	Unknown	388 kWh	Production in 2020
	J4500e CHARGE	200 miles	450 kWh	Production in 2020
VanHool/Proterra	CX45E	Unknown	Unknown	Production in 2020
Double Decker Buses				
Alexander Dennis/Proterra	500EV	200 miles	660 kWh	TBD
BYD	C10MS	230 miles	446 kWh	Today
GreenPower	EV550	240 miles	478 kWh	Today
Yard Trucks				
BYD	8Y	10 hours	217 kWh	Today
Kalamar	T2E	“3 shifts”	220 kWh	Today
Orange EV	T-Series	24 hours	160 kWh	Today
Terberg	YT202	62 miles	Unknown	Today

Note: Ranges represent the maximum values reported by manufacturers. Models available “today” are defined as vehicles eligible for California’s Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project incentive funding, if not otherwise commercially available for purchase. Parent companies are listed in parentheses. Manufacturer partnerships are designated with a slash.

BEV and FCEV powertrain use is expected to increase in the heavy-duty market. The rate of growth ranges widely across forecasting models; for instance, the 2018 Annual Energy Outlook shows medium-duty BEVs making up 0.08% of total truck vehicle miles traveled (VMT) in 2030, whereas a 2018 National Renewable Energy Laboratory (NREL) study suggests 29% for the same time frame.^{94,95} A variety of factors will influence the extent to which BEVs and FCEVs are available for purchase and enter the market.^{91,92} NACFE looked at 22 factors on which to compare BEVs and FCEVs with heavy-duty diesel vehicles; they found that for the Class 7/8 market, a current lack of production vehicles resulted in BEVs and FCEVs performing worse than diesels in 2019, but each performing equal to, or better than diesel on most factors by 2030.^{CC,74}

The lifetime total cost of ownership (TCO), which includes maintenance and fuel costs, is likely a primary factor for fleets considering BEV and/or FCEV purchases. In fact, a 2018 survey of fleet owners showed "lower cost of ownership" as the second most important motivator for electrifying their fleet.^{DD,104} An International Council for Clean Transportation (ICCT) analysis suggests that TCO for light- and medium heavy-duty battery-electric vehicles could reach cost parity with diesel in the early 2020s, while heavy heavy-duty battery-electric or hydrogen vehicles are likely to reach cost parity with diesel closer to the 2030 timeframe.¹⁰² Recent findings from Phadke et al. suggest that BEV TCO could be 13% less than that of a diesel truck if electricity pricing is optimized.¹⁰³ Their analysis further suggests that BEV TCO could be as low 40% less than that of a diesel truck if battery costs reach \$100/kWh, electricity is provided through solar, wind, or other sources free of GHG-emissions, and environmental benefits of BEVs are monetized.¹⁰³

As both the ICCT and Phadke et al. study suggest, fuel costs are an important part of TCO. While assumptions about vehicle weight and size can make straight comparisons between BEVs, FCEVs, and ICEs challenging, data show greater energy efficiency of battery-electric technology relative to an ICE, with comparable or better energy efficiency of FCEVs relative to an ICE.^{EE,74,104} Better energy efficiency leads to better fuel economy and thus lower fuel costs for BEVs and FCEVs relative to ICEs.^{74,104} Maintenance and service costs are also an important component within TCO; although there is limited data available on actual maintenance costs for BEVs and FCEVs, early experience with BEV medium heavy-duty vehicles and transit buses suggests the potential for lower maintenance costs after an initial period of learning to refine both component durability and maintenance procedures.⁷⁴ To facilitate fleets transitioning to BEVs, some manufacturers are currently including maintenance in leasing agreements with

^{BB} Table adapted from UCS (2019)⁹⁹

^{CC} Factors that NACFE considered fell into the following categories: weight, cost, maintenance effort, vehicle life, range, "fuel" availability, and general; for additional information on the factors and how they compare in 2019 and 2030, see NACFE (2019) "Guidance Report: Viable Class 7/8 Electric, Hybrid and Alternative Fuel Tractors", available online at: <https://nacfe.org/downloads/viable-class-7-8-alternative-vehicles/>

^{DD} The primary motivator for fleet managers was "Sustainability and environmental goals"; the survey was conducted by UPS and GreenBiz.

^{EE} Fuel costs here refers to diesel or gasoline for an ICE and electricity or hydrogen for a BEV or FCEV, respectively.

fleets; it is unclear the extent to which a full service leasing model will persist or is transitioned to a more traditional purchase after an initial period of learning.^{105,106}

The potential for lower fuel and maintenance costs to outweigh a higher upfront cost for BEVs and FCEVs is reflected in ICCT and other's projections of BEVs and FCEVs reaching cost parity with diesels within the next several years; however, the current upfront cost can exceed a diesel vehicle by 60% or more.¹⁰⁴ Upfront purchase price was listed as the primary barrier to fleet electrification in a 2017 survey of fleet managers, which suggests that state or local incentive programs to offset BEV or FCEV purchase costs will play an important role in the near term, with improvements in battery and hydrogen fuel cell costs playing a role in reducing costs in the longer-term.^{FF,104}

Another large factor in TCO for fleet adoption of BEVs and FCEVs is charging and refueling infrastructure, respectively.¹⁰⁴ In early 2020, there were over 24,000 publicly accessible EV charging stations in the US, 3,400 of which were DC Fast Chargers (with the remaining being Level 2 charging stations); the majority of these charging stations were built for light-duty vehicles in terms of location and power availability, thus while some of the existing Level 2 charging might be suitable for overnight charging of medium-heavy-duty vehicles, DC Fast Charging or chargers capable of even higher peak power demand will likely be necessary for most heavy-duty vehicles, and many fleets will generally want to have their own charging infrastructure onsite.^{107,74} For FCEVs, there were 50 public and private hydrogen refueling stations in the US in early 2020, the majority of which are located in California.¹⁰⁷ Building out charging and refueling infrastructure will be a critical component of BEV and FCEV technologies continuing to enter the heavy-duty market. In the case of BEV charging infrastructure, fleets need to work through a number of considerations, such as: space and siting requirements (e.g., space for trucks charging over long periods of time, proximity to electrical equipment), electrical power infrastructure (e.g., amount of power that can safely be offered to a site without distribution grid upgrades), their fleet's energy needs, charging station maintenance, and energy pricing (e.g., , peak demand charges during certain times of day).^{104,103} Programs to support BEV charging infrastructure are increasingly being offered through utility or other state programs, and NACFE has published a resource to help fleets navigate the charging infrastructure procurement process.^{GG, 104} As noted above, some manufacturers are offering lease options that include maintenance; these leases can also include "fuel" (electricity or hydrogen). Nikola Motors for instance is including hydrogen refueling in the cost of leasing one of its future FCEVs and plans to build 700 hydrogen refueling stations across the US and Canada by 2028.¹⁰⁸ Notably, Phadke et al. find that charging cost has the largest impact on the payback period for a BEV relative to a diesel truck.^{103,HH,109,110}

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

^{GG} Further discussion on factors such as noise levels, vehicle weight, payload capacity, operational range, charging/refueling time, energy conversion efficiency, safety, and other driver preferences is available in guidance reports by NACFE (NACFE Class7/8Report, BEVs where they make sense, MD TCO report).

^{HH} Note that alternative charging technologies, such as wireless or overhead charging, are being explored (see ICCT 2019 and ICCT 2017 for more discussion)

Driver preferences such as acceleration speed and noise levels can also influence fleet decisions to purchase BEVs and/or FCEVs.^{92,104} Electric motors offer a faster acceleration from stop and faster speed going up grade, which may be attractive to delivery drivers looking to minimize their route time.¹⁰⁴ Similarly, BEVs are generally thought to operate at lower noise levels relative to ICE vehicles, which could be attractive for both drivers and local communities.¹⁰⁴ Furthermore, BEVs and FCEVs generate occupational health benefits by reducing driver exposure to heavy-duty vehicle emissions while on duty. State and local activities, such as the Advanced Clean Trucks (ACT) rulemaking recently finalized in California could also influence the market trajectory for battery-electric and fuel cell technologies.¹¹¹ The ACT requires manufacturers to sell a certain percentage of zero emission heavy-duty vehicles (BEVs or FCEVs) for each model year, starting in MY 2024. The sales requirements vary by vehicle class, but start at 5 to 9 percent of total MY 2024 heavy-duty vehicle sales in California and increase up to 40 to 75 percent of MY 2035 and beyond sales.¹¹² Outside of California, many states also have fleet incentive programs in the form of grants, tax incentives, rebates, exemptions, etc. that may help to accelerate fleet purchases of BEVs or FCEVs.⁷⁴ In July 2020, fifteen states and the District of Columbia signed a Memorandum of Understanding affirming a commitment to strive towards at least 30 percent of new heavy-duty vehicle sales being zero emission vehicles by 2030 and to reach 100 percent of new sales by 2050.¹¹³ In addition, cities such as New York, Los Angeles, and San Francisco have committed to transitioning their transit bus fleets to all electric in the 2030 to 2040 timeframe.¹⁰⁴

Chapter 2 Compliance Provisions

2.1 Compression-Ignition Engine Dynamometer Test Procedures

Test procedures are a crucial aspect of the heavy-duty criteria pollutant program. This rulemaking is proposing to establish several new test procedures for spark and compression ignition engine compliance. This chapter will describe the existing test procedures as well as the development process for the test procedures being proposed. This includes the determination of emissions from both engines and hybrid powertrains as well as the development of new duty cycles.

2.1.1 Current CI Test procedures

heavy-duty compression-ignition engines currently are certified for non-greenhouse gas (GHG) pollutants using the Heavy-Duty Diesel Engine Federal Test Procedure (HDDE FTP) and Supplemental Emission Test Ramped Modal Cycle (SET). For 2007 and later Heavy-Duty engines, 40 CFR Parts 86 – “Control of Emissions from New and In-Use Highway Vehicles and Engines” and 1065 – “Engine Testing Procedures” detail the certification process. 40 CFR 86.007-11 defines the standard settings of Oxides of Nitrogen, Non-Methane Hydrocarbons, Carbon Monoxide, and Particulate Matter. The duty cycles are defined in Part 86. The HDDE FTP is defined in 40 CFR part 86 Appendix I. The SET is defined in 40 CFR 86.1362(a). All emission measurements and calculations are defined in Part 1065, with exceptions as noted in 40 CFR 86.007-11. The data requirements are defined in 40 CFR 86.001-23 and 40 CFR 1065.695.

The measurement method for CO is described in 40 CFR 1065.250. For measurement of NMHC, refer to 40 CFR 1065.260. For measurement of NO_x, refer to 40 CFR 1065.270. For measurement of PM, refer to 40 CFR 1065.140, 1065.170, and 1065.290. Table 1 of 40 CFR 1065.205 provides performance specifications that we recommend analyzers meet. Note that 40 CFR 1065.307 provides linearity verifications that the system must meet. For the calculation method for brake specific mass emissions for CO, NMHC, NO_x and PM, refer to 40 CFR 1065.650.

2.1.1.1 HDDE FTP

The Heavy-Duty Diesel Engine Federal Test Procedure (HDDE FTP) is a transient test consisting of second-by-second sequences of engine speed and torque pairs with values given in normalized percent of maximum form. The cycle was computer generated from a dataset of 88 heavy-duty trucks in urban operation in New York and Los Angeles. This procedure is well-defined, mirrors in-use operating parameters, and continues to be appropriate for assessment of criteria pollutant emissions from heavy duty engines.

A complete HDDE FTP involves three test sequences. First, a 20-minute test is run over the duty-cycle with the engine at the same ambient temperature as the test cell (between 68°F and 86°F). The engine undergoes a 10-minute hot-soak following the cold-start. A 20-minute hot start test is run over the duty-cycle following the hot-soak. The HDDE FTP emission level for the engine is determined by weighting the cold start emissions by 1/7 (about 14 percent) and the hot-start emission results by 6/7 (about 86 percent).

2.1.1.2 SET

The Supplemental Emission Test Ramped Modal Cycle (SET) is a 13-mode, steady-state engine dynamometer test that replaced the steady-state modal run SET and is based on the European Stationary Cycle (ESC). The engine is tested on an engine dynamometer over a sequence of steady-state modes. Emissions are collected over both the steady-state and transition portions (20-second transitions) of the test and the results are integrated to produce a single emission result to show compliance with the standard.

The current weighting of modes within the SET for engines complying with the 2010 NO_x and Phase 1 GHG standards is given in Table 2-1. A, B, and C speeds are determined according to 40 CFR 1065.610.

Table 2-1: SET Mode Weighting Factors for the 2010 NO_x and Phase 1 GHG Standards

Speed, % Load	Weighting factors of SET (%)
Idle	15
A, 100	8
B, 50	10
B, 75	10
A, 50	5
A, 75	5
A, 25	5
B, 100	9
B, 25	10
C, 100	8
C, 25	5
C, 75	5
C, 50	5
Total	100
Idle Speed	15
Total A Speed	23
Total B Speed	39
Total C Speed	23

2.1.1.3 Powertrain

Powertrain test procedures were created under EPA's Heavy-duty Greenhouse Gas: Phase 2 (Phase 2) rulemaking for vehicle certification.^{114,115} At the time of their development, no certification procedure existed for powertrain certification of heavy-duty hybrid vehicles to any engine standards. The powertrain test was updated for powertrain certification of the engine to engine standards for GHG pollutants in the Heavy-Duty Engine and Vehicle Test Procedures, and Other Technical Amendments rulemaking (hereinafter "HD Technical Amendments").¹¹⁶ The powertrain certification test was finalized for certification to both the FTP and SET and is carried out by following 40 CFR 1037.550 as described in 40 CFR 1036.505 and 40 CFR

1036.510 and is applicable for powertrain systems with the hybrid function located in the P0, P1, P2, and P3 positions.

The development of these test procedures required the addition of a speed and road grade profile to the existing HDDE FTP, HDOC FTP, and newly proposed LLC duty-cycles in the recently finalized Appendix II of 40 CFR part 1036 and to the SET in 40 CFR 1036.505.¹¹⁶ It also required the development of vehicle parameters to be used in place of those in 40 CFR 1037.550; namely vehicle test mass, vehicle frontal area, vehicle drag area, vehicle coefficient of rolling resistance, drive axle ratio, tire radius, vehicle curb mass, and linear equivalent mass of rotational moment of inertias. Determination of system and continuous rated power along with the maximum vehicle speed (C speed) is also required using 40 CFR 1036.527. The combination of the generic vehicle parameters, the engine duty-cycle vehicle speed profile, and road grade profile fully defines the system load and this is designed to match up the powertrain load with the HDDE vFTP, HDOC vFTP, vSET, and vLLC load for an equally powered engine.

The development of these test procedures was previously described in detail in the HD Technical Amendments.¹¹⁶

2.1.2 Potential updates to CI Test procedures

2.1.2.1 HDDE FTP

We are proposing no changes to the HDDE FTP weighting factors or the duty-cycle torque values from the duty-cycle that currently applies to criteria pollutant regulations in 40 CFR part 86 Appendix I (f)(2). We are proposing a change to the speed values that does not influence the ultimate denormalized speed, as noted below and finalized in the HD Technical Amendments, apply to criteria pollutant certification as well. We started the migration of some heavy-duty highway engine standard setting part test procedures to 40 CFR part 1036 in the HD Technical Amendments. This included the migration of the HDDE FTP drive schedule to Appendix II (c) of part 1036 in order to add vehicle speed and road grade to the duty-cycle to facilitate powertrain testing of hybrids for compliance with the Phase 2 GHG standards.

The change that was made for GHG and that is being proposed to apply to criteria pollutant certification as well took the normalized vehicle speeds over the HDDE FTP duty-cycle and multiplied them by 100/112 to eliminate the need to divide by 112 in the diesel engine denormalization equation in 40 CFR 86.1333(a)(1)(i). This eliminated the need for inclusion of a denormalization equation in the standard setting part and allows commonization of (between compression and spark ignition engines) the use of the denormalization equation in 40 CFR 1065.610(c)(1) (equation 1065.610-3), with no effect on stringency.

2.1.2.2 SET

The SET weighting currently used for certification of heavy-duty highway compression ignition engines for criteria pollutants and Phase 1 GHG has a relatively large weighting in C speed. The C speed is typically in the range of 1800 rpm for current heavy heavy-duty engine designs. However, it is becoming much less common for engines to operate at such a high speed in real-world driving conditions, especially during cruise vehicle speeds in the 55 to 65 mph vehicle speed range. This trend has been corroborated by engine manufacturers' in-use data that has been submitted to the agencies in comments and presented at technical conferences.¹¹⁷ Thus, although the current criteria pollutant and HD Phase 1 GHG SET represents highway operation

better than the FTP cycle, improvements have been made via the HD Phase 2 GHG program by adjusting its weighting factors to better reflect modern trends in in-use engine operation. The most recent trends for compliance with the Phase 2 GHG standards indicate that manufacturers are configuring drivetrains to operate engines at speeds down to a range of 1050-1200 rpm at a vehicle speed of 65mph.

To address this trend toward in-use engine down-speeding, the agencies are proposing to apply the refined SET weighting factors and resulting SET developed for the HD Phase 2 GHG standards to the proposed rulemaking criteria pollutant standards. The Phase 2 GHG SET mode weightings move most of the C weighting to the A speed, as shown in Table 2-2. To better align with in-use data, these changes also include a reduction of the idle speed weighting factor. This proposal would apply the Phase 2 mode weightings to both criteria pollutants and the Phase 2 CO₂ emission and fuel consumption standards starting in model year 2027.

Table 2-2: New SET Mode Weighting Factors in Phase 2

Speed/% Load	Weighting Factor in Phase 2 (%)
Idle	12
A, 100	9
B, 50	10
B, 75	10
A, 50	12
A, 75	12
A, 25	12
B, 100	9
B, 25	9
C, 100	2
C, 25	1
C, 75	1
C, 50	1
Total	100
Idle Speed	12
Total A Speed	45
Total B Speed	38
Total C Speed	5

The Phase 2 SET mode weighting moves most of the C speed weighting to A speed and reduces the weighting factor on idle speed. These values are based on data from vehicle manufacturers that have been claimed as confidential business information. These revised SET weighting factors better reflect the lower engine speed operation of modern engines, which frequently occurs at tractor cruise speeds.

To evaluate how current engines perform on this cycle, we tested a 2018 Detroit DD15 and a 2018 Cummins B6.7. For both engines there was no significant difference for any of the measured criteria pollutants between the two cycles. These results are summarized in

Chapter 4.1.2 of the RIA. To assess the effect of stringency between the two SET cycles, the CARB Stage 3 demonstration engine was also run on both versions of the SET. The results from these tests can be found in Chapter 4.1.1.1 of the draft RIA.

2.1.2.3 LLC

Current certifications cycles (FTP and SET) and in-use not-to-exceed (NTE) compliance requirements do not account for emissions over sustained low load operation. This is either because the idle time in the duty-cycle is too short, or, in-use, the operation is excluded from compliance requirements.

We are proposing a new low load certification cycle to address deficiencies in our current certification duty-cycles and NTE in-use testing program with respect to emission control at low load.

The National Renewable Energy Lab (NREL) and Southwest Research Institute (SwRI) under contract with the California Air Resources Board (CARB) developed a suite of candidate low load cycles (LLC) from urban tractor and vocational vehicle real-world activity data. The goal of the cycle development was to develop a duty-cycle that was representative of real-world urban tractor and vocational vehicle operations that are characterized by low engine loads, have average power and duration adequate for demonstrating that hardware and controls needed to deal with low load challenges are present and functional, and set an emission standard that balances the need for NO_x emission reductions and any associated GHG emission impacts.^{118, 119, 120, 121}

NREL combined their Fleet DNA and CARB's heavy-duty diesel vehicle activity datasets, incorporating a total of 751 unique vehicles across the United States, to develop the LLC. The combined dataset included vehicles from 25 distinct locations, 26 combined vocational designations, and 55 unique fleets incorporating both urban tractor and vocational applications. A breakdown of the applications that were included can be found in Table 2-3.

Table 2-3: Breakdown of vehicles from combined NREL Fleet DNA and CARB datasets.

Vehicle Application	Number of Vehicles
Parcel delivery	100
Refuse pickup	90
Line Haul	84
Beverage delivery	65
Mass transit	61
Food delivery	60
Drayage	41
Utility	32
Linen delivery	30
Transfer truck	29
Tanker	25
Telecom	24
Freight	22
Public work	13
School bus	11
Agricultural	10
Snow plow	9
Warehouse delivery	9
Construction	8
Dump truck	7
Refrigerated truck	6
Local delivery	5
Towing	4
Concrete	3
Dry van	3
Delivery	1

NREL initially developed a list of drive cycle metrics, including engine load specific calculations to describe engine/vehicle operation. Vehicle operation was then broken down into microtrips for operation over a given shift-day, where a single microtrip was defined as the duration over which a vehicle speed increases from 0 mph to the time where the vehicle stops, including operation until the vehicle speed starts to increase above 0 mph again. 10 microtrips were averaged using moving average windows based on a sensitivity analysis of moving average windows of 5, 10, and 15 microtrips. The total number of microtrips from the combined data sets was approximately 1.25 million and resulted in a trimodal distribution with two large primary peaks and a tertiary lower load peak as shown in Figure 2-1.

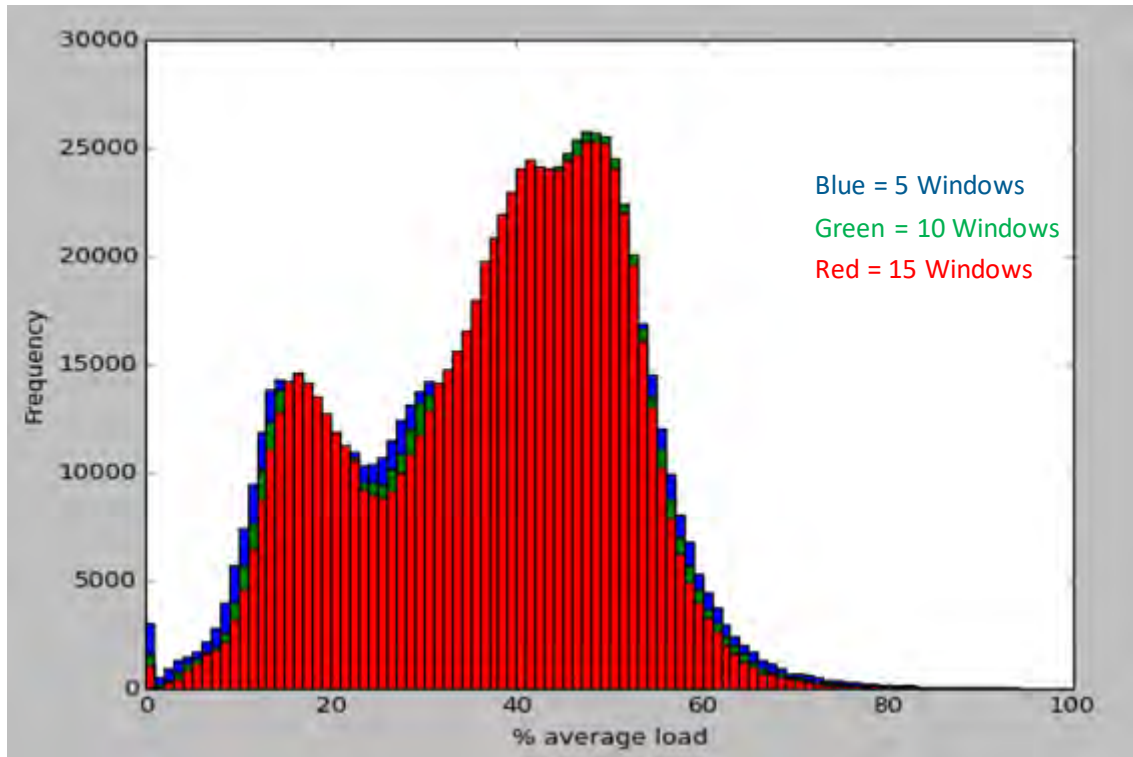


Figure 2-1: Window size comparison and load distribution profile.

The microtrips were then equated to operational profiles and profiles that contained average loads of 20% or less were considered further for construction of the LLC. These remaining profiles were then subjected to cluster analysis to identify unique groups of operation and to assess for outliers. K-means clustering was chosen to be applied to the dataset due to its computational efficiency and ability to identify and remove outliers during pre-processing. Elbow analysis was then applied to determine optimal cluster number. The resulting optimal cluster number was three.

Representative profiles from each cluster were then selected for Greenhouse Gas Emissions Model (GEM) simulation. Results for each cluster were ranked based on their distance to cluster center to identify the most representative profiles. Profiles were examined for behavior and final suitability for testing, starting with profiles closest to cluster center. Five primary modes of operation were generally observed in the low load profiles: sustained low load, long idle, motoring/short idle cooling (high to low load), post-cooling breakthrough (low to high load), and mid-speed cruise motoring. Profiles found to have outlying behavior were removed and not used for GEM modeling. These outliers were found to have one or more of the following: prolonged periods of idle, long key off periods, and missing data. The load data broadcast by engines is not accurate enough to allow translation of vehicle-based to engine-based profiles to create the engine duty-cycle, so the Phase 2 GEM simulation model was used to develop the normalized engine duty-cycle. A representative summary of ten GEM generated profiles is shown in Table 2-4.

Initial LLC candidate duty-cycles were constructed using DRIVE to include at least one example of each of the five primary modes of operation, incorporating five of the GEM generated duty-cycles. It should be noted that these candidate cycles did not always include the entire GEM generated profile if the candidate cycle could be completed in a shorter amount of time by removing portions of the profile that did not adversely affect the target modes of operation. Figure 2-2 gives an example of a candidate cycle incorporating representative profiles v9892 c0, v11660 c5, v073 c1, v9892 c1, and v11806 c5.

CARB narrowed the range of candidate LLC duty-cycles to the three that best represented the target modes of low load. The three were LLC Candidates 7, 8, and 10. Candidate cycle 7 is 90 minutes in duration, has 30 minutes of sustained low load operation, and retains the v073 c1 mid-speed cruise/motoring segment. Candidate cycle 8 is 81 minutes in duration, has 30 minutes of sustained low load operation, and has a shorter v073 c1 mid-speed cruise/motoring segment to assess breakthrough only. Candidate cycle 10 is 70 minutes in duration, has 20 minutes of sustained low load operation, and has a shorter v073 c1 mid-speed cruise/motoring segment to assess breakthrough only. Emission results for a representative engine compliant to EPA 2010 NO_x standard for the three-candidate duty-cycles can be found in Table 2-5.

CARB recently reported that it selected candidate cycle 7, with an option to add auxiliary load (1.5, 2.5, and 3.5 kW for LHD, MHD, and HHD engines respectfully), as the LLC that it plans to move forward with in its upcoming heavy-duty low NO_x program. This cycle was chosen by CARB for inclusion of the highest percentage of non-idle operation when compared to the other two candidate cycles. CARB's decision to move forward with the option to add auxiliary load was based on making the duty-cycle more realistic with respect to real world operation as it affords more effective function of technologies such as cylinder deactivation (CDA) during idle.

We agree with CARB's assessment of the candidate low load cycles and their adoption of cycle 7. Thus we are proposing to adopt LLC 7, however we are proposing to require the use of auxiliary load, to bolster the current FTP and SET duty-cycles and to better align laboratory duty-cycles with the proposed changes we are making to in-use testing and compliance requirements, which afford better low load NO_x reduction. We are requiring the use of auxiliary load because this results in more representative testing with respect to in-use operation. This duty-cycle also contains vehicle speed and road grade profiles to facilitate powertrain certification of hybrid powertrains to the engine standard. These profiles were developed in the same manner as the HDDE FTP and HDOC FTP as well as the SET as discussed in the HD Technical Amendments.¹¹⁶ The LLC can be found in 40 CFR part 1036 Appendix II(d).

Table 2-4: Representative Summary of GEM Generated Profiles for the Engine Duty-cycle

Profile	Vehicle	Cluster	Length	Avg % Speed	Avg % Torque	Repeats in SwRI Test Runs	Class	Chassis	Engine	Trans	Gears	Vocation
1	v9892	0	800	26.9	6.9	4	8	4x2	Volvo D13	AMT	12	Food Service
2	v11660	0	1295	21.4	6.6	3	8	6x4	Mack MP8-415C	MT	13	Drayage
3	v075	0	1130	26.3	7.4	3	8	6x4	Mack MP8-415C	AMT	10	Drayage
4	v11815	1	1949	11.5	8.8	3	8	6x4	Cummins ISX 15	MT	13	Transfer Truck
5	v11646	1	904	15.9	10.7	4	4	4x2	Cummins ISB 6.7	AT	6	Parcel Delivery
6	v073	1	1410	33.8	18.1	3	8	6x4	Mack MP8-415C	AMT	10	Drayage
7	v9892	1	1616	27	10.6	3	8	4x2	Volvo D13	AMT	12	Food Service
8	v11660	5	615	16.2	3.5	4	8	6x4	Mack MP8-415C	MT	13	Drayage
9	v11806	5	1810	7.5	6.8	3	8	6x4	Cummins ISX 12	AMT	10	Transfer Truck
10	v11817	5	739	15.3	7.7	4	8	6x4	Cummins ISM 11	AMT	10	Transfer Truck

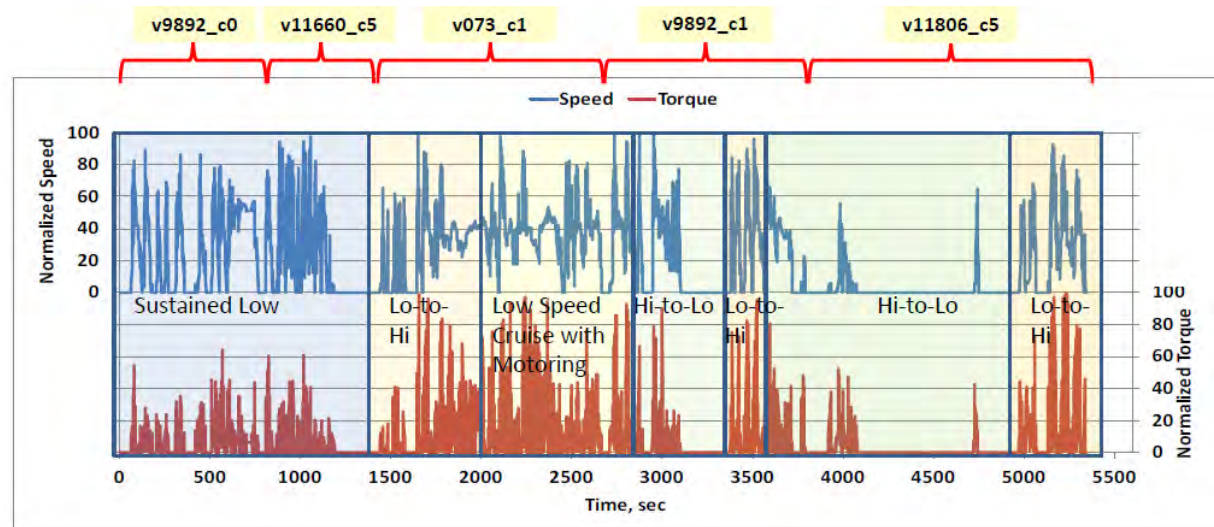


Figure 2-2: Example of a LLC 7 Candidate Cycle

Table 2-5: NO_x Emission Levels for a 2010 Compliant Engine on Three Candidate LLCs

Candidate #	Cycle Duration	NO_x Conversion Efficiency (%)	Engine Out NO_x (g/hp-hr)	Tailpipe NO_x (g/hp-hr)
7	90	74	3.2	0.8
8	81	77	2.9	0.7
10	70	69	3.2	1.0

2.1.2.4 Powertrain

We are proposing to allow the use of powertrain testing as an option for certification of hybrid powertrains to criteria pollutant standards. It is envisioned that this will capture CO₂ and NO_x co-optimization benefits for hybrid integration; including engine start/stop, electric motor assist, electric vehicle mode, and brake energy recovery. The powertrain test procedures to facilitate this type of certification testing have already been developed during the HD Technical Amendments and are directly applicable to criteria pollutant testing. Duty-cycles that incorporate vehicle speed and road grade for the HDDE FTP, HDOC FTP, and the SET were finalized in the HD Technical Amendments where development of these cycles was discussed.¹¹⁶ The proposed addition of the low load cycle in Chapter 2.1.2.3 also included a discussion of the vehicle speed and road grade profile development for powertrain testing.

2.2 Manufacturer-Run In-Use Testing Program for Compression-Ignition Engines

The manufacturer run in-use testing program is crucial to ensuring compliance with the heavy-duty criteria pollutant program. This rulemaking is proposing to establish a new test procedure for evaluating off-cycle compression ignition engine compliance. This chapter will describe the existing test procedure as well as the development process for the test procedure being proposed.

2.2.1 Current In-Use Program and Standards

EPA's current regulatory program for on-highway heavy-duty engines has evolved over the past four decades from relatively simple standards and test procedures appropriate for the mechanically controlled engines of the 1970s and 1980s, to a multi-faceted program designed to reduce emissions from modern computer-controlled engines. However, throughout the years, the compliance paradigm has focused heavily on the pre-production certification process, during which the manufacturers demonstrate that their engines will meet the applicable standards and related requirements.

Until fairly recently, compliance was determined by testing engines in a laboratory on an engine dynamometer. Prior to model year 2004, engines were evaluated over a single transient test cycle commonly referred to as the Heavy-Duty Diesel Engine FTP (HDDE FTP) cycle. Beginning with the 2004 standards, EPA added the engine dynamometer-based Supplemental

Emission Test (SET)^{II}, and Not-to-Exceed (NTE) emission limits that are evaluated on heavy-duty engines while in-use on the road.

Heavy-duty diesel engines are currently subject to Not-To-Exceed (NTE) standards that are not limited to specific test cycles, which means they can be evaluated during in-use operation. In-use data are collected by manufacturers as described in section 2.2.1. The data is then analyzed pursuant to 40 CFR 86.1370 and 40 CFR 86.1912 to generate a set of engine-specific NTE events, which are intervals of at least 30-seconds when engine speeds and loads remain in the control area. The express purpose of the NTE test procedure is to apply the emission standard to engine operation conditions that could reasonably be expected to be seen by that engine in normal vehicle operation and use, including a wide range of real ambient conditions.

The NTE zone defines the range of engine operation where the engine must comply. The NTE zone is based on engine speed and load and includes some carve outs that include low load operation (excludes load points less than 30% of T_{max} and P_{max} , and less than 15% of the European Stationary Cycle speed), as described in 40 CFR 86.1370. In addition, there are carve outs for altitude (> 5500 ft), maximum ambient temperature (100 °F at sea level, 86 °F at 5500 ft), aftertreatment temperature for NO_x aftertreatment and oxidizing catalysts (carves out operation at temperatures < 250°C), and provides a cold temperature operating exclusion for EGR equipped engines (calculation based on intake manifold temperature, engine coolant temperature, and intake manifold pressure).^{JJ}

Heavy-duty engines are required to comply with not-to-exceed (NTE) emission limits during in-use operation. Engine manufacturers must acquire and submit data through the manufacturer run in-use testing program. These in-use emission limits are 1.5 (1.25 for CO) times the laboratory certification standard or family emission limit (FEL) for NO_x, NMHC, PM and CO and can be found in 40 CFR 86.007-11. A measurement allowance value is added on to the standard to account for measurement inaccuracies that are associated with in-use measurement over short time periods and can be found in 40 CFR 86.1912. The engine standards and measurement allowances are in Table 2-6.

Table 2-6: Engine Standards and In-use Measurement Allowance

	NO_x (g/hp-hr)	PM (g/hp-hr)	CO (g/hp-hr)	NMHC (g/hp-hr)
Engine Standards	0.20	0.01	15.5	0.14
NTE Standards	0.30	0.015	19.4	0.21
Measurement Allowance	0.15	0.006	0.25	0.01

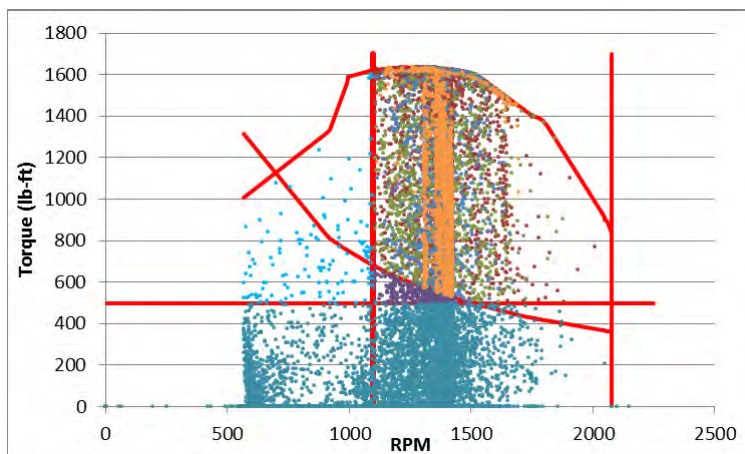
A valid NTE event is described as an event that is 30 seconds or more in duration under engine, aftertreatment, and ambient conditions that are within the NTE zone (i.e., do not occur during the aforementioned exclusion conditions), see 40 CFR 86.1370 and 40 CFR 86.1912. The engine must meet a vehicle pass ratio of 90% of valid NTE events (i.e., 90% of the valid NTE

^{II} The SET was later modified to run as a single continuous test (similar to how a transient cycle is run) and renamed the Supplemental Emission Test Ramped-Modal Cycle.

^{JJ} For more on our NTE provisions, see 40 CFR 86.1370.

events must comply with the in-use standard (0.45 g/hp-hr for NO_x) for the engine to be considered compliant) as described in 40 CFR 86.1912.

We have concerns with whether the current NTE regulations ensure that compliance can be achieved over the entire operating regime of the engine due to low temperature aftertreatment exclusions, and the narrow engine operation that has to be met for at least 30 consecutive seconds, as shown in Figure 2-3. Removal of these exclusions would require the engine manufacturer to act to maintain aftertreatment temperature at low load modes of operation, and this in turn would lead to better in-use performance with respect to emission compliance.¹²²



Points excluded by reason:

- Intake Manifold Temperature
- Aftertreatment Out Temperature
- Power
- Torque
- RPM
- Duration
- NTE Event

Figure 2-3: Sample of valid and invalid NTE events, separated by exclusion zones.

Data submitted under the current regulatory program has been acquired over more than 120,000 miles of vehicle testing. The data was generated by more than 540 unique vehicles and submitted by 14 different engine manufacturers. The percentage of test results meeting or exceeding the 0.9 pass ratio threshold since 2005 is presented in Table 2-7. A typical data set representing one test for an engine will contain twenty to forty valid NTE events, but under some routes no valid NTE events are measured.

Table 2-7: Percentage of Tests Meeting or Exceeding 0.90 Pass Ratio Threshold

Constituent	Percentage of Tests Meeting or Exceeding the 0.9 Pass Ratio
NO _x	96.0
CO	99.6
PM	99.4

The average pass ratio for each of the three constituents, for all data submitted since 2005, is presented in Table 2-8.

Table 2-8: Average Pass Ratios for Data Submitted Since 2005

Constituent	Overall Constituent Pass Ratio
NO _x	0.980
CO	0.996
PM	0.997

NTE standards have been successful in broadening the types of operation for which manufacturers design their emission controls to remain effective. However, our analysis of existing in-use test data indicates that less than five percent of a typical time-based dataset are valid NTE events that are subject to the in-use NTE standards; the remaining data are excluded. Furthermore, we found that emissions are high during many of the excluded periods of operation, such as when the aftertreatment temperature drops below the catalyst light-off temperature. For example, 96 percent of tests from 2014, 2015, and 2016 in-use testing orders passed with NO_x emissions for valid NTE events well below the 0.3 g/hp-hr NTE standard. When we used the same data to calculate NO_x emissions over all operation measured, not limited to valid NTE events, the NO_x emissions were more than double (0.5 g/hp-hr).¹²³ The results were higher when we analyzed the data to only consider NO_x emissions that occur during low load events. These results suggest there may be great potential to improve in-use performance by considering more of the engine operation when we evaluate in-use compliance. The average value of idle NO_x for the 2014, 2015 and 2016 Test Orders is approximately 16 g/hr.

2.2.2 Information evaluated for proposed updates

2.2.2.1 CE-CERT Program description

The CE-CERT study involves instrumenting about 100 trucks and collecting in-use second by second activity data over the course of one month from on-board GPS units and ECU scan tools. The instrumented vehicles are equipped with MY 2010 and later heavy-duty diesel engines utilizing SCR. Over 170 parameters are recorded including GPS based location, speed, elevation, ECU based vehicle speed, ECU based engine parameters (RPM, MAP, MAF, load), and aftertreatment variables (temperature, NO_x ppm). The vehicles cover 19 different groups based on vocational use, GVWR, and geographic operation.

Key findings of this study: Average speed varies from 41 mph for out-of-state line haul trucks to 9 mph for drayage trucks. In-state line haul trucks average 32 mph because they spend less time on freeways and double the time idling, compared to out-state line haul trucks. Most vocational vehicles spent about 33% of time operating at idle, irrespective of the time they spent on the freeway. SCR temperature for line haul operation has a bi-modal distribution with peaks at 100°C and 260-280°C. Drayage truck operation in Northern California exhibits a peak SCR operating temperature of around 110°C. Overall, the vehicles in this study spent 42-91% of their operating time with SCR temperatures below 250°C. Based on a generic SCR emission control efficacy versus SCR temperature curve, the average engine-out NO_x reduction could be 16% and 69% for agricultural trucks and refuse trucks, respectively.

In addition to giving a picture of heavy-duty vehicle activity, the study also provided data on NO_x sensors “on-time”. It is widely known that NO_x sensors are not turned on when the humidity level of the exhaust is high enough to produced condensed water, but there is little data

on how much time the sensors are off during heavy-duty vehicle operation. This information is useful if NO_x sensors are to be used as a compliance tool for an in-use standard. The sensors were not operational, or the tailpipe NO_x sensors were not reporting valid concentrations for 40% of the operating time based on the data collected. Figure 2-4 shows the time it takes until the sensors start reporting data from a cold-start. The majority of the engine out sensors report data within the first 10 minutes after a cold-start. The tailpipe sensors report data within the first 30 minutes, much later than the engine out sensors. This is understandable as the catalysts act as a heat sink, absorbing heat from the exhaust during warm-up and preventing this thermal energy from making it to the tailpipe sensor.

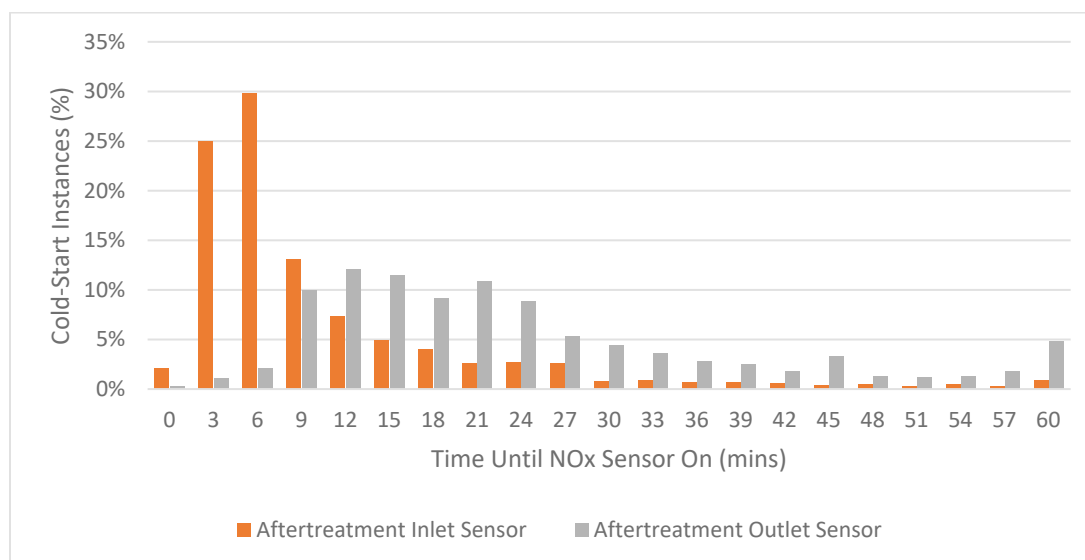


Figure 2-4: NO_x sensor time to on after engine cold-start

2.2.2.2 Summary of HDIUT Data

To evaluate the efficacy of current technology NO_x emissions controls, EPA analyzed the data from engines selected for testing in calendar years 2010 through 2016. This dataset covers 44 engine families, model years 2010 to 2015, from 11 manufacturers. The dataset includes about 8 million seconds of quality-assured second-by-second data collected during 68,000 miles of driving. The operational conditions include a wide range of driving speeds, transient and steady-state conditions, engine loads, and exhaust temperature conditions that have implications for emissions control efficacy, particularly for NO_x.¹²⁴ For the HHD class, out of a total 159 vehicles, 109 were line-haul, 46 were delivery, and the remaining were marked as “Other” in the metadata. Table 2-9 illustrates the distribution of family emission limit (FEL) values for the 291 vehicles tested. An FEL is a manufacturer-specified value that represents the maximum emission rate from the engines in that group during certification testing.

Table 2-9: Number of Diesel Vehicles with MY 2010+ Engines by NO_x FEL Group from the heavy-duty in-use testing Program

Regulatory Class	NO _x FEL Group			Total
	0.20	0.35	0.50	
HHD	49	0	15	64
MHD	26	23	9	58
LHD	93	31	35	159
Urban Bus	0	10	0	10
Total	168	64	59	291

The following sections describe three analyses that use the HDIUT data to investigate the relationship between aftertreatment temperatures and NO_x emissions, and identify operations where emissions are elevated.

2.2.2.3 HDIUT Data by MOVES OpMode

For the first analysis, the data was grouped by operating mode (OpMode) used by EPA's Motor Vehicle Emission Simulator (MOVES) emissions inventory model. MOVES OpModes are defined in terms of power output using a scaled tractive power (STP_t) parameter, shown in Equation 2-1, and vehicle speed.

Equation 2-1

$$STP_t = \frac{Av_t + Bv_t^2 + Cv_t^3 + M \cdot v_t(a_t + g \cdot \sin\theta_t)}{f_{scale}}$$

Where:

STP_t = the scaled tractive power at time t [scaled kW or skW]

A = the rolling resistance coefficient [kW·sec/m],

B = the rotational resistance coefficient [kW·sec²/m²],

C = the aerodynamic drag coefficient [kW·sec³/m³],

m = mass of individual test vehicle [metric ton],

f_{scale} = fixed mass factor (LHD = 5, MHD = 7, HHD = 10),

v_t = instantaneous vehicle velocity at time t [m/s],

a_t = instantaneous vehicle acceleration [m/s²]

g = the acceleration due to gravity [9.8 m/s²]

$\sin \theta_t$ = the (fractional) road grade at time t

OpMode 0 is reserved for deceleration and braking events. OpMode 1 represents idle, defined as vehicle speeds less than 1.0 mph. The remaining OpModes are defined by STP_t ranges and vehicle speed (v_t) ranges of 1 to 25 mph, 25 to 50 mph, and greater than 50 mph. Figure 2-5 is a graphical representation of the MOVES OpModes, showing their relationship to STP_t and v_t . See the MOVES Technical Report on heavy-duty emission rates for more information about OpModes.¹²⁵

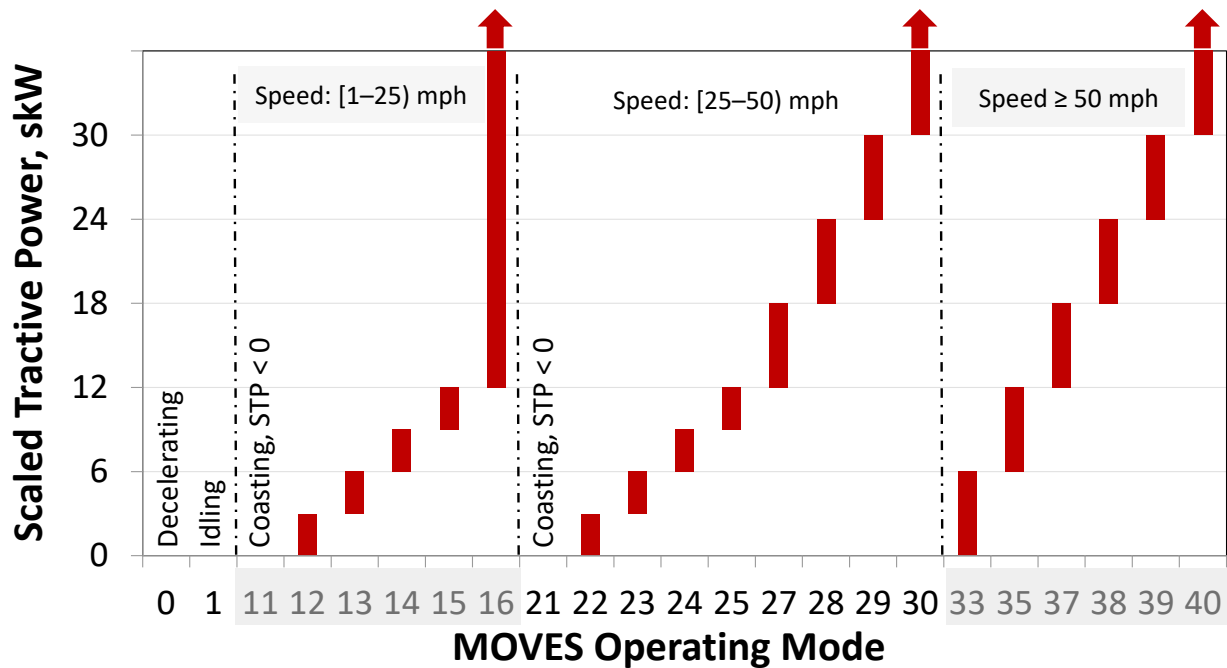


Figure 2-5: MOVES Operating Modes (OpModes) by scaled tractive power and vehicle speed

Figure 2-6 shows the NO_x emission rates in g/s for 65 vehicles from five manufacturers (by color) measured during in-use testing. The engines are categorized into eight HHD engine families (E-1 through E-8 by shape) with a NO_x FEL certification level of 0.20 g/bhp-hr. Real-world operation is known to produce large variability in emission rates, compared to certification testing that is performed in a lab. The graph shows that there is significant inter-engine family and intra-engine family variability in these in-use tests. For example, rates for E-1 are consistently lower than E-8. There is also variability within an engine family as represented by errors bars for each point. The spread is larger for engine families with higher emission rates, for example E-8. Similar trends are seen in MHD and LHD engine families.

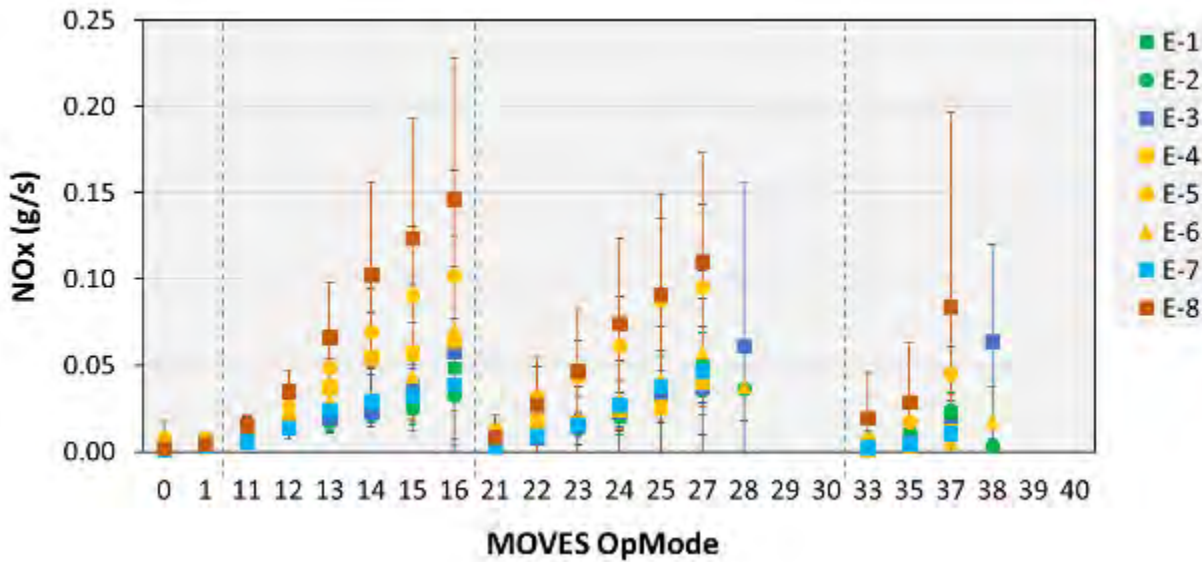


Figure 2-6: MOVES OpMode Emission Rates from HHD Engine Broken Down by Engine Family

Figure 2-7, Figure 2-8, Figure 2-9 show the OpMode-based NO_x emission rates for vehicles with NO_x FELs of 0.20 g/bhp-hr or better split by aftertreatment temperature. The figures do not include all tested vehicles, as some tests did not report aftertreatment temperature. Figure 2-7 is based on data from 81 vehicles with HHD engines, Figure 2-8 is from 20 vehicles with MHD engines, and Figure 2-9 is from 42 vehicles with LHD engines. For all engines and most OpModes, the NO_x emission rates when a vehicle is operating with an aftertreatment temperature below 250°C are more than double compared to operation with an aftertreatment temperature above 250°C. The figures also show that high NO_x emissions occur across all OpModes and are not limited to low-speed or idle operation.

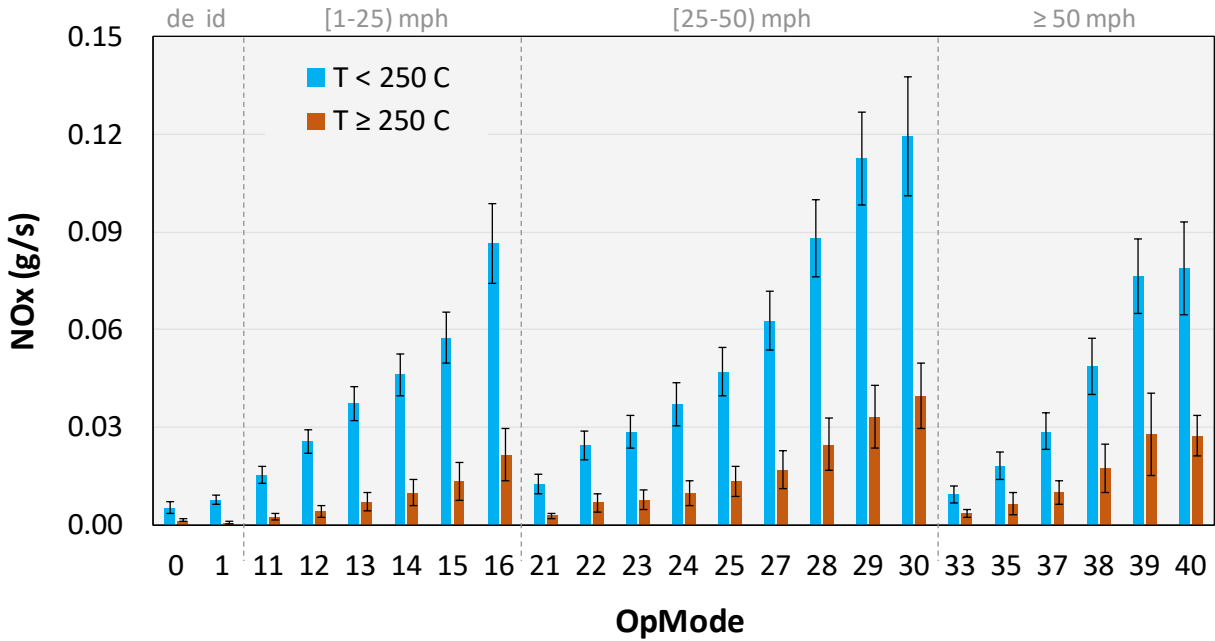


Figure 2-7: NO_x Emission Rates from 81 Vehicles with 0.20 g/bhp-hr FEL HHD Engines by MOVES OpMode and Aftertreatment Temperature

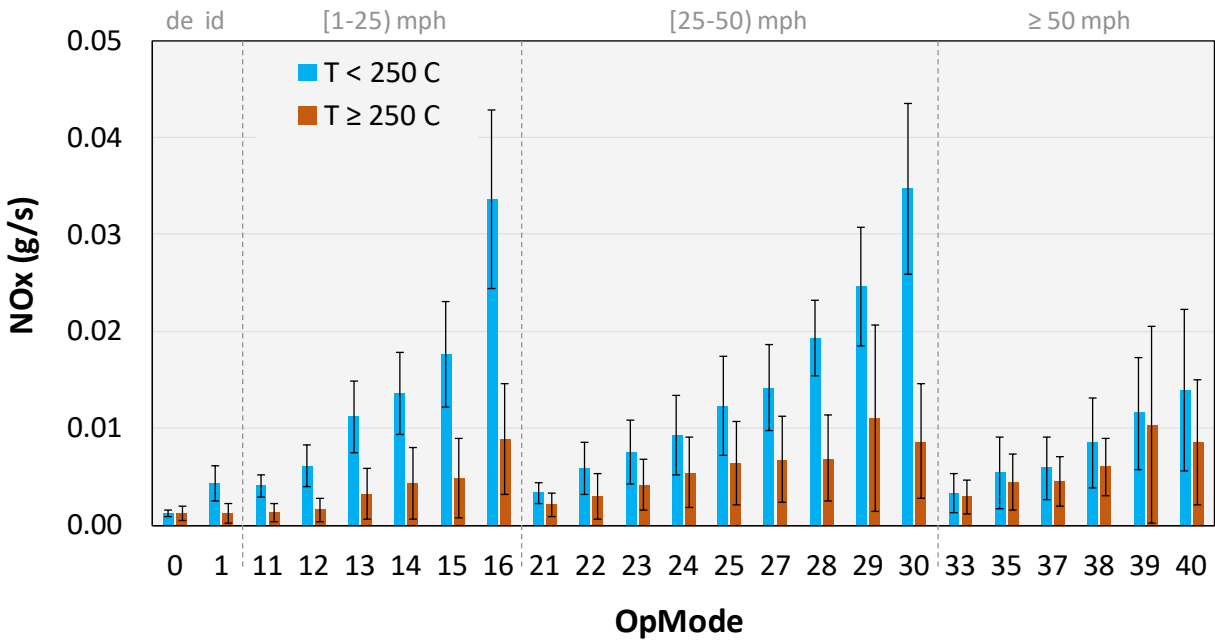


Figure 2-8: NO_x Emission Rates from 20 Vehicles with 0.20 g/bhp-hr FEL MHD Engines by MOVES OpMode and Aftertreatment Temperature

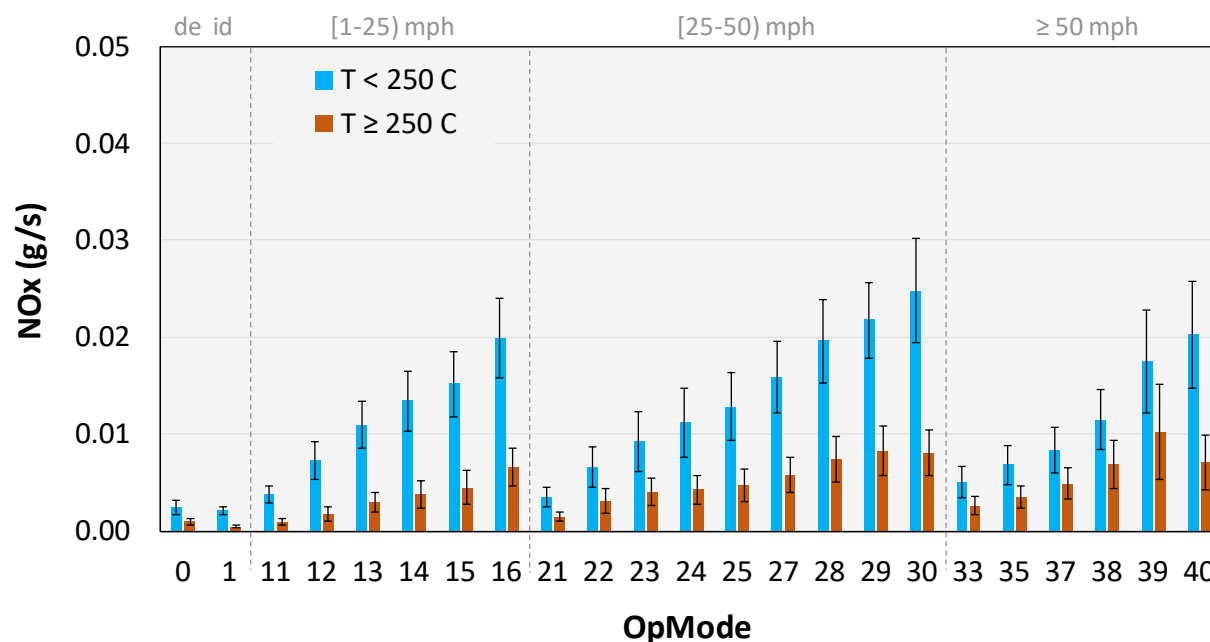


Figure 2-9: NO_x Emission Rates from 42 Vehicles with 0.20 g/bhp-hr FEL LHD Engines by MOVES OpMode and Aftertreatment Temperature

Figure 2-10, Figure 2-11, and Figure 2-12 compare the same data in terms of operational time by aftertreatment temperature. As expected, when the vehicles are operating at idle or low speeds, more time is spent at the lower temperature bin. However, even at high speeds, a nontrivial amount of time is spent at aftertreatment temperatures below 250°C.

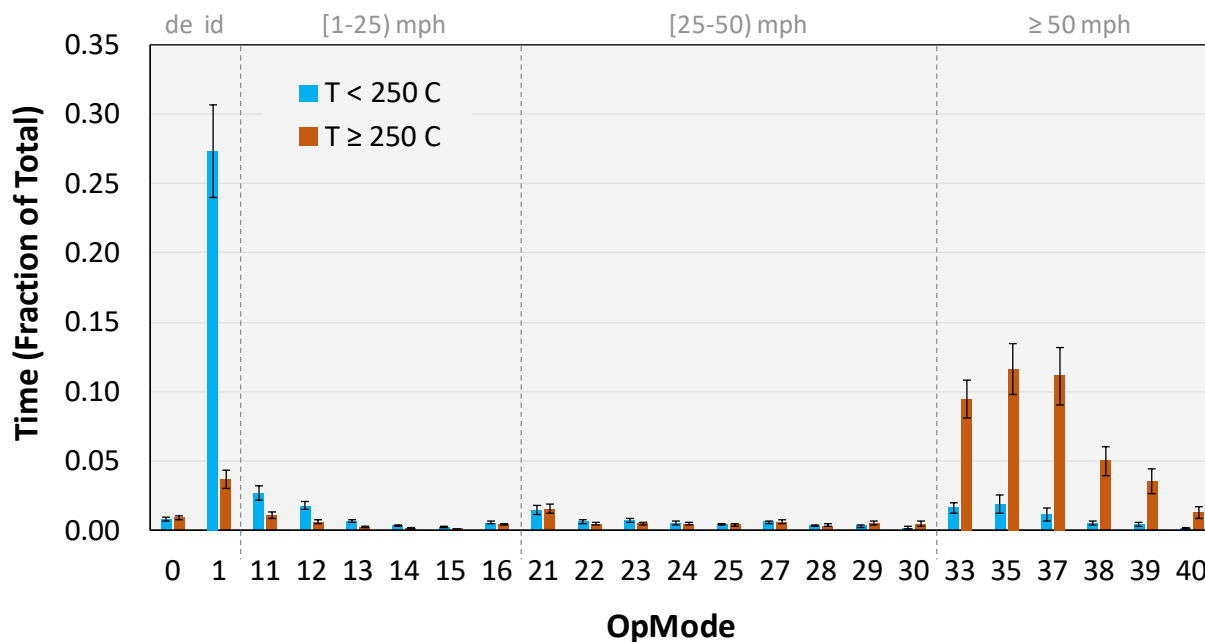


Figure 2-10: Time Fraction from 81 Vehicles with 0.20 g/bhp-hr FEL HHD Engines by MOVES OpMode and Aftertreatment Temperature

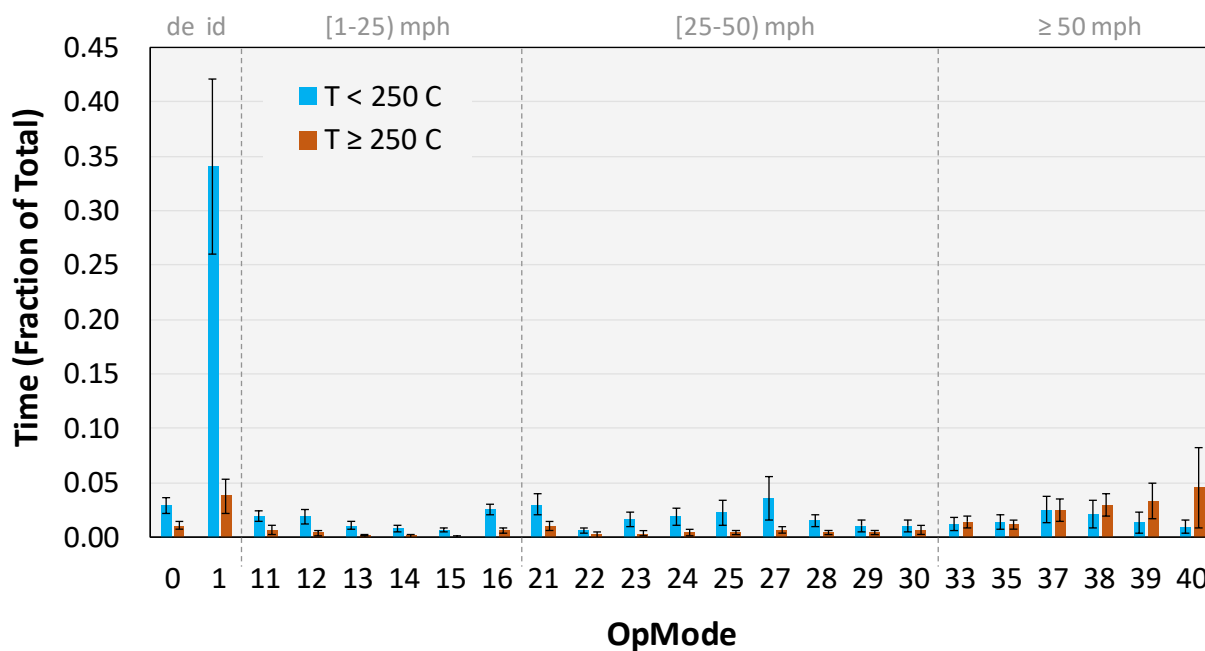


Figure 2-11: Time Fraction from 20 Vehicles with 0.20 g/bhp-hr FEL MHD Engines by MOVES OpMode and Aftertreatment Temperature

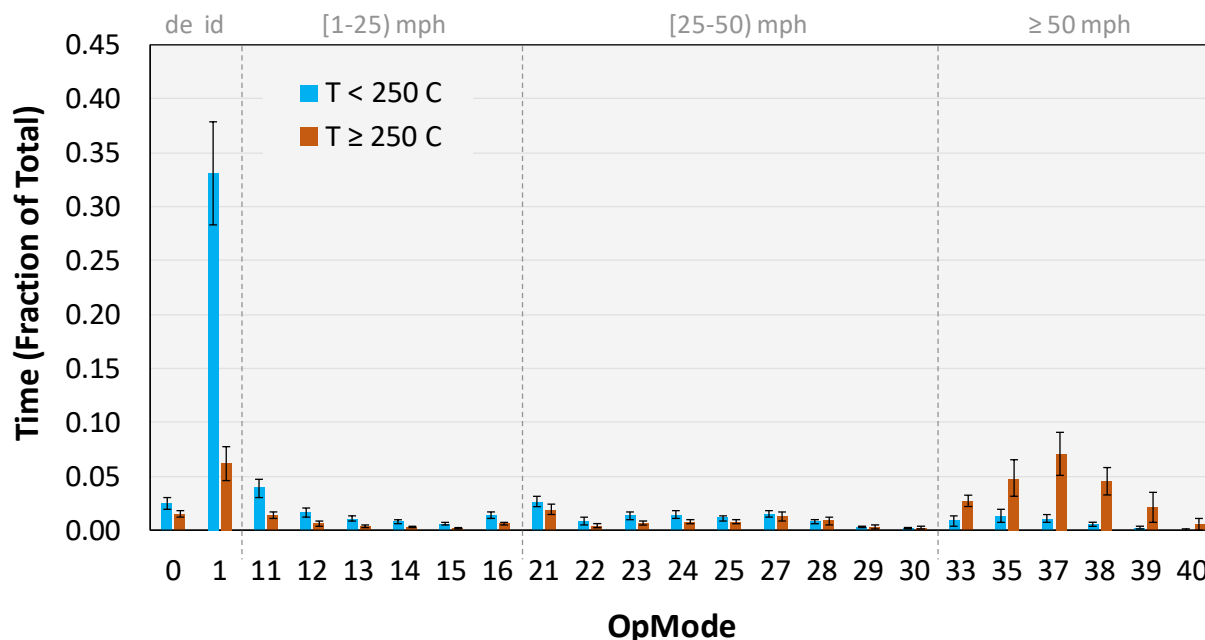


Figure 2-12: Time Fraction from 42 Vehicles with 0.20 g/bhp-hr FEL LHD Engines by MOVES OpMode and Aftertreatment Temperature

By combining the NO_x emission rate data with the time data, we can estimate the total NO_x contribution by operation, as shown in Figure 2-13, Figure 2-14, and Figure 2-15. The imbedded tables in each figure display the fraction of data in each temperature bin by operation time and NO_x mass. The emissions increase from low aftertreatment temperatures is not uniform across all operating modes. For HHD engines (Figure 2-13), the aftertreatment temperatures spent nearly as much time below 250°C as above it, but the contribution to total NO_x is much higher from the lower temperature operation due to the higher emission rates. The MHD and LHD engines spent much more time in low aftertreatment temperatures conditions, and it is reflected in a higher contribution to NO_x. For all engines, the low- and mid-speed operating ranges contribute the most NO_x emissions. These figures highlight the need to consider both activity and emission rate to effectively reduce NO_x.

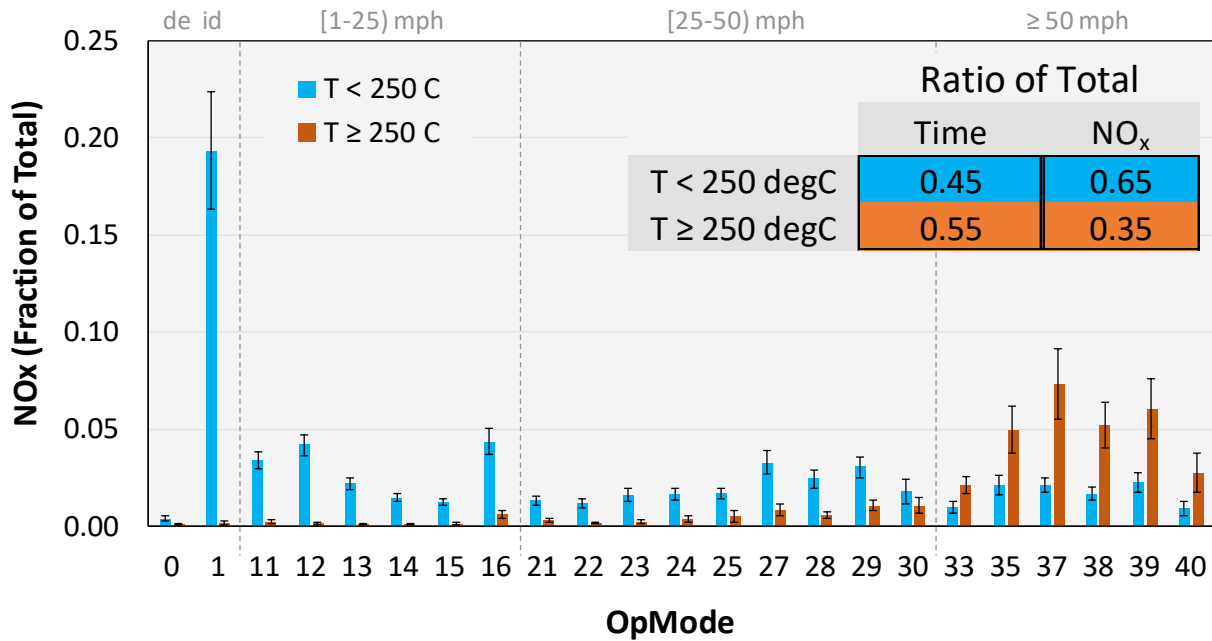


Figure 2-13: Total NO_x Contribution from 81 vehicles with 0.20 g/bhp-hr FEL HHD Engines by MOVES OpMode and Aftertreatment Temperature

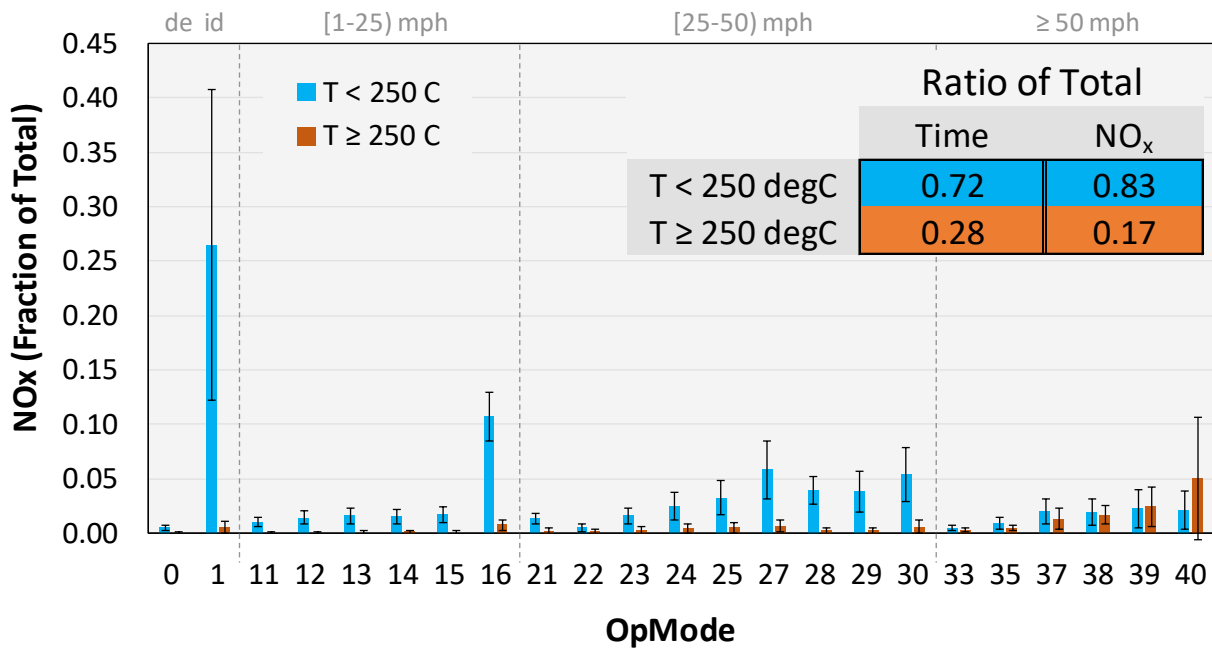


Figure 2-14: Total NO_x Contribution from 20 vehicles with 0.20 g/bhp-hr FEL MHD Engines by MOVES OpMode and Aftertreatment Temperature

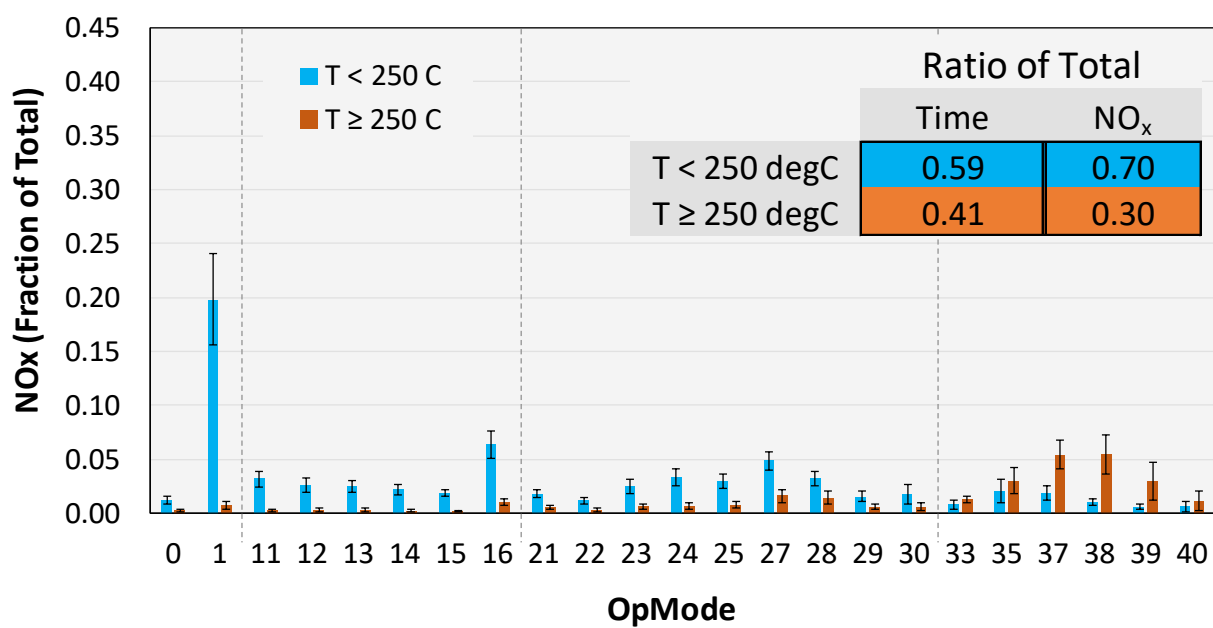


Figure 2-15: Total NO_x Contribution from 42 vehicles with 0.20 g/bhp-hr FEL LHD Engines by MOVES OpMode and Aftertreatment Temperature

2.2.2.4 HDIUT Data by Speed

Figure 2-16, Figure 2-17, and Figure 2-18 show the data binned by speed for HHD, MHD, and LHD vehicles, respectively, with NO_x FEL at or below 0.20g/bhp-hr. Operation below 5 km/hr was excluded to fully remove any idle time or low creep operation, where emission rates are drastically higher.^{KK} The 0.20 g/bhp-hr FEL vehicles' average NO_x emission rate in the lowest speed bin is much higher compared to higher speeds. The overall average NO_x emission rate, shown in the right-most bin, is more than twice the certification value of 0.20 g/bp-hr. The figure suggests the difference is even greater for vehicles that spend significant time at lower speeds. The average time fraction (diamond marker) and the average NO_x fraction (square marker) reveal the outsized contribution to total NO_x from the low and medium speed bins where the time fraction is lower than the NO_x fraction.

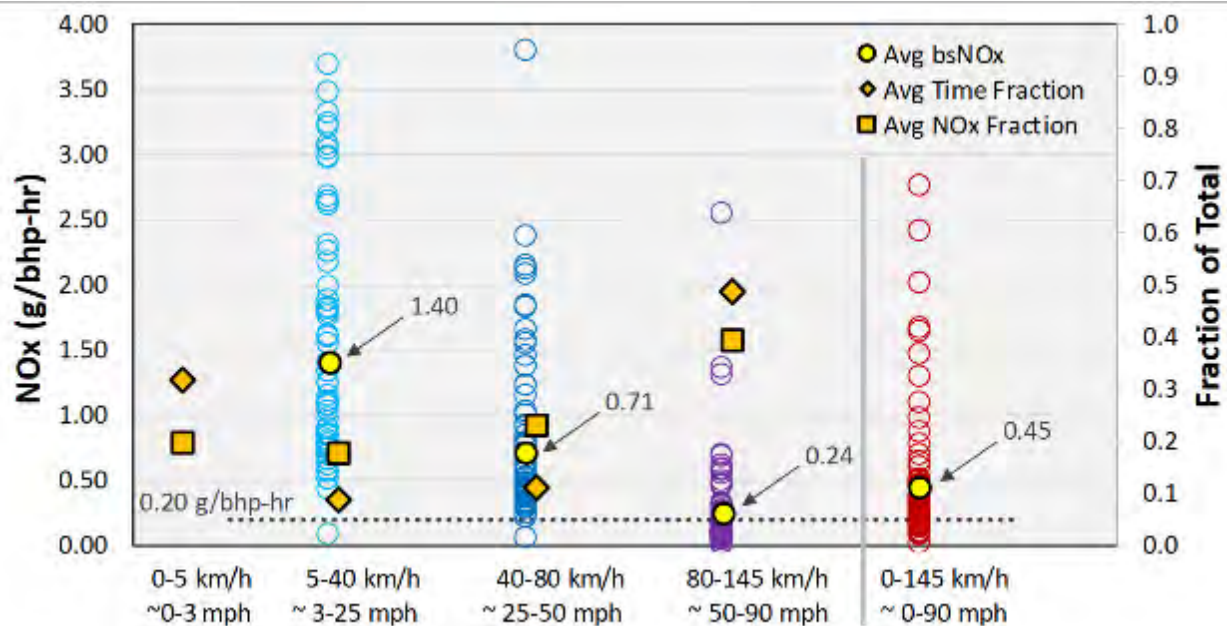


Figure 2-16: Brake-specific NO_x by Vehicle Speed Bins for 93 Vehicles with HHD Diesel Engines and an FEL of 0.20 g/bhp-hr

^{KK} Average NO_x emission rate for HHD, MHD, and LHD are 6.38 g/bhp-hr, 7.65 g/bhp-hr, and 4.61 g/bhp-hr, respectively.

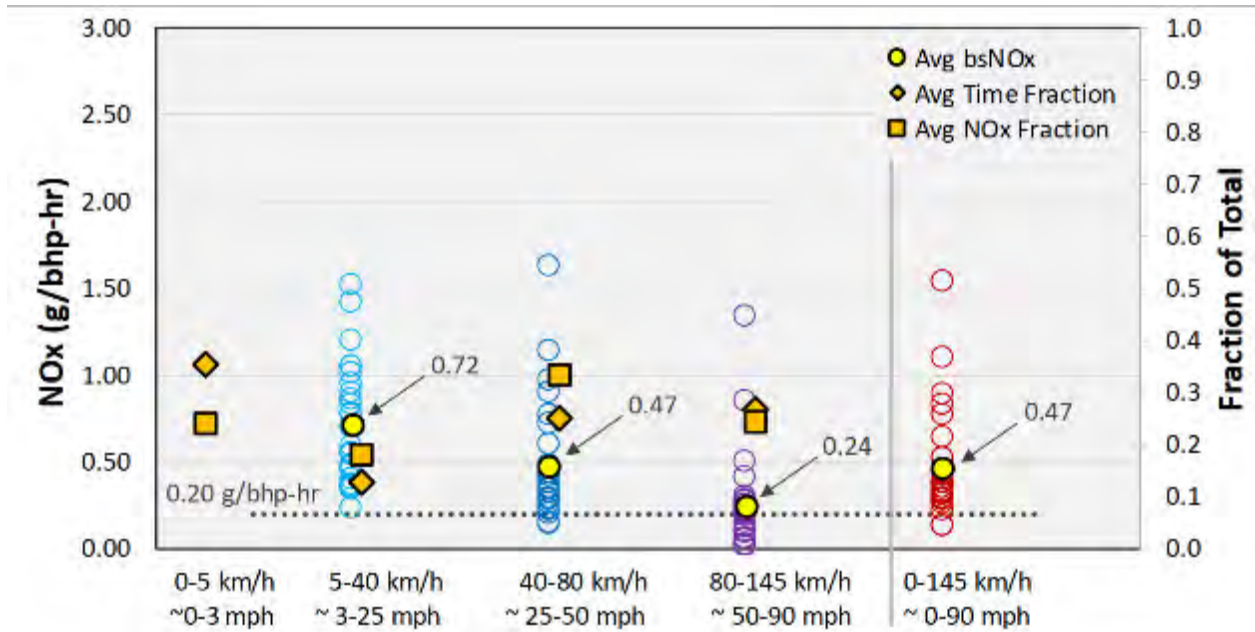


Figure 2-17: Brake-specific NO_x by Vehicle Speed Bins for 26 Vehicles with MHD Diesel Engines and an FEL of 0.20 g/bhp-hr

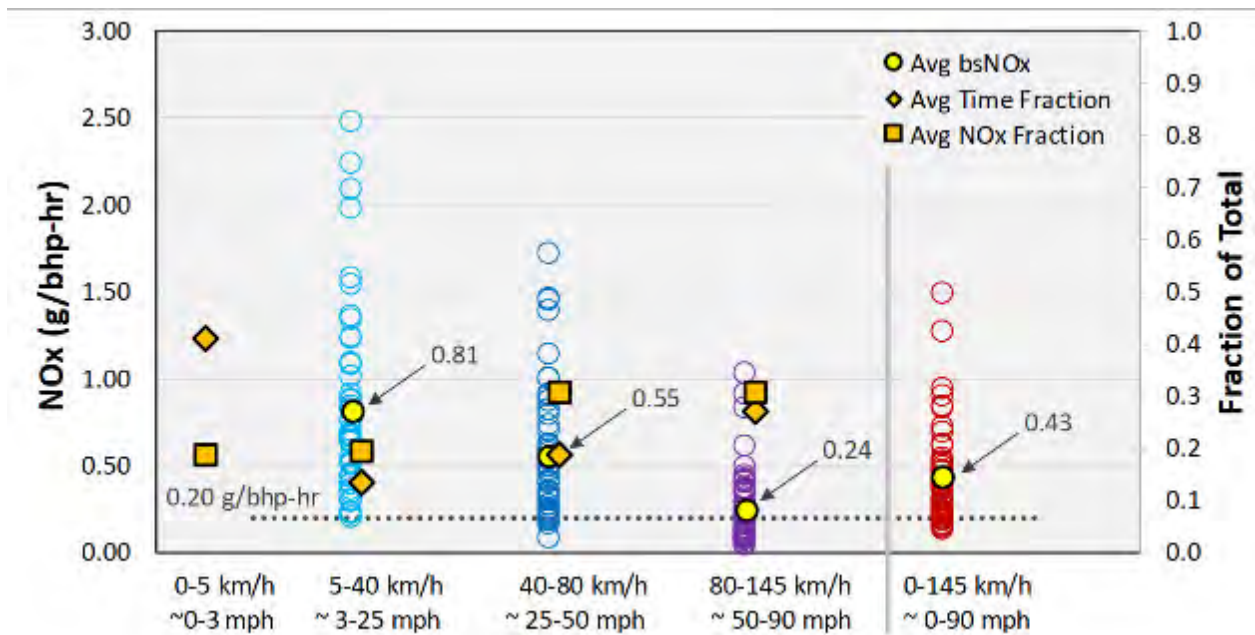


Figure 2-18: Brake-specific NO_x by Vehicle Speed Bins for 49 Vehicles with LHD Diesel Engines and an FEL of 0.20 g/bhp-hr

2.2.2.5 HDIUT Data by Work-Based Window

Figure 2-19 shows a comparison of brake-specific NO_x (g/bhp-hr) calculated using the standard method ("bsNO_x method") and CO₂ based method ("NO_x/CO₂ method"). This graph is based on measurement data from 85 HHD diesel vehicles with NO_x FEL ≤ 0.20 g/bhp-hr. The binning is by average power of the window over engine rated power. The windows are continuous and non-exclusive – window $n+1$ starts at time $t=n+1$. The amount of time in each window is based on the engine power demand during the window. This analysis led to 2.90 million windows. The height of the columns represents the mean of all the windows in that power bin and the error bars represent standard deviation of the mean. The 95% confidence interval is not shown since windows are not independent. The CO₂ based method is more robust at very small loads, such as the 0-5% and 5-10% average power windows. In these cases, the small amount of work done (bhp-hr) leads to higher brake-specific NO_x values for the standard method while also causing very large standard deviation. The CO₂ based method addresses the low-load in the denominator issue while also not penalizing vehicles that have lower CO₂ emissions, by normalizing against CO₂ over work (the second term in the equation). Another takeaway is that emissions are much higher at lower loads, lowest at loads near the FTP and SET cycles, and then creep up at higher loads. This suggests the engines are tuned to perform best at loads/conditions similar to the certification cycle while less optimized for other real-world operation.

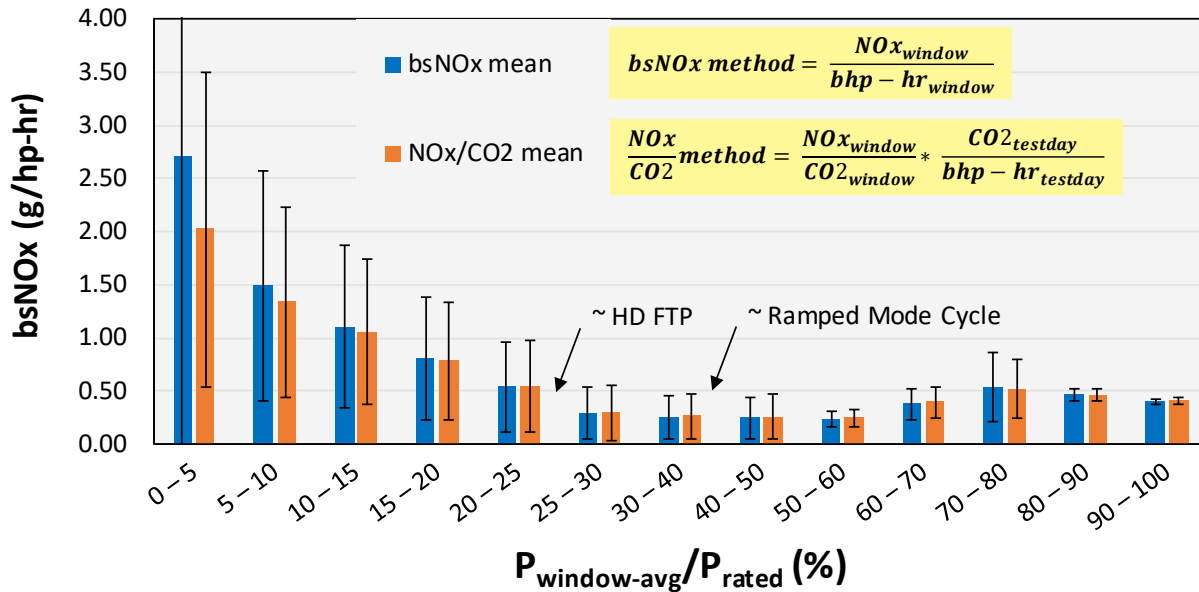


Figure 2-19: Brake-specific NO_x by Window Average Power Bins for 85 Vehicles with HHD Diesel Engines and an FEL of 0.20 g/bhp-hr

2.2.2.6 HDIUT Data by Simulated Cycle

Figure 2-20 and Figure 2-21 show analysis using simulated cycles. Figure 2-20 shows the drive cycles, which are converted to an OpMode time distribution, which is then combined with the OpMode based emission rates for each vehicle in the HDIUT data set. The MOVES national run OpMode distribution is also included for comparison in Figure 2-21. The Vehicle FTP and UDDS drive cycles have similar speed traces and thus their OpMode distributions are also similar. The transient drive cycle has a considerable amount of low speed transient operation, which shows up as higher time spent in OpModes 11-14 and particularly OpMode 12. The MOVES national run for combination-long haul trucks has most of its operation at highway speeds, and thus most of the time is allocated to OpModes 33 and above.

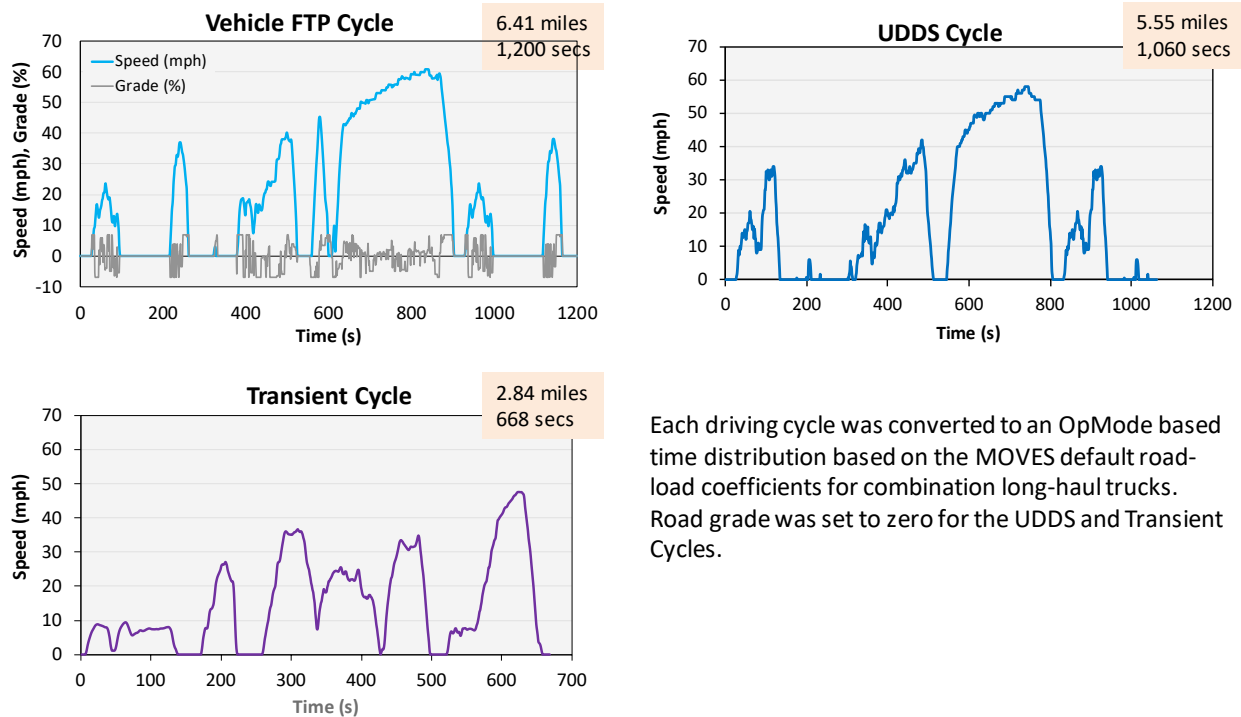


Figure 2-20: Vehicle Speed Profile of HD Duty Cycles

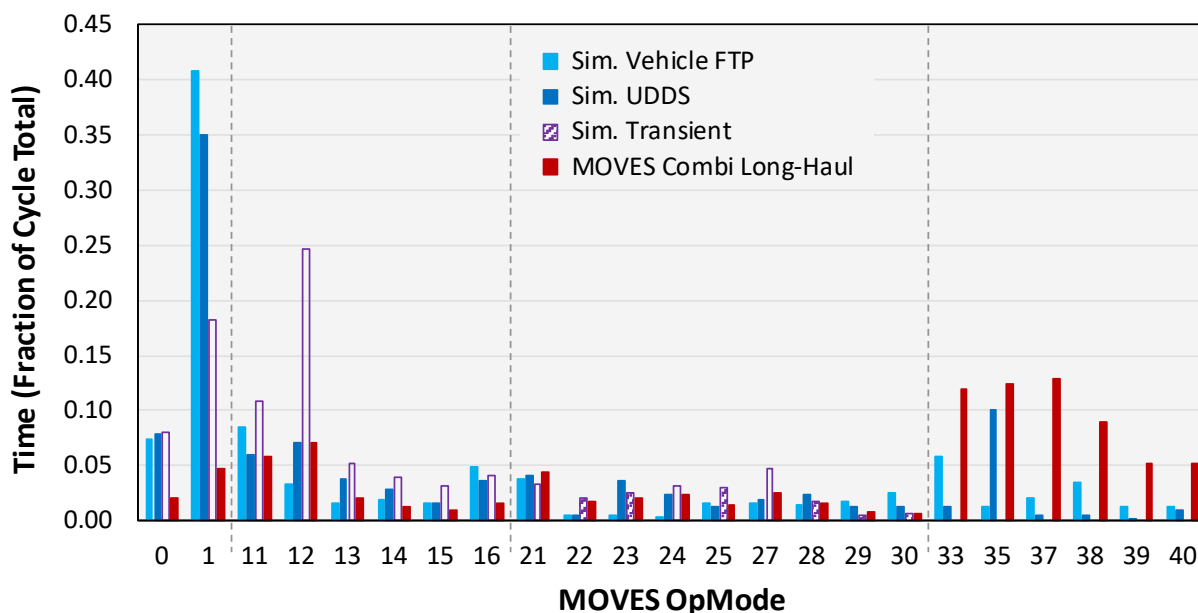


Figure 2-21: MOVES OpMode Time Fraction for each Simulated HD Combination Long-Haul Duty Cycle

Figure 2-22 and Figure 2-23 show the cycle average NO_x emission rates calculated using the per vehicle OpMode based emission rate and the drive cycle OpMode time distribution shown in Figure 2-21. The average rate and spread for Vehicle FTP and UDDS are similar, since the cycles are similar. The transient cycle produces the highest average rate because of low speed operation that has lower aftertreatment temperature. The transient cycle also has the largest spread, similar to the larger spread for the low speed analysis in Figure 2-16. The MOVES cycle has the lowest average and spread because the operation is predominantly in the high-speed zone, where emission rates are better controlled.

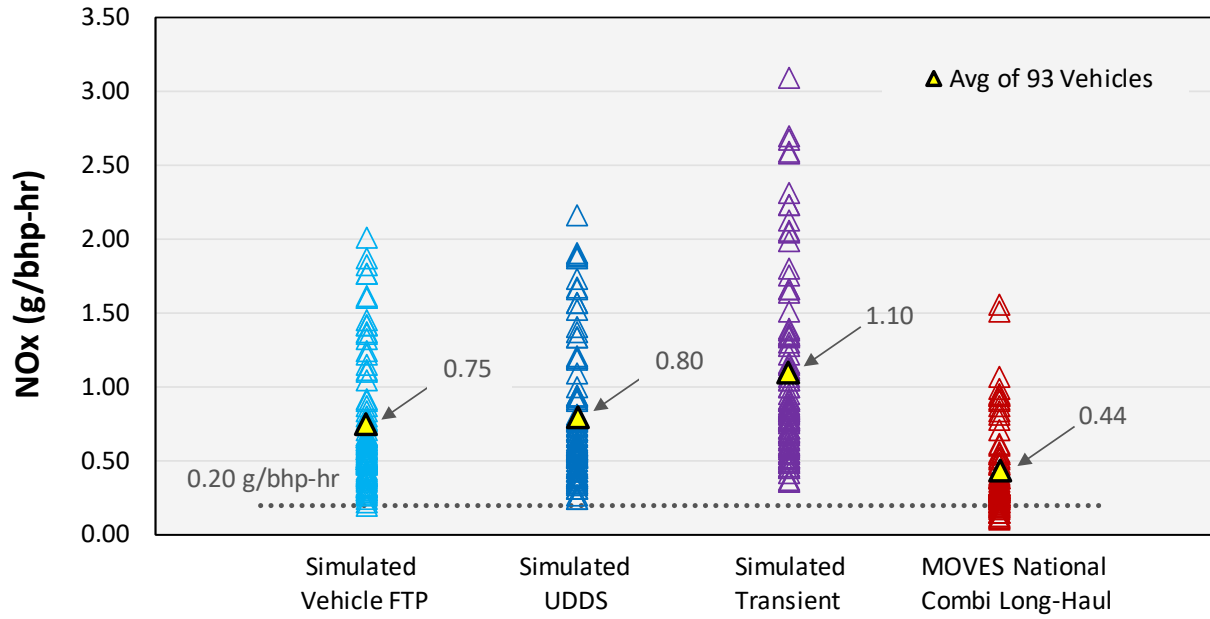


Figure 2-22: Brake-specific NO_x emissions by simulated cycle for HHD diesel engines with NO_x FEL of 0.20 g/bhp-hr

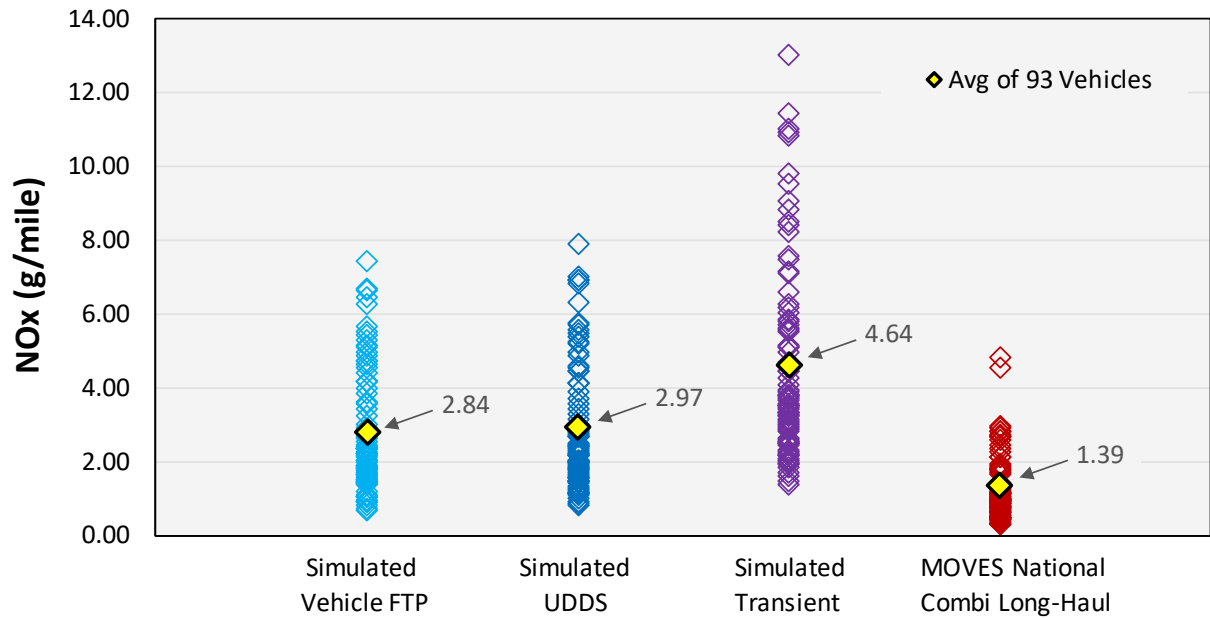


Figure 2-23: Distance-specific NO_x emissions by simulated cycle for HHD diesel engines with NO_x FEL of 0.20 g/bhp-hr

2.2.3 Proposed Updates to CI Engine In-Use Test Program and Off-Cycle Standards

The focus of the current in-use NTE compliance testing is operation at relatively high load; the data analysis procedure thus excludes a wide range of vehicle operations that occur in-use, in particular operations at lower loads. Importantly, the excluded portion of the data makes up the bulk of vehicle operation, specifically areas where NO_x production is high.

To improve the coverage of the in-use testing program, we propose updates to the program to include all vehicle operation within the regulated in-use standard. To keep the results representative of actual engine/aftertreatment performance and minimize issues with temporally misaligned data, we propose the analysis methodology be based on a series of moving average windows (MAW).

2.2.3.1 Background on Euro VI MAW

The European Union Euro VI emission standards for heavy-duty engines requires testing for in-service conformity starting with model year (MY) 2014 engines using portable emission measurement systems (PEMS).^{126,127} The intent is to confirm whether heavy-duty engines continue to comply with the emissions standards while in use, under normal operation, over time, under real world conditions. Manufacturers must check for “in-service conformity” by operating their engines over a mix of urban, rural, and freeway driving on prescribed routes using portable emission measurement system (PEMS) equipment to measure emissions. Compliance is determined using a work-based windows approach where emissions data are evaluated over segments or “windows.” A window consists of consecutive 1 Hz data points that are summed until the engine performs an amount of work equivalent to the European transient engine test cycle (World Harmonized Transient Cycle).

Engines are tested over a mix of urban, rural, and freeway driving. Testing starts at 18 months and a minimum of 25,000 km, and continues every two years thereafter out to seven years and 700,000 km. There are no carve-outs for engine load or aftertreatment low temperature operation. There are carve-outs for altitude (> 5577 ft), maximum ambient temperature (100 °F at sea level), and minimum ambient temperature ≥ 20 °F. There is no cold start emission measurement requirement. Emission and work integration start when engine coolant temp >70°C and is stable to within $\pm 2^\circ\text{C}$, or 20 minutes after engine start, whichever is first. Vehicle payload must be 50 to 60 % of maximum.

Compliance is determined using a work-based windows approach where emissions are evaluated over data segments or windows. A window consists of consecutive 1 Hz data points that are summed until an amount of work equivalent to the World Harmonized Transient Cycle (WHTC) is performed. For the window to be considered valid, the average power within a window must be $\geq 15\%$ of engine maximum power for MY 2014 – 2018 and $\geq 10\%$ for MY 2019 and later. The vehicle must accumulate at least 5 complete windows over its shift-day and 50% of the windows must be valid. Compliance is demonstrated at 1.5 times the EURO VI emission limit and there is no separate measurement allowance to account for in-use measurement uncertainty (it is built into the conformity factor multiplier of 1.5).

EPA and others have compared the performance of US-certified engines and Euro VI-certified engines and concluded that the European engines’ NO_x emissions are comparable to US 2010 standards-certified engines under city and highway operation, but lower in light-load

conditions.¹²⁸ This suggests that manufacturers responded to the Euro VI test procedures by designing their emission controls to perform well over broader operation. EPA intends the proposed rulemaking, if finalized, to expand our in-use procedures to capture nearly all real-world operation. We are considering an approach similar to the European in-use program, with key distinctions that improve upon the Euro VI approach, as discussed below.

2.2.3.2 Proposed Updates

For the updated in-use testing data analysis method, we propose using a MAW methodology similar to that established in the Euro VI emission standards. However, most carve-outs would be eliminated. Additionally, in order to adequately capture all vehicle operation, there would be no minimum power requirement for valid windows. We are not currently proposing prescribed routes for our in-use compliance test program. Our current program requires data to be collected in real-world operation and we would consider it an unnecessary step backward to change that aspect of the procedure. In what we believe to be an improvement to a work-based window, we are proposing a moving average window (MAW) approach consisting of time-based windows. Instead of basing window size on an amount of work, the proposed MAW includes a window size of 300 seconds.^{LL} The time-based windows are intended to equally weight each data point collected.

We also recognize that it would be difficult to develop a single standard that would be appropriate to cover the entire range of operation that heavy-duty engines experience. For example, a numerical standard for CO₂ specific NO_x that would be technologically feasible under worst case conditions such as idle, would be higher than the levels that are feasible when the aftertreatment is functioning optimally.

Thus, we are proposing separate standards for distinct modes of operation. Our proposal is to group the 300-second windows constructed from the second-by-second in-use data into one of three bins using the nominal “normalized average CO₂ rate” from the certification test cycles to identify the boundaries. The normalized CO₂ rate is defined as the average CO₂ rate in the window divided by the engine's maximum CO₂ rate. Our proposal to define the engine's maximum CO₂ rate is to use the engine's rated maximum power multiplied by the engine's family certification level (FCL) for the FTP certification cycle.

Windows with a normalized average CO₂ rate greater than 20 percent (equivalent to the average power of the current FTP) would be classified as medium/high-load operation and binned together. Windows with a normalized average CO₂ rate of 6 percent or less (6 percent is equivalent to the average power of the low-load certification cycle) would be classified as idle and binned together. The remaining windows, bounded by the idle and medium/high-load bins, would be binned together in the low-load bin.

We are proposing that the emissions performance of the binned data in the medium/high and low load bins would be determined using the sum of the total mass of emissions divided by the sum of CO₂ mass emissions. Emissions performance for the binned data in the idle bin would be determined using the mass rate (total mass of emissions divided by total time) of the emissions. This “sum-over-sum” approach would successfully account for all emissions; however, it

^{LL} Our evaluation includes weighing our current understanding that shorter windows are more sensitive to measurement error and longer windows make it difficult to distinguish between duty cycles.

requires the measurement system (PEMS or a NO_x sensor) to be accurate across the complete range of emission concentrations. We have also considered the advantages or disadvantages of other statistical approaches that evaluate a high percentile of the data (for example the 90th or 95th percentile) instead of the full data set.

As mentioned previously, we are proposing a separate MAW-based standard for each bin. In our current NTE-based program, the NTE standards are 1.5 times the certification duty-cycle standards. Similarly, for the MAW-based standards, we propose that the in-use program standards correspond to the laboratory-based cycles, with each bin having its own standard.

2.2.3.3 Data Collection and Exclusion

For the HDUIT, emissions data are to be collected from key-on ($t = 0$) until the end of the shift day when the engine is turned off. Data are to be collected once every second (i.e., 1-Hz data).

From the data collected at 1 Hz, some data points are to be excluded from the remaining process. Data to be excluded are (1) data collected during the PEMS zero drift check, (2) data collected where the engine is off, (3) data collected during infrequent regeneration events, and (4) data collected when any approved AECD for emergency vehicle applications is active.

2.2.3.4 Defining Windows

With the extended idle times frequently present in HDIUT samples, a work-based window approach would include longer period of time for these windows, and the methodology would be very sensitive to small inaccuracies in power measurement. To ensure the final set of windows more accurately reflects the operation of the vehicle, we propose adopting a time-based window approach, where each window contains an equal amount of time rather than an equal amount of work, as in the Euro VI work-based window approach.

For this proposed methodology, a window will consist of the summation of 300 consecutive 1-Hz data points (i.e., a 300-second window). The windows are continuous and non-exclusive, with subsequent windows beginning one second after previous windows (i.e., at the next data point). The first window will begin at initial key-on ($t = 0$), and the final sequential window will begin 300 seconds before the last data point taken. To limit the impact of instances where data exclusions would reduce the weighting of an individual data point, exclusions of ≤ 600 seconds are removed and the remaining data concatenated. For exclusions > 600 seconds, the final pre-exclusion window begins 300 seconds before the exclusion, and the next subsequent window begins immediately after the exclusion.

Except for the data points at the beginning and end of the test and those around long data exclusions, this methodology equally weights emissions at each data point during the in-use testing. We believe this is appropriate, as the under-weighted data points consist of a small percentage of the HDIUT data, which contain a minimum of 10,800 1-Hz data points.

2.2.3.5 Emission bins

The agency recognizes that including operation currently excluded from the standard, including low-load operation and low aftertreatment temperature, will result in a higher range of variability in both the vehicle operation represented, and in the data captured during testing.

Thus, we are proposing to differentiate the data collected by vehicle operation, and independently set standards for each operational characteristic.

To differentiate among various types of operation, we are proposing to divide the windows among three bins that are characterized by the normalized average CO₂ rate: an idle bin, a low-load bin, and a medium/high load bin. The normalized CO₂ rate of each window is defined as the total window CO₂ mass divided by the 300-second window length and then divided by the maximum CO₂ rate of the engine. The engine's maximum CO₂ rate is defined as the engine's rated maximum power multiplied by its family certification level (FCL) for the FTP certification cycle.

The three bins we are proposing are defined as follows:

- Idle bin: window normalized average CO₂ rate $\leq 6\%$
- Low-load bin: window normalized average CO₂ rate $> 6\%$ and $\leq 20\%$
- Medium/high-load bin: window normalized average CO₂ rate $> 20\%$

2.2.3.6 Bin Size and Test Validity

We are proposing that, for a test to be considered valid, all bins must contain a minimum of 2400 windows. To ensure there are enough windows in the idle bin you may idle the engine any time during the shift day. If any bin contains fewer than 2400 windows, the vehicle must be tested over an additional shift day. The resulting windows from the second or subsequent shift day are added to the appropriate bin, so that all windows from all shift days are included.

Using data from 168 previous HDUIT tests of one shift day each, the 1-Hz data from these tests was collected into windows and binned according to the proposed process as seen in Figure 2-24. Of these single shift day tests, a total of 73% contained 2400 windows in each bin. An additional 16% contained over 1200 windows in each bin (and thus would be likely to contain over 2400 windows in each bin if data were recorded over two shift days). Note some HDUIT tests have multiple bins containing fewer than 2400 windows. From this data, we estimate that, under the proposed process, approximately 73% of tests would be valid with a single shift day's worth of data, and most of the remainder would have over 2400 windows with a two-shift-day test.

If, after consideration of comments on this rule and other available data, EPA's technical assessment is that a minimum amount of data is required to adequately characterize emission performance over the wide range of vehicle operations that occur in-use, we will consider other options that require a minimum number of windows in each bin.

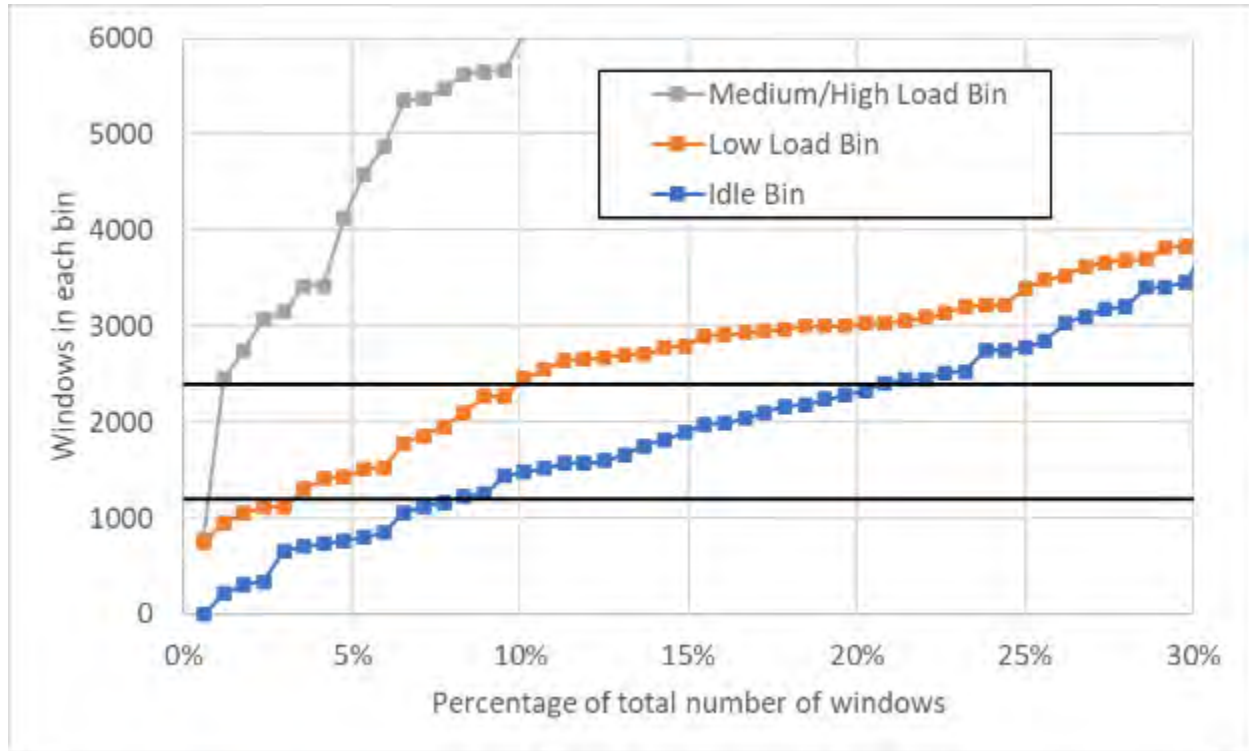


Figure 2-24: Number of windows in each bin from 168 HDUIT shift days, sorted in order (the first 30% are shown). The black lines indicate 2400 windows and 1200 windows. Note some HDUIT tests have multiple bins containing fewer than 2400 windows.

2.2.3.7 Defining Bin Emissions

Historically, engine standards have been work-specific. Using this approach, the standards can apply to a wide range of engine sizes. Where this approach is challenged is when the test interval that is being evaluated has very little to no work produced, such that the emissions are then divided by zero or near zero. Thus, we propose establishing an “equivalent work” standard based on CO₂ emitted from the engine. This methodology also does not rely on estimating or recording the second-by-second power output of the engine to determine work done. For this standard, the engine’s FTP FCL CO₂ emission value ($e_{CO2FTPFL}$) is used to convert the CO₂ specific emissions to equivalent work specific emissions.

For the HDUIT data processing, emission values are calculated for each bin, using a sum-over-sum value. For the low-power and medium/high-power bins, CO₂ specific emissions are determined for each bin, which are converted to work specific emissions using the engine’s FTP FCL CO₂ emission value ($e_{CO2FTPFL}$) as follows:

Equation 2-2

$$e\left(\frac{g}{hp-hr}\right) = \frac{\text{Total bin emission}}{\text{Total bin CO}_2} \times e_{CO2FTPFL}$$

In the idle bin, under nominal idle conditions the engine produces no work, giving an incentive to minimize CO₂ production in these operation modes (for example, with cylinder

deactivation). So as not to artificially increase the stringency of the idle bin standard for engines with low idle CO₂, we propose setting standards as emission rates rather than work specific values. For the idle bin, the emission rate would also be calculated using a sum-over-sum value as follows:

Equation 2-3

$$e\left(\frac{g}{hr}\right) = \frac{\text{Total bin emission}}{\text{Total bin time}}$$

We are also considering defining bin emissions for the idle bin on a work specific basis, as in Equation 2-2.

2.2.3.8 Bin Emissions and Standards

We propose that the standards apply to the sum-over-sum emissions value for the entire bin, as shown in Equation 2-2 and Equation 2-3. This methodology accounts for all emissions included in a particular bin equally and reduces the influence of potential errors in data collection. See Figure 2-25.

If, after consideration of comments to this rule or review of any additional data, EPA's technical assessment is that emissions cannot be quantified accurately over the entire emission range of the engine, we will consider options that would minimize the importance of quantifying low emissions rates. One possibility for doing this is calculating sum-over-sum emission values for each window independently. Within each bin, the windows are ordered by the magnitude of emissions in g/hp-hr, from smallest to largest. From these, the emissions values for the windows at specific percentiles (for example, the 60th and 95th percentiles) are selected and compared to a standard. If this approach was used the standards for these percentiles in each of the three bins would replace the single bin standards.

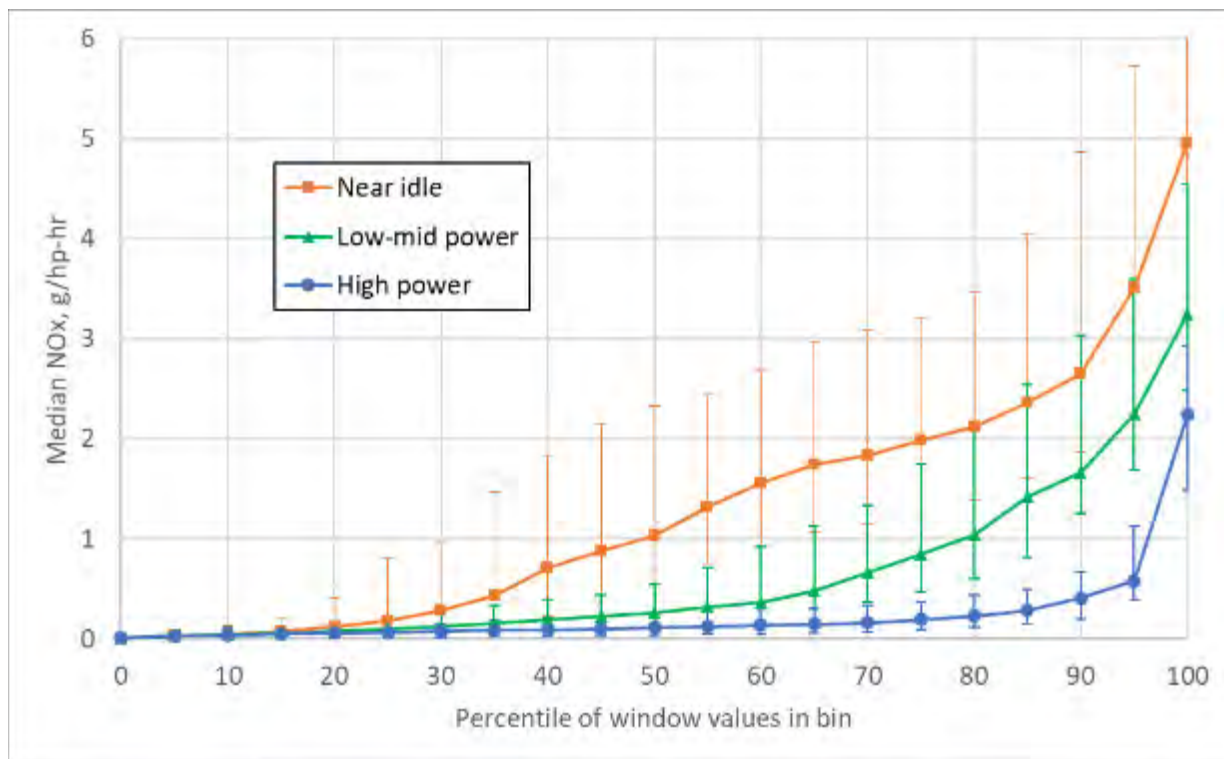


Figure 2-25: Range of NO_x rates in windows in each bin, using data from 93 HDIUT results in the HHD, 0.2 FEL category. The heavy line is the median value from all tests, with error bars represent the 25th and 75th percentile of the data.

2.3 Spark-Ignition Test Procedures and Standards

Spark-ignition test procedures are a crucial aspect of the heavy-duty criteria pollutant program. This rulemaking is proposing to establish several new test procedures for spark ignition engine compliance. This chapter describes the existing test procedures as well as the development process for the test procedures being proposed. This includes the determination of emissions from both engines and hybrid powertrains as well as the development of new duty cycles.

2.3.1 Current SI Test procedures

Heavy-duty spark-ignition engines currently are certified for criteria pollutants using the Heavy-Duty Otto-Cycle Engine Federal Test Procedure (HDOE FTP). For 2007 and later Heavy-Duty engines, 40 CFR Parts 86 – “Control of Emissions from New and In-Use Highway Vehicles and Engines” and 1065 – “Engine Testing Procedures” detail the certification process. 40 CFR 86.007-11 defines the standard settings of Oxides of Nitrogen, Non-Methane Hydrocarbons, Carbon Monoxide, and Particulate Matter. The HDOE FTP duty cycle is defined in 40 CFR part 86 Appendix I. All emission measurements and calculations are defined in Part 1065, with exceptions as noted in 40 CFR 86.007-11. The data requirements are defined in 40 CFR 86.001-23 and 40 CFR 1065.695.

The measurement method for CO is described in 40 CFR 1065.250. For measurement of NMHC refer to 40 CFR 1065.260. For measurement of NO_x refer to 40 CFR 1065.270. For measurement of PM, refer to 40 CFR 1065.140, 1065.170, and 1065.290. Table 1 of 40 CFR 1065.205 provides performance specifications that we recommend analyzers meet. Note that 40 CFR 1065.307 provides linearity verifications that the system must meet. For the calculation method brake specific mass emissions for CO, NMHC, NO_x and PM refer to 40 CFR 1065.650.

2.3.1.1 HDOE FTP

The current HDOE FTP is a transient test consisting of second-by-second sequences of engine speed and torque pairs with values given in normalized percent of maximum form. The cycle was computer generated from a dataset of 88 heavy-duty trucks in urban operation in New York and Los Angeles. This procedure is well-defined, mirrors in-use operating parameters, and continues to be appropriate also for the continued assessment of criteria pollutant emissions from heavy duty engines.

A complete HDOE FTP involves three test sequences. First, a 20-minute test is run over the duty-cycle with the engine at the same ambient temperature as the test cell (between 68°F and 86°F). The engine undergoes a 10-minute hot-soak following the cold-start. A 20-minute hot start test is run over the same duty-cycle following the hot-soak. The HDOE FTP emission level for the engine is determined by weighting the cold start emissions by 1/7 (14 percent) and the hot-start emission results by 6/7 (86 percent).

2.3.1.2 Test Procedure Engine Mapping Improvements

The heavy-duty FTP test cycle is composed of second by second speed and torque targets that are based on the engine's design operating speeds and the torque levels produced over the full range of allowed speeds. In order to determine the torque level at any engine speed, a mapping of the engine is performed prior to the actual FTP testing. The mapping is a sweep across the mechanically- or electronically-allowed operating speeds to determine the highest possible torque level the engine can produce at any specific speed. From this "maximum torque" sweep, the FTP targets are determined for the subsequent transient FTP test and for any additional test (e.g. SET).

As noted above, the measured torque values are intended to represent the maximum torque the engine can achieve under fully warmed-up operation with the appropriate design fuel grade (i.e. regular grade octane fuel) across the allowed range of engine speeds from idle to the typically electronically limited highest RPM. The intent is to reflect a torque value that would be maintained if the engine were to stabilize at a specific speed over a longer period of time such as what might be observed in a "real world" condition when an engine is held by a transmission in a specific RPM by the selected gear.

Electronic control of all aspects of engine hardware and operation has resulted in some challenges to performing the mapping of the engine. Variable torque levels have been observed in engine testing related to such things as electronic control response to fuel octane, anticipated exhaust thermal conditions, transmission torque limiting models, and other electronic features incorporated into the engine management strategies. This torque variability has been particularly evident after the change to the mapping test procedures in 40 CFR part 1065.510(b)(5)(i), which requires that an engine be mapped by performing a transient sweep from idle to maximum rated

speed. Prior to this change in the test procedure, the mapping procedure required the engine to stabilize at discrete engine speed breakpoints before recording the engine torque value for that engine speed that would be used for the FTP and other testing.

There are two potential improvements to reduce the torque measurement variability. One option could be to perform the sweep in both directions (i.e. idle to rated maximum speed and back to idle) and determine the torque value at any speed to be the highest measured torque level. Typically, we would expect any torque limiting AECDs (e.g. power enrichment delay) to be active during the sweep up, allowing the maximum torque to be determined during the sweep down after any torque limiting AECD has concluded. A second option could require manufacturers to turn off the torque limiting AECDs during the torque mapping sequence and allow them to perform the procedure as written today. For example, an AECD that results in delay of component thermal protection due to a temperature model would not be allowed for the power mapping sequence since any stabilized operation at a temperature limited speed point would typically require thermal protection. During the transient FTP test however, the AECD could be active to simulate real world operation and thermal management strategies implemented to improve emission performance and conserve fuel.

2.3.2 Proposed updates to SI Test procedures and Standards

We are proposing an overarching update to the location of our highway heavy-duty engine regulations, moving from the current 40 CFR part 86 to part 1036. As part of this process, we propose to clarify our nomenclature and no longer refer to "otto-cycle" engines; instead, these engines are more accurately labeled spark-ignition engines throughout part 1036. This section provides additional details related to the test procedures we are proposing in Section III.D. of the preamble to this rulemaking. Refer to the preamble for specific requests for comment related to these procedures.

2.3.2.1 HD SI FTP

As part of our proposed migration to part 1036, the FTP duty cycle maintains the weighting factors or the duty cycle speed values from the current HDOE FTP duty cycle that applies to criteria pollutant regulation in 40 CFR part 86 Appendix I (f)(1). We are proposing a change to the negative torque values, as noted below. The HD Technical Amendments that were published in June, 29 2021 finalized the migration of some heavy-duty highway engine standard setting part test procedures from 40 CFR part 86 to part 1036. This included the migration of the HDOE FTP drive schedule to Appendix II (b) of part 1036 in order to add vehicle speed and road grade to the duty-cycle to facilitate powertrain testing of hybrid powertrains for compliance with the HD Phase 2 GHG standards.

We are proposing in this rule to align the changes made for certification to GHG standards with criteria pollutant testing. Specifically, the removal of and footnoting of the negative normalized vehicle torque values over the HDOE FTP duty-cycle. The footnote denotes that these torque points are controlled using closed throttle motoring, which would then match how negative torque values have been controlled in the HDDE FTP. This change reflects the way that engine manufacturers were already controlling to negative torque from spark-ignition engines and harmonizes the methodology with the HDDE FTP, with no effect on stringency.

The spark-ignition engine denormalization equation in 40 CFR 86.1333(a)(1)(ii) contains a divide by 100 which equates it to the denormalization equation in 40 CFR 1065.610(c)(1) (equation 1065.610-3), thus the elimination of the 40 CFR part 86 equation from the standard setting part will have no consequence.

2.3.2.2 Engine mapping

We are proposing to change the procedure for SI engine torque mapping in 40 CFR part 1065.510. In order to determine the torque level at any engine speed, a mapping of the engine is performed prior to the actual FTP testing. The mapping is a sweep across the mechanically- or electronically-allowed operating speeds to determine the highest possible torque level the engine can produce at any specific speed. From this "maximum torque" sweep, the FTP targets are determined for the subsequent transient FTP test and for any additional test (e.g. SET).

The measured torque values are intended to represent the maximum torque the engine can achieve under fully warmed-up operation with the appropriate design fuel grade (i.e. regular grade octane fuel) across the allowed range of engine speeds from idle to the typically electronically limited highest RPM. The intent is to reflect a torque value that would be maintained if the engine were to stabilize at a specific speed over a longer period of time such as what might be observed in a "real world" condition when an engine is held by a transmission to a specific RPM by the selected gear.

Variable torque levels have been observed in engine testing related to such things as electronic control response to fuel octane, anticipated exhaust thermal conditions, transmission torque limiting models, and other electronic features incorporated into the engine management strategies. This torque variability has been particularly evident with the change to the mapping test procedures in 40 CFR part 1065.510(b)(5)(i), which allowed an engine to be mapped by performing a transient sweep from idle to maximum rated speed. Prior to this change in the test procedure, the mapping procedure required the engine to stabilize at discrete engine speed breakpoints before recording the engine torque value for that engine speed that would be used for the FTP and other testing.

We are proposing to require the engine to achieve a stabilized torque reading at the different speeds prior to recording the final torque values, which would be accomplished by disabling any controls that limit torque during the engine mapping test.

2.3.2.3 Supplemental Emissions Test for HD SI

As noted in Section 2.1.1.2, the compression-ignition engines currently comply with SET-based standards that represent high-speed and high-load operation. The SET duty cycle is a ramped modal cycle in which the engine is tested on an engine dynamometer over a sequence of steady-state modes. As we show in Section 4.2.3.2, there are opportunities to reduce emissions in high-load operating conditions where engines often experience enrichment for either catalyst protection or a power boost. We are proposing to include SET-based standards for HD SI engines to ensure that emission controls are properly functioning in the high load conditions covered by that duty cycle. We are proposing the same CI-based SET procedure, summarized in Section 2.1.2.2, for HD SI engines, including the existing weighting factors shown in Table 2-2.

2.3.2.4 Onboard Refueling Vapor Recovery

The current ORVR test procedure, which can be found in 40 CFR 1066, subpart J, for measuring emissions from chassis-certified vehicles during a refueling event, requires that the testing occur in a sealed housing evaporative determination (SHED) enclosure containing the complete vehicle. This procedure applies to all light-duty and heavy-duty complete vehicles subject to the ORVR standards, and manufacturers designed and built the SHEDs at their test facilities for these vehicles.

During a recent test program, EPA discovered that very few SHEDs are available that could fit vehicles in the over-14,000 lb GVWR class because of a combination of the length and height of these work vehicles. Additionally, the limited large volume SHEDs that were available at third-party laboratories proved to have challenges measuring the refueling emissions because of the very large volume inside the enclosures.¹²⁹

Large background volumes of ambient air create a challenge for evaporative emissions testing because a measurement is only considered representative if emissions are able to reach a homogeneous distribution throughout the cell prior to initiating a measurement by the emission analyzers. In EPA's test program, we found that the two heavy-duty test vehicles required a substantially longer mixing time than the current test procedure developed for light-duty vehicles.^{129,130} Another challenge in regards to adopting the existing procedures for larger vehicles is that the calculations must account for the volume displaced in the SHED by the test vehicle, which can be highly variable for the range of commercial vehicle designs. If a full SHED test is desired for ORVR certification, we must consider an appropriate duration of the test to achieve a representative emissions distribution in the larger SHED, as well as an appropriate means of calculating the displaced volume of these diverse vehicle designs in order to get an accurate measurement of the refueling emissions.^{129,130}

Figure 2-26 and Figure 2-27 show examples of the estimated extrapolated mixing time for the two trucks that were tested in the summer of 2018. It is not known how much additional mixing time is necessary without additional testing, but it is at least three minutes based on the extrapolated test results from this program. It might make more sense to require stabilization of the analyzer hydrocarbon readings rather than a specific time length.

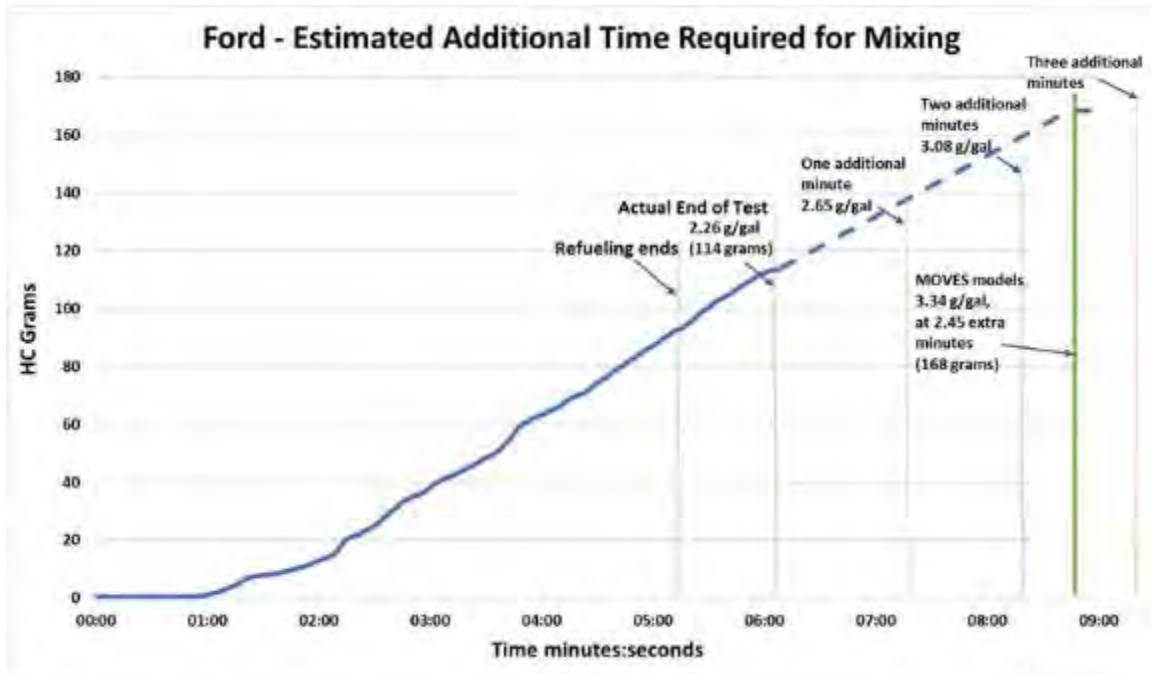


Figure 2-26: Estimated Projected Ford E-450 ORVR Results based on Extrapolation

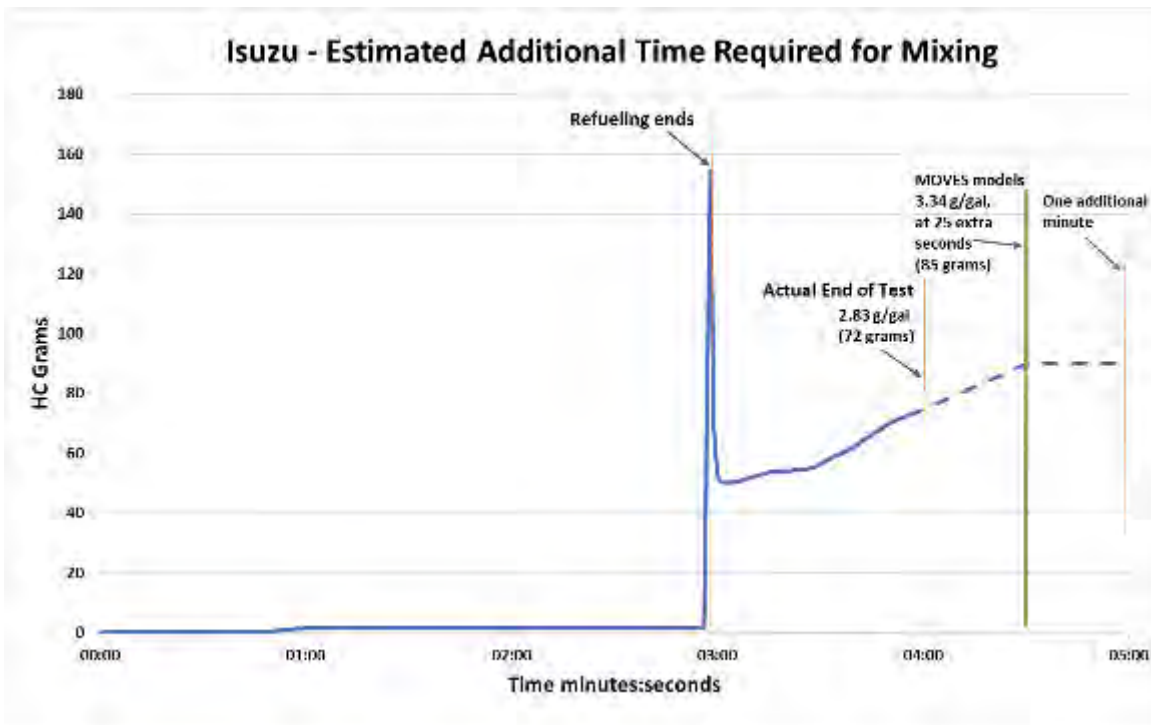


Figure 2-27: Estimated Projected Isuzu ORVR Results based on Extrapolation

One potential solution to issues related to testing these commercial vehicles in limited availability and large volume SHED equipment could be to allow demonstration of compliance by testing the complete ORVR system with all of the components (fuel tank, filler pipe, canister, control valves, etc.) independent of the actual vehicle using an existing SHED designed for smaller vehicles, such as light-duty applications. These existing SHED enclosures are widely available to test and certify all ORVR-required vehicles. This approach of only testing the components associated with refueling emissions would remove the challenge of finding a SHED with sufficient dimensions to contain the vastly larger (i.e. longer and taller) commercial vehicles that are part of this proposal. Testing the refueling related components independent of the vehicle also eliminates the challenge of minimizing other hydrocarbon sources not associated with fuel or the fuel system (i.e. tires, plastics, paints, etc).

Another option would be to allow independent ORVR hardware described above to be tested in a small enclosure designed for only component specific testing (i.e. mini-SHED) similar to the methodology for the "rig" test, allowed for other evaporative testing by California and accepted by EPA. Similar to the ORVR system-based concept described previously, the mini-SHED approach would provide a simpler test methodology that would capture just the refueling-related emissions. Furthermore, this smaller scale, component-based test would eliminate much of the variability encountered when attempting to test a full vehicle or hardware in a large SHED.

For both system- and component-based ORVR testing, the canister would require a specific conditioning cycle to get it into a representative state of a real-world loading entering a refueling event. This could be performed on or correlated to an actual vehicle driven over an existing EPA test cycle or a "real world" drive cycle. The current preparatory cycle used by today's ORVR-required vehicles is designed for light-duty vehicle driving patterns and vehicles with typically much smaller fuel tanks and canisters. The current conditioning procedure is designed to challenge the purge system in scenarios such as heavy traffic, slow speeds and start-stop events. Heavy-duty vehicles, with larger fuel tanks and canisters, may drive more miles and have greater power demands that may help purge the larger canisters more easily than allowed for in the current light duty vehicle test. Commercial vehicles may still drive under heavy traffic scenarios but the expectation is that they will drive more miles daily and operate under higher loads on a regular basis which help to purge larger amount of vapors from the system.

A final potential option would be to leverage similar vehicles already required to test as a surrogate for certification compliance demonstration. The current 2-day and 3-day evaporative standards program for this class of heavy-duty vehicles acknowledged that vehicles currently tested in the lighter classes (i.e. under 14,000 lb GVWR) may contain the exact same hardware- and purge-related calibrations providing a high degree of confidence that the heavier versions will also comply with the 2-day and 3-day evaporative requirements. Because of this similarity between the classes and a high degree in consistent performance, the agency allows the data and testing from the lighter vehicle to be accepted for the certification compliance demonstration of the larger class of vehicles. The ORVR systems could similarly be of the same design and purge calibrations between the vehicles in this proposal and vehicles already required to comply with ORVR requirements. In these cases, it would seem appropriate to allow the use of the results of the tested lighter vehicle class along with "good engineering judgement" statements as a means to demonstrate compliance for the larger vehicles.

2.3.3 Idle Test Procedures Considered

As noted in the preamble, we are proposing to ensure that the main component of the emission control system, the catalyst, remains effective during prolonged idle situations. The current heavy-duty FTP test does not include extended idle conditions indicative of real-world behaviors when work vehicles are started and allowed to idle while warming-up the engine or when the vehicle operator requires the interior temperature to stabilize with either heat or air conditioning. This prolonged idle can also occur when the vehicle is brought to a stop for unloading or a similar situation.

We considered the addition of a new test procedure to ensure idle emission controls are maintained. We considered the FTP or SET run as a pre-conditioning cycle to stabilize the engine and emission control system, followed by 10-30 minutes of idle. Previous idle provisions, established for in-use inspection and maintenance programs, required a 0.50 percent by volume CO limit over a 30-minute idle period, but did not set a limit for NMHC or NO_x.¹³¹

We also considered options that take advantage the existing SET duty cycle to avoid introducing a new test procedure. One option could be to reevaluate the weighting factors of the SET to place a greater emphasis on the idle modes, but this option has two drawbacks. First, providing more weight to the idle mode would have the counter effect of deemphasizing the high-load modes that we believe are critical to encouraging reduced fuel enrichment. Second, the existing SET procedure collects the emissions from all modes in a single bag for analysis, which means idle performance would be masked by the composite result and the additional weighting at idle would require us to reevaluate the SET standard feasibility. Another option could be to require two bags for SET such that the idle modes would be collected in the second bag. This option would isolate the idle results but would require two separate standards. While this option would reduce the need for a new test procedure, manufacturers would still likely need to make adjustments to their test cells to accommodate the second bag.

2.4 Compliance Assurance

2.4.1 Improved Engine Control Module Security as a Deterrent to Tampering

Today's highway trucks have many interconnected, computer-based systems which control a variety of vehicle features and functions necessary for safe and efficient operation. While these electronically controlled systems greatly expand the capability of vehicles, they also create a potential pathway for individuals to tamper with or alter the software and or calibrations in ways which significantly increase emissions. As more and more functions of vehicles are automated and rely on computer controls, securing these systems from malicious attacks or tampering is a topic of concern to vehicle manufacturers and owners alike. These attacks or acts of tampering can be direct, where an individual has access to the engine control module ("ECM") on a single vehicle, or indirect, where reprogramming or modification of the ECM is initiated via an over-the-air or wireless connection (a "cyber" attack) on one or many vehicles. While there are safety, financial, operational, and privacy concerns when these systems are attacked or compromised, this discussion will focus on the 'operational' aspect, where tampering with the engine and emissions control computers can have a negative impact on the emissions and/or diagnostic performance of a vehicle.¹³²

A common method of tampering is the practice of modifying a vehicle's ECM to allow the use of aftermarket defeat devices, engine tuning kits, or full aftertreatment delete kits, where the removal, bypass, or disabling of DPF, SCR, DOC, and EGR components can have the effect of bringing the vehicle emissions to a pre-standards condition. In addition, tampering with certified calibrations in the ECM with an engine tuning kit may exacerbate the emissions increase, as changing critical combustion control parameters to increase fuel economy or engine performance can result in increased NO_x and PM emissions as well. For example, the fuel maps in the ECM may be modified to advance the injection timing, resulting in higher cylinder pressures, which promote the formation of NO_x. Tampering may also include the installation of devices which mimic a valid signal from emissions control sensors or disabling OBD monitors which, in turn, can override the inducement or engine derate strategies that are necessary to ensure that high-quality diesel exhaust fluid ("DEF") is added to the vehicle.

To better understand how manufacturers and industry are securing ECMs from tampering, ensuring that the engine and vehicle will remain emissions compliant throughout its useful life and beyond, we met with manufacturers to understand the measures they are employing to secure these devices. We also met with telematics providers and industry technical organizations to learn about the efforts currently underway to establish ECM and data security standards and protocols. Given the increased emissions that a tampered truck will produce throughout its operational life, it was important for EPA to study and understand the methods and procedures that manufacturers are currently employing to secure the ECM from tampering efforts, as well as those that are under development by technical associations such as the Society of Automotive Engineers (SAE) and the Automotive Information Sharing and Analysis Center (Auto-ISAC), as well as the National Highway Transportation Safety Administration (NHTSA). As we learned in these meetings and discussions, there are many approaches currently being used to secure vehicle computer systems from tampering and malicious attacks, but these approaches are ever changing, as the sophistication of those seeking to compromise these systems is also increasing, prompting additional countermeasures by manufacturers.

EPA was considering whether a collection of industry best-practices regarding ECM security could be identified, and whether it would be beneficial and feasible to include those practices as a prescribed set of regulatory requirements in a future rulemaking proposal. However, as we learned throughout these discussions, there are many ways to accomplish ECM security, and they will by nature always be in a state of change, adapting to the latest threats. As a result, EPA is not proposing a prescribed set of security requirements, and is instead proposing that manufacturers document the security measures they are employing on their products at time of application for certification. We considered more prescriptive approaches for addressing ECM security, but at this time, we are choosing to propose a requirement that will better allow manufacturers, industry groups, and safety regulators to take the lead on developing security requirements for these systems in a timely manner, as issues emerge. In the course of our study of security practices and discussion with industry and technical experts, we determined that the topic of computer security is complex, varied in methodology, and rapidly changing, and even if EPA were to promulgate specific requirements for ECM security, those requirements would have to be updated annually at a minimum, as the pace of change in security technology is rapid. Manufacturers need to have the ability to quickly implement securing changes, without the burden of following prescriptive regulatory requirements.

However, some assurance is needed when a product is sold that appropriate measures have been taken to ensure that the ECM is tamper-proof and that it is not vulnerable to attack using readily available tools. Section 203(a)(3)(A) and (B) of the Clean Air Act not only prohibit tampering, but also prohibit the manufacture of a product where a person knows or should know that "the principal effect of the part or component is to bypass, defeat, or render inoperative any device or element of design installed on or in a motor vehicle in compliance with regulations."

The process of re-programming or re-flashing the ECM can occur by several methods but most, if not all, of the methods involve an access through the data link connector (DLC or commonly known as the OBD port). In some cases, the owner of the vehicle purchases a device that is capable of re-programming the ECM, and the device is plugged in to the DLC, where the owner can select one of the preloaded calibrations, or "tunes," that are preloaded on the device. Another method of re-programming involves remote flashing of the ECM. In this case, the vehicle owner will purchase a wireless CAN adapter that is connected to the DLC, which allows the manufacturer of this device to remotely access the vehicle's ECM and initiate the re-flash via an internet or cellular data connection.

To ensure that there are measures in place to prevent ECM tampering, we are proposing that manufacturers include a document at time of certification which outlines and describes the process and/or industry technical standards that were used to prevent unauthorized access to the ECM on the vehicle. This document shall describe the measures that a manufacturer has used to: prevent unauthorized access to the ECM; ensure that calibration values, software, or diagnostic features cannot be overwritten or otherwise disabled; and respond to repeated, unauthorized attempts to reprogram the ECM, if they become aware of such attempts.

Chapter 3 Feasibility Analysis for the Proposed Standards

3.1 Compression-Ignition Technology Feasibility

3.1.1 Diesel Technology Demonstration Programs

3.1.1.1 CARB Heavy-duty Low NO_x Stage 3 Research Program

In 2016, The California Air Resources Board (CARB) funded the Heavy-duty Low NO_x Research Program at Southwest Research Institute (SwRI) in San Antonio, TX to explore the feasibility of diesel HDEs achieving 0.02 g/bhp-hr NO_x composite emissions over the FTP transient test cycle. Stage 3 of this research program investigated the use of dual-SCR systems, cylinder deactivation (CDA), heated urea dosing system, intercooler bypass, turbine bypass, and EGR cooler bypass via engine dynamometer testing of a developmental engine based on the MY2017 Cummins X15 diesel Heavy HDE. Major specifications for the engine are shown in Table 3-1. Like many other MY2010 and later diesel HDEs, the X15 is equipped with a variable geometry turbocharger (VGT), high pressure common rail fuel injection and cooled EGR. The X15's original equipment exhaust aftertreatment system (EAS) consists of a DOC, DPF, SCR, and ASC in series. The X15 engine was modified by SwRI and Eaton to incorporate individual cylinder deactivation. SwRI also developed an engine calibration to aid catalyst warmup using a combination of later combustion phasing and increased idle speed. Further details of the specific, fixed CDA modes evaluated and other details regarding CDA development and engine instrumentation can be found in two papers by SwRI and Eaton.^{133,134} Details regarding the EAS, control systems, and calibration are summarized in three additional papers by SwRI.^{135,136,137} The complete summary of the work completed as part of Stage 3 is included in the final report from SwRI.¹³⁸

Table 3-1: Major engine specifications for the MY2017 Cummins X15 engine used for the CARB Low NO_x Stage 3 Research Program

Engine Displacement	14.95 L
Bore X Stroke	137 X 169 mm
Rated Power @ Speed	373 kW @ 1800 rpm
Rated Torque @ Speed	2500 N·m @ 1000 rpm



Figure 3-1: Developmental Cummins X15 Engine equipped with individual cylinder deactivation undergoing engine dynamometer testing as part of the CARB Stage 3 research at SwRI.

A schematic layout of the developmental EAS with light-off SCR is shown in Figure 3-2. Photos of the EAS showing details of its installation within the engine dynamometer test cell are shown in Figure 3-3. The heated urea dosing system, mixer, and light-off SCR with ASC zone-coated onto the rear of the SCR substrate were mounted downstream of the turbocharger. The remaining components were mounted in an insulated single-box housing to improve heat retention. Catalyst substrate specifications are summarized in Table 3-2. The total EAS volume was approximately 4.6 times the engine displacement. The total volume of the SCR, not including ASC, was approximately 2.8 times engine displacement. The volume of the light-off SCR was approximately 0.58 times engine displacement and the volume of the downstream SCR system was approximately 2.2 times engine displacement (both excluding ASC). The volume of the downstream SCR is comparable to the sales-weighted displacement-specific SCR volume for MY2019 Heavy HDE, so the increase in total SCR volume relative to 2019 Heavy HDE applications was due to the addition of light-off SCR.

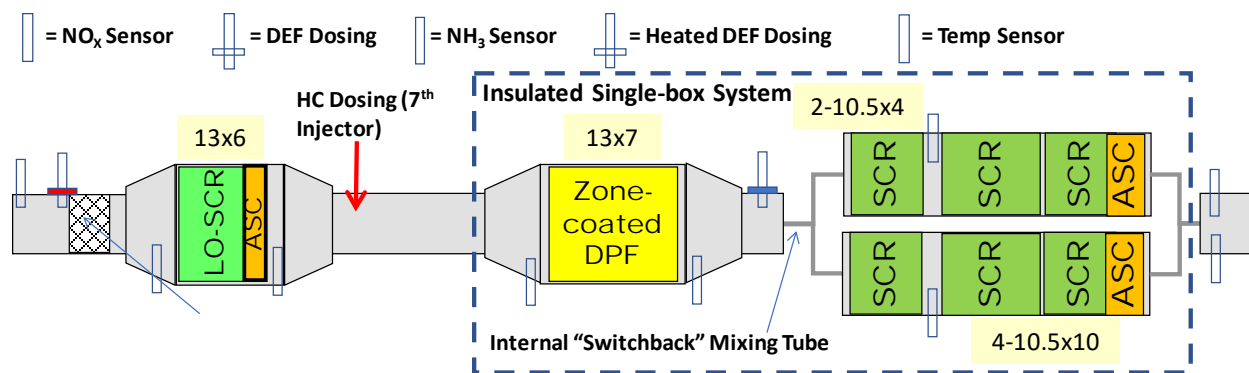


Figure 3-2: Schematic layout (not to scale) of the dual-SCR EAS tested as part of the CARB Stage 3 research at SwRI.

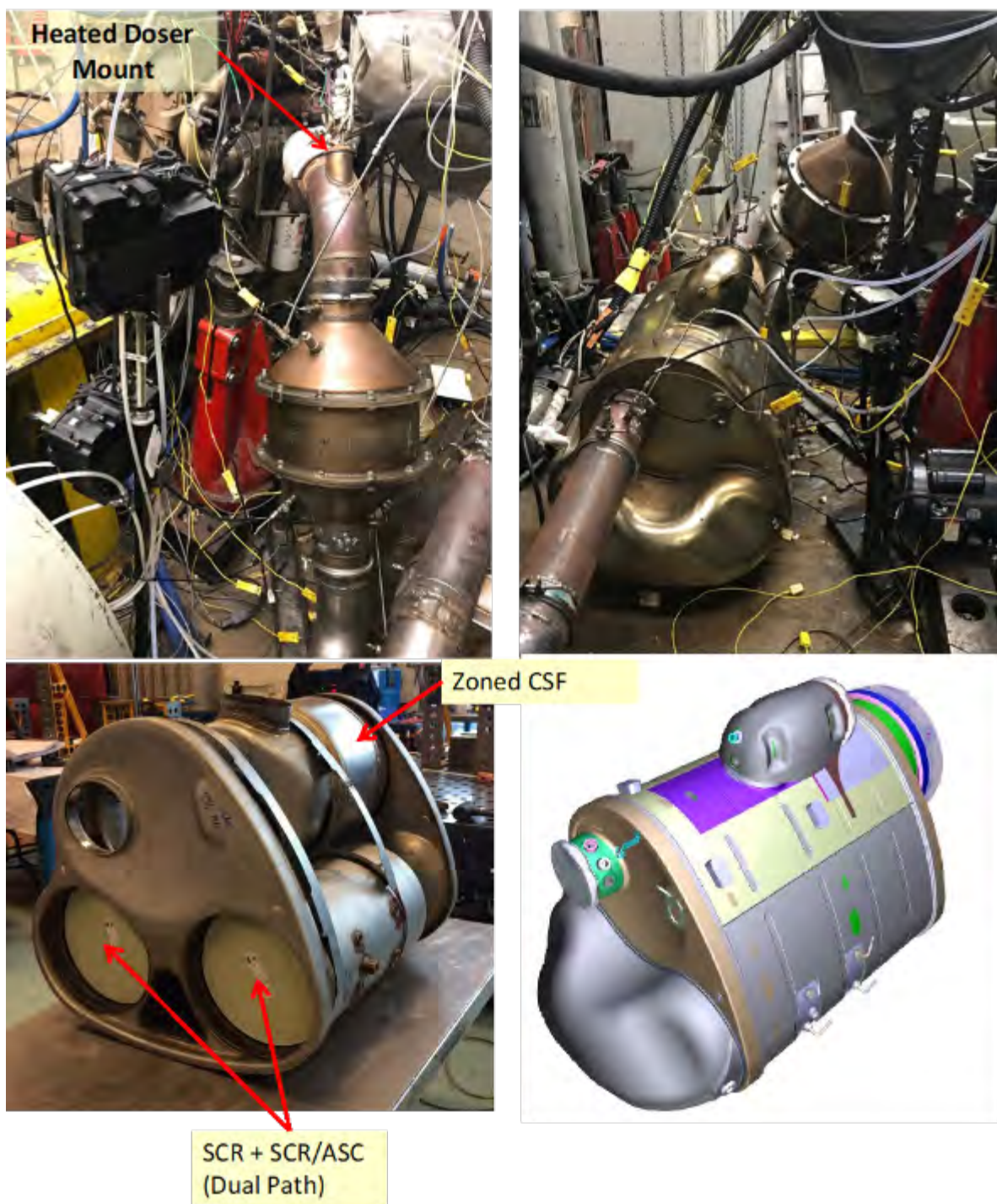


Figure 3-3: Developmental EAS with light-off SCR installed in engine dynamometer test cell at SwRI (upper left, upper right) and details of the downstream, single "box" unit (lower left, lower right).

Table 3-2: Summary of catalyst specifications for developmental EAS with light-off SCR.

Component	Dimensions, Dia. X Length (inches)	Substrate Volume (liters)	Cell Density (cpsi) / wall thickness (mil)	Notes
Light-off SCR/ASC	13 X 6	13.1	400/4	ASC is zone-coated to the rearmost 2" of the light-off SCR substrate
Zone-coated CDPF	13 X 7	15.2	300/7	Zone-coated wall-flow substrate providing both DOC and CDPF functionality
SCR	10.5 X 4	11.4	600/4.5	Two substrates in parallel
SCR	10.5 X 5	14.2	600/4.5	Two substrates in parallel
SCR/ASC	10.5 X 5	14.2	600/4.5	Two substrates in parallel, both with ASC zone-coated to the rearmost 2" of the SCR substrates

Emissions were evaluated using engine dynamometer testing over the cold-start and hot-start FTP transient cycle, the SET, the LLC, and over specific cycles representing in-use operation that were provided by the Engine Manufacturers Association (EMA). A baseline, original equipment 2017 Cummins X15 EAS was tested at a low-hour, degreened condition. The developmental EAS with light-off SCR was tested in a degreened state and then was subjected accelerated aging using the Diesel Aftertreatment Accelerated Aging Cycle (DAAAC).¹³⁹ The DAAAC incorporated chemical deSO_x at 30 hour intervals and DPF ash maintenance at 500 hour intervals. Emissions results over the FTP, SET, and LLC for the baseline and developmental EAS are summarized in Table 3-3 through Table 3-7. FTP Composite and SET NO_x emissions results are just over 20 mg/bhp-hr after accelerated aging equivalent to approximately 435,000 miles and the NO_x emissions results over the LLC were just under 50 mg/bhp-hr. Emissions of N₂O were approximately half of the current 0.10 g/bhp-hr standards. The infrequent regeneration factor (IRAF) for this engine is 2 mg/hp-hr for the FTP and SET and 5 mg/hp-hr for the LLC.

Table 3-3: Baseline (degreened) emissions results for the OE Cummins EAS

Cycle Results:	FTP cold	95% CI	FTP hot	95% CI	FTP composite	95% CI	SET	95% CI	SET (2021)	95% CI
NO _x (mg/bhp-hr)	271	31	132	99	152	87	140	6	1005	335
PM (mg/bhp-hr)	2.0	0.2	2.0	1.0	2.0	0.9	1.2	0.3	NA	NA
NMHC (mg/bhp-hr)	3	7	2	2	3	3	1.7	0.2	12	25
CO (mg/bhp-hr)	48	37	17	31	22	29	7.9	0.9	30	24
CO ₂ (g/bhp-hr)	530	4	508	8	511	8	452	4	609	7
N ₂ O (mg/bhp-hr)	42	2	63	9	61	11	68	8	64	NA*

*Single LLC test - no repeats.

For results where the 95% CI is greater than the average, the results are not statistically different from zero based on a 2-sided Student's t-test at $\alpha=0.05$

Table 3-4: 0-hour (degreened) emissions results for the developmental EAS system with light-off SCR

Cycle Results:	FTP cold	95% CI	FTP hot	95% CI	FTP composite	95% CI	SET	95% CI	SET (2021)	95% CI
NO _x (mg/bhp-hr)	54.7	0.8	11	2	17	1	8.9	0.8	20	8
PM (mg/bhp-hr)	2	1	1.4	0.1	1.5	0.2	0.9	0.2	4.0	0.7
NMHC (mg/bhp-hr)	23	56	12	50	14	51	1	2	47	171
CO (mg/bhp-hr)	110	41	12	3	26	6	7	1	62	51
CO ₂ (g/bhp-hr)	539	4	499	1	505	2	454	3	600	4
N ₂ O (mg/bhp-hr)	39	3	47	1	46	2	53	9	43	9

For results where the 95% CI is greater than the average, the results are not statistically different from zero based on a 2-sided Student's t-test at $\alpha=0.05$

Table 3-5: Emissions results for the developmental EAS system with light-off SCR after 334 hours of accelerated thermal and chemical aging using the DAAAC (equivalent to approximately 145,000 miles of operation). The SET (2021) results represent updated 40 CFR §1036.505 SET procedures.

Cycle Results:	FTP cold	95% CI	FTP hot	95% CI	FTP composite	95% CI	SET	95% CI	SET (2021)	95% CI	LLC	95% CI
NO _x (mg/bhp-hr)	56	5	12	2	18	2	15	2	15	2	22	9
PM (mg/bhp-hr)	1.3	0.2	1.6	0.5	1.6	0.4	0.7	0.0	0.7	0.4	3	6
NMHC (mg/bhp-hr)	33	58	18	42	20	44	10	15	3.0	0.6	19	18
CO (mg/bhp-hr)	186	94	25	10	48	22	7	1	8	2	104	45
CO ₂ (g/bhp-hr)	541	4	506	5	511	5	454	1	450	2	602	2
N ₂ O (mg/bhp-hr)	31	4	37	4	36	4	34	2	34	1	32	17

For results where the 95% CI is greater than the average, the results are not statistically different from zero based on a 2-sided Student's t-test at $\alpha=0.05$

Table 3-6: Emissions results for the developmental EAS system with light-off SCR after 667 hours of accelerated thermal and chemical aging using the DAAAC (equivalent to approximately 290,000 miles of operation). The SET (2021) results represent updated 40 CFR §1036.505 SET procedures.

Cycle Results:	FTP cold	95% CI	FTP hot	95% CI	FTP composite	95% CI	SET	95% CI	SET (2021)	95% CI	LLC	95% CI
NO _x (mg/bhp-hr)	63	6	15	2	22	3	19	2	14.8	0.4	50	6
PM (mg/bhp-hr)	1.8	0.4	2.0	1.3	2.0	1.0	1	2	0.8	0.3	4.5	0.5
NMHC (mg/bhp-hr)	29	12	12	5	14	3	3	2	2.1	0.7	43	5
CO (mg/bhp-hr)	227	40	139	25	151	17	10	2	11	3	305	42
CO ₂ (g/bhp-hr)	538	1	512	2	515	2	461	2	454.1	0.7	616	1
N ₂ O (mg/bhp-hr)	28	9	32	7	31	7	23	3	25	1	21	6

Table 3-7: Emissions results for the developmental EAS system with light-off SCR after 1000 hours of accelerated thermal and chemical aging using the DAAAC (equivalent to approximately 435,000 miles of operation). The SET (2021) results represent updated 40 CFR §1036.505 SET procedures.

Cycle Results:	FTP cold	95% CI	FTP hot	95% CI	FTP composite	95% CI	SET	95% CI	SET (2021)	95% CI	LLC	95% CI
NO _x (mg/bhp-hr)	61	8	17	3	23	3	22	4	20	4	47	4
PM (mg/bhp-hr)	2	0	2	1	2	1	2	0	1	0	6	1
NMHC (mg/bhp-hr)	41	10	24	13	26	12	5	5	4	0	28	77
CO (mg/bhp-hr)	257	44	184	38	194	34	12	1	11	1	371	79
CO ₂ (g/bhp-hr)	535	9	512	1	515	2	461	6	456	2	617	1
N ₂ O (mg/bhp-hr)	37	7	42	21	41	18	23	2	23	1	18	12

For results where the 95% CI is greater than the average, the results are not statistically different from zero based on a 2-sided Student's t-test at $\alpha=0.05$

In addition to the evaluating the feasibility of the new criteria pollutant standards, we also evaluated how CO₂ was impacted on the CARB Stage 3 engine for both, the test procedures used to show compliance with the engine standards in 40 CFR 1036.108 and the vehicles standards in 40 CFR 1037 Subpart B. To do this we evaluated how CO₂ emissions changed from the base engine on the FTP, SET, and LLC, as well as the fuel mapping test procedures defined in 40 CFR 1036.535 and 40 CFR 1036.540. For all three cycles the Stage 3 engine emitted CO₂ with no statistically significant difference at a 95% level of confidence when compared to the base 2017 Cummins X15 engine. Comparing the CARB Stage 3 engine with the 0-hour (degreened) aftertreatment which provides the most direct comparison with the 2017 Cummins X15 engine (since the 2017 Cummins X15 aftertreatment was degreened but not chemically aged) the percent reduction in CO₂ for the FTP, SET and LLC, was 1, 0 and 1% respectively. Although, since SwRI made changes to the thermal management strategies of the CARB Stage 3 engine (which increased CO₂ emissions from the engine), to improve NO_x reduction at low SCR temperatures after this data was taken, there is no direct comparison between the baseline engine and the CARB Stage 3 engine. The data at equivalent of 435,000 miles that includes these changes, the percent increase in CO₂ for the FTP, SET and LLC, was 0.6, 0.7 and 1.3% respectively, but since the aftertreatment had been aged to an equivalent of 435,000 miles prior to these tests, which included the ash exposure from this aging, that increased the back pressure on the engine as shown in Figure 3-4, this is not a direct comparison with the baseline engine. To evaluate impacts to CO₂ emissions of the CARB Stage 3 engine on the HD GHG Phase 2 test procedure, the test procedures were executed with both the baseline engine and the CARB Stage 3 engine with development aged aftertreatment. The fuel maps from these tests were run in GEM. The results from this analysis that is summarized in the SwRI Stage 3 report¹³⁸, also showed that the Stage 3 engine emitted CO₂ at the same rate as the 2017 Cummins X15.

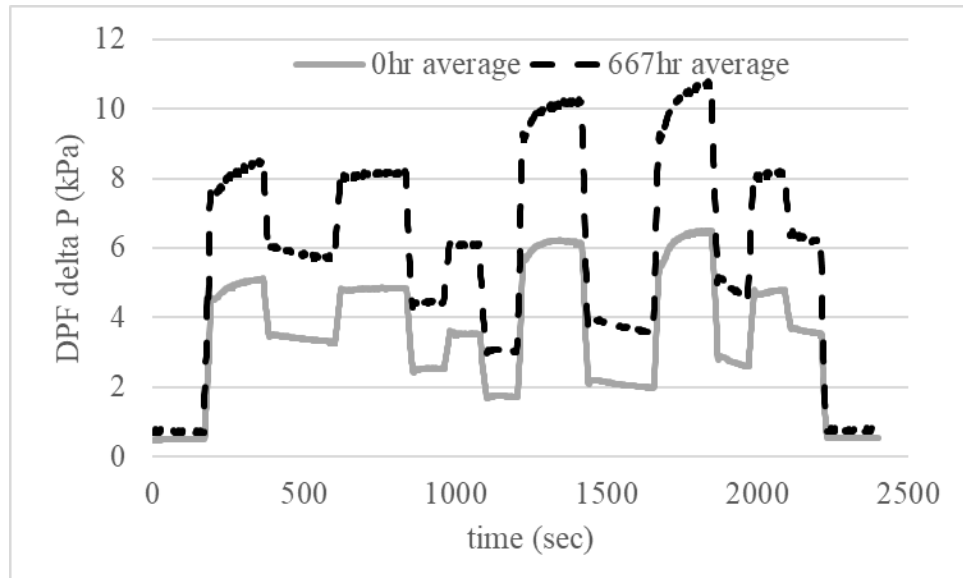


Figure 3-4: The average pressure drop across the DPF on the SET for the degreened aftertreatment and the equivalent of 290,000 miles of operation aftertreatment

Once the CARB Stage 3 demonstration was completed a second phase of the demonstration, that was led by EPA and is referred to as the EPA Stage 3 engine. In this phase improvements were made to the aftertreatment by replacing the zone-coated catalyzed soot filter with a separate DOC and diesel particulate filter (DPF) that were chemically- and hydrothermally-aged to the equivalent of 800,000 miles and improving the mixing of the DEF with exhaust for the underfloor SCR. A schematic of the aftertreatment is shown in Figure 3-5. The results of testing the EPA Stage 3 engine at the equivalent of 435,000 and 600,000 miles are shown in Table 3-8 and Table 3-9. Test results at the equivalent of 800,000 miles of age will be added to the docket when they become available.

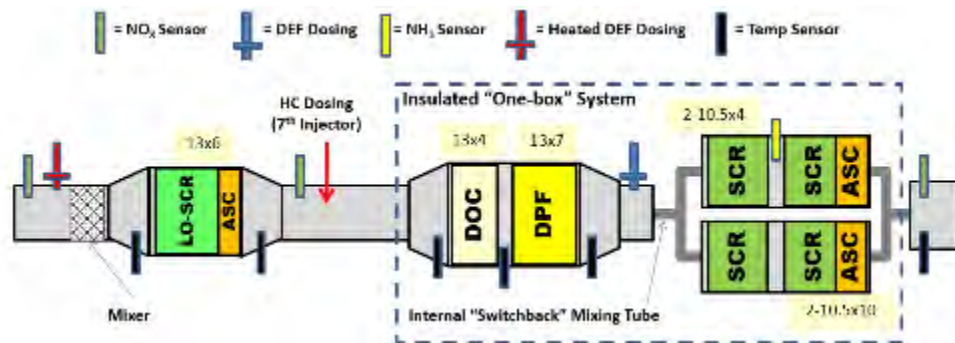


Figure 3-5: Schematic layout (not to scale) of the dual-SCR EAS tested as part of the EPA Stage 3 research at SwRI.

Table 3-8: Emissions results for the developmental EPA Stage 3 EAS system with light-off SCR and separate DOC and DPF after 1000 hours of accelerated thermal and chemical aging using the DAAAC (equivalent to

approximately 435,000 miles of operation). The SET (2021) results represent updated 40 CFR §1036.505 SET procedures.

Cycle Results:	FTP cold	95% CI	FTP hot	95% CI	FTP composite	95% CI	SET (2021)	95% CI	LLC	95% CI
NO _x (mg/bhp-hr)	55	1	14	1	20	1	17	1	29	11
PM (mg/bhp-hr)	2	1	2	1	2	1	1	1	3	1
NMHC (mg/bhp-hr)	25	7	9	2	12	2	1	1	35	51
CO (mg/bhp-hr)	221	61	128	77	141	75	30	22	245	438
CO ₂ (g/bhp-hr)	534	1	511	2	514	2	455	4	617	11
N ₂ O (mg/bhp-hr)	84	7	74	9	76	9	24	69	132	45

Yellow highlighting designates values that are not statistically different from zero based on a 2-sided Student's t-test at $\alpha=0.05$

Table 3-9: Emissions results for the developmental EPA Stage 3 EAS system with light-off SCR and separate DOC and DPF after 1379 hours of accelerated thermal and chemical aging using the DAAAC (equivalent to approximately 600,000 miles of operation). The SET (2021) results represent updated 40 CFR §1036.505 SET procedures.

Cycle Results:	FTP cold	95% CI	FTP hot	95% CI	FTP composite	95% CI	SET (2021)	95% CI	LLC	95% CI
NO _x (mg/bhp-hr)	61	5	21	2	27	2	24	1	33	2
PM (mg/bhp-hr)	2	0	1	2	1	2	1	0	4	1
NMHC (mg/bhp-hr)	23	11	7	4	9	5	1	0	16	6
CO (mg/bhp-hr)	245	31	127	134	144	119	15	0	153	20
CO ₂ (g/bhp-hr)	546	3	515	2	519	2	460	1	623	6
N ₂ O (mg/bhp-hr)	69	9	57	4	58	4	30	6	64	22

For results where the 95% CI is greater than the average, the results are not statistically different from zero based on a 2-sided Student's t-test at $\alpha=0.05$

3.1.1.1.1 EPA Stage 3 Off-cycle Emissions Performance

In addition to the FTP, SET and LLC, the Stage 3 engine with the DAAAC aged aftertreatment to an equivalent of 435,000 miles was run on 5 cycles that cover a range of off-cycle operation. These cycles are the CARB Southern Route Cycle, Grocery Delivery Truck Cycle, Drayage Truck Cycle, Euro-VI ISC Cycle and the ACES 4-hour Cycle. The CARB Southern Route Cycle is dominantly highway operation with elevation changes resulting in extended motoring sections followed by high power operation. The Grocery Delivery Truck Cycle represents goods delivery from regional warehouses to downtown and suburban supermarkets and extended engine-off events characteristic of unloading events at supermarkets.

Drayage Truck Cycle includes near dock and local operation of drayage trucks, with extended idle and creep operation. Euro-VI ISC Cycle is modeled after Euro VI ISC route requirements with a mix of 30% urban, 25% rural and 45% highway operation. ACES 4-hour Cycle includes 5 mode cycle developed as part of ACES program. Figure 3-6 through Figure 3-10 show the engine speed, engine torque and vehicle speed of the cycles. The engine speed and torque shown in the plots are specific to the Stage 3 engine.

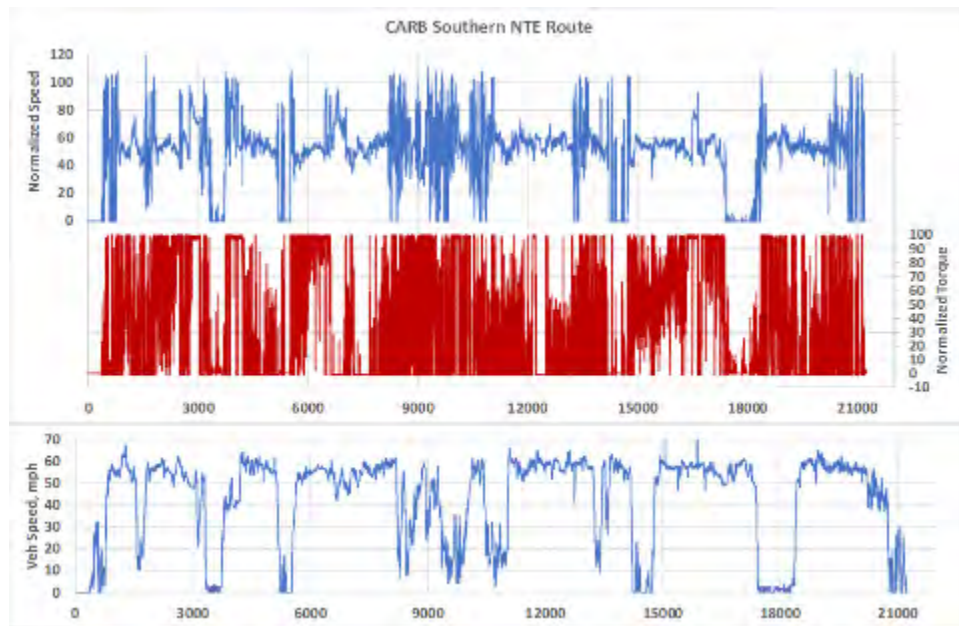


Figure 3-6: CARB Southern Route Cycle

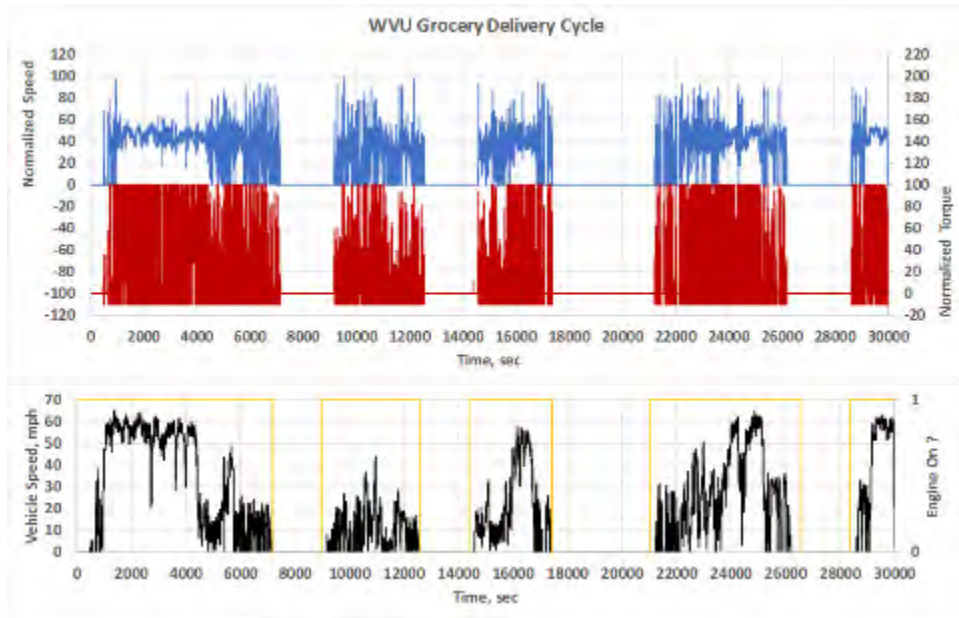


Figure 3-7: Grocery Delivery Truck Cycle

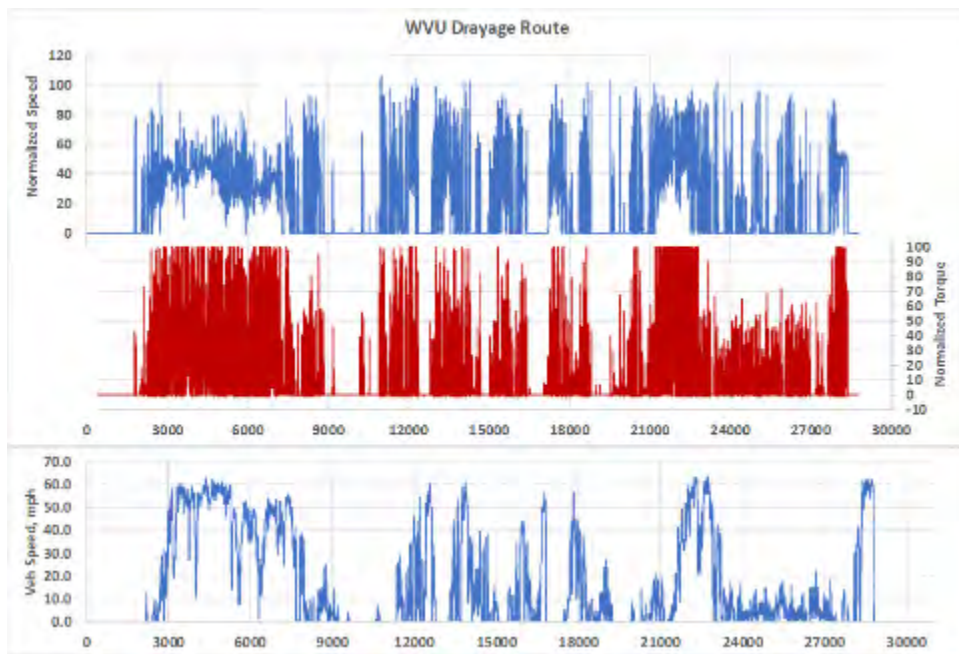


Figure 3-8: Drayage Truck Cycle

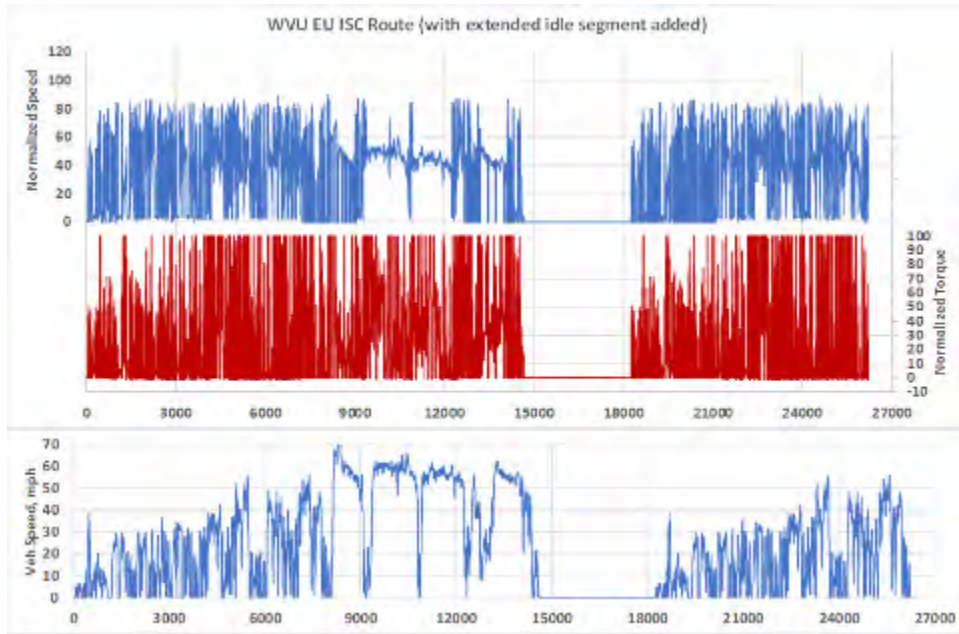


Figure 3-9: Euro-VI ISC Cycle

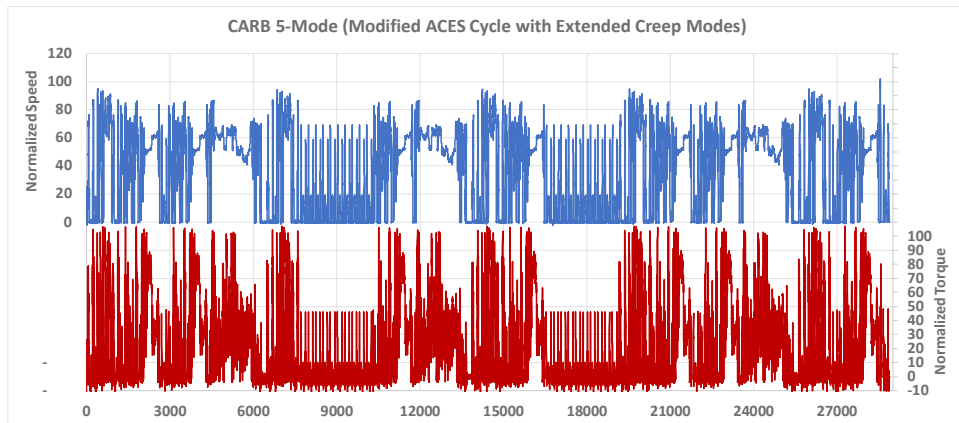


Figure 3-10: ACES 4-hour Cycle

Even with this very challenging cycle, the NO_x emissions from the Stage 3 engine with aftertreatment aged to the equivalent of 435,000 miles below the proposed Option 1 off-cycle standards at 800,000 miles as shown in Table 3-10. Table 3-11 and Table 3-12 show that the NHMC the emissions from this engine are well below the proposed Option 1 HC and CO standards.

Table 3-10: Off-cycle NO_x emissions results for the developmental EAS system with light-off SCR and separate DOC and DPF after 1000 hours of accelerated thermal and chemical aging using the DAAAC (equivalent to approximately 435,000 miles of operation)

Bin	SNTE	Grocery Cycle	ACES	EU ISC	Drayage
Idle (g/hr)	0.7	1.0	0.9	0.4	0.3
Low (mg/hp-hr)	41	25	29	25	15
Mid/High (mg/hp-hr)	30	18	16	33	23

Table 3-11: Off-cycle NMHC emissions results for the developmental EAS system with light-off SCR and separate DOC and DPF after 1000 hours of accelerated thermal and chemical aging using the DAAAC (equivalent to approximately 435,000 miles of operation)

Bin	SNTE	Grocery Cycle	ACES	EU ISC	Drayage
Idle (g/hr)	-0.2	-0.6	-0.4	-0.1	0.0
Low (mg/hp-hr)	2	28	1	6	12
Mid/High (mg/hp-hr)	2	4	1	0	7

Table 3-12: Off-cycle CO emissions results for the developmental EAS system with light-off SCR and separate DOC and DPF after 1000 hours of accelerated thermal and chemical aging using the DAAAC (equivalent to approximately 435,000 miles of operation)

Bin	SNTE	Grocery Cycle	ACES	EU ISC	Drayage
Idle (g/hr)	0.3	12.7	1.0	1.9	7.6
Low (mg/hp-hr)	40	265	66	90	461
Mid/High (mg/hp-hr)	12	21	18	18	44

3.1.1.2 EPA Heavy-duty Diesel Low NO_x Demonstration Program

EPA will be evaluating two different EAS designs provided to the Agency by the Manufacturers of Emissions Control Association (MECA). Both EAS designs incorporate light-off SCR and dual urea injection. One of the systems will use close-coupling of the light-off SCR (Figure 3-11, Table 3-13). The other EAS design mounts the light-off SCR closer to the other EAS components in an under-cab position (Figure 3-12, Table 3-14).

Both EAS designs utilize conventional urea dosing systems for the downstream SCR position. Both EAS will be evaluated using a heated urea dosing system in the upstream SCR position. The systems will be tested using a developmental version of a MY2018 Cummins X15 15-liter Heavy HDE engine (Figure 3-13 and Table 3-15). EPA's developmental X15 engine is equipped with a prototype cylinder deactivation system capable of deactivating the intake and exhaust valves for each of the engine's six cylinders. The engine is equipped with a low-thermal inertia air-gap exhaust manifold design and air-gap construction for exhaust piping located either immediately downstream of the light-off SCR (close-coupled system) or immediately upstream of the urea dosing for the light-off SCR (under-cab system).

The under-cab EAS will also be installed in a MY2018 Navistar Daycab Class 8 Tractor equipped with a second EPA developmental X15 engine. The engine and cab are instrumented to allow evaluation of NVH characteristics during truck operation when using CDA.

EPA's developmental X15 is nearly identical to the engine equipped with cylinder deactivation and tested as part of CARB's Stage 3 Low NO_x Research Program at SwRI with the exception of some instrumentation differences, EGR routing changes, and differences in EAS designs.¹³³ The EPA developmental X15 also has identical power and torque ratings to the engine from the Stage 3 Program. Under contracts with the EPA [contract # 68HERC20D0014], SwRI is currently assisting us with engine instrumentation and will be providing initial CDA calibration strategies, model-based urea dosing calibration strategies, chemical deSO_x strategies and other engine and EAS calibration strategies that were originally developed as part of the CARB Phase 3 development effort. EPA engineering staff will independently evaluate the SwRI engine and EAS controls using our developmental X15 engine and will build upon the previous CARB Stage 3 project via the development of additional engine and EAS strategies. For example, fixed cylinder deactivation (i.e., 2, 3, or 4 cylinders deactivated) was used for active thermal management in the CARB Stage 3 work and dynamic, individual cylinder deactivation will be explored as part of EPA's continuation of this work. EPA's X15 developmental engine also incorporates a simpler EGR cooler bypass design that allows 100% bypass instead of the 50% bypass used in the CARB stage 3 work. There are also additional changes that have been made to EGR system routing to better facilitate simultaneous EGR and dynamic CDA control and to improve EGR distribution to the firing cylinders when CDA is active.

EPA's developmental X15 engine is instrumented with a high-speed data acquisition system to allow collection of cylinder pressure and crank angle position data, which will allow determination of apparent rate of heat release and characterization of combustion phasing (e.g., crank angle for 50% fuel burned or CA50) and other combustion phenomena. The engine is also instrumented with non-contact, variable reluctance sensors on the valve bridges in order to sense valve motion during engine operation (Figure 3-14).

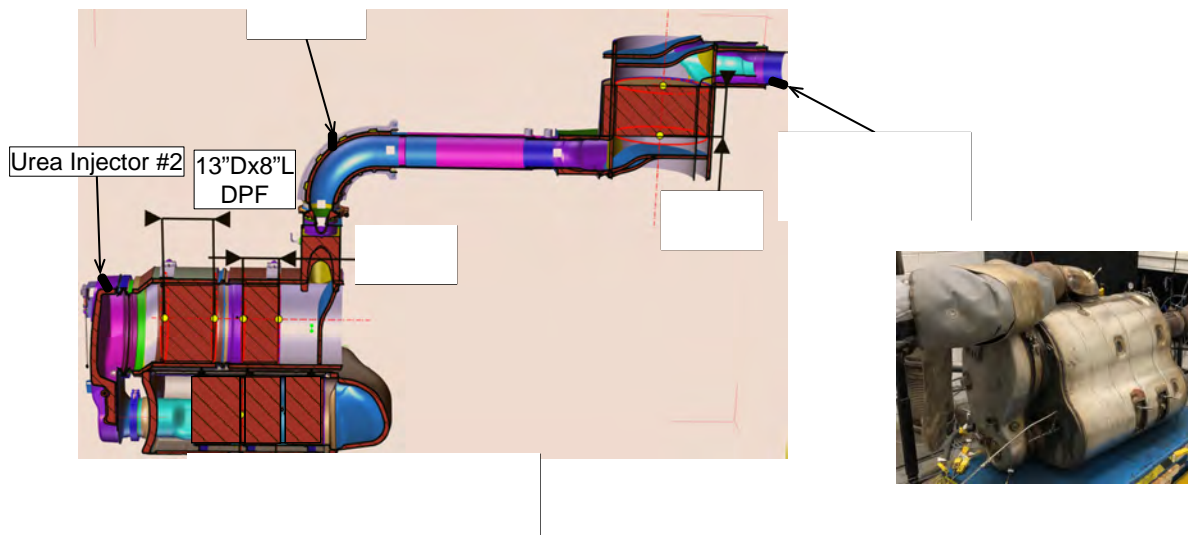


Figure 3-11: EAS with close-coupled light-off SCR.

Table 3-13: Summary of catalyst specifications for developmental EAS with close-coupled light-off SCR.

Component	Substrate Dimensions, Dia. X Length (inches)	Substrate Volume (liters)	Cell Density (cps) / wall thickness (mil)	Notes
Light-off SCR/ASC	13 X 7	15.2	400/4	Thin wall/low-mass substrate with ASC zone-coated to the rearmost 2"
DOC	13 X 4	8.7	400/4	Thin wall/low-mass substrate
CDPF	13 X 8	17.4	300/7	
SCR	10.5 X 7	19.9	600/2	Two substrates in parallel
SCR	10.5 X 5	14.2	600/2	Two substrates in parallel
SCR/ASC	10.5 X 5	14.2	600/2	Two substrates in parallel, both with ASC zone-coated to the rearmost 2" of the SCR substrates

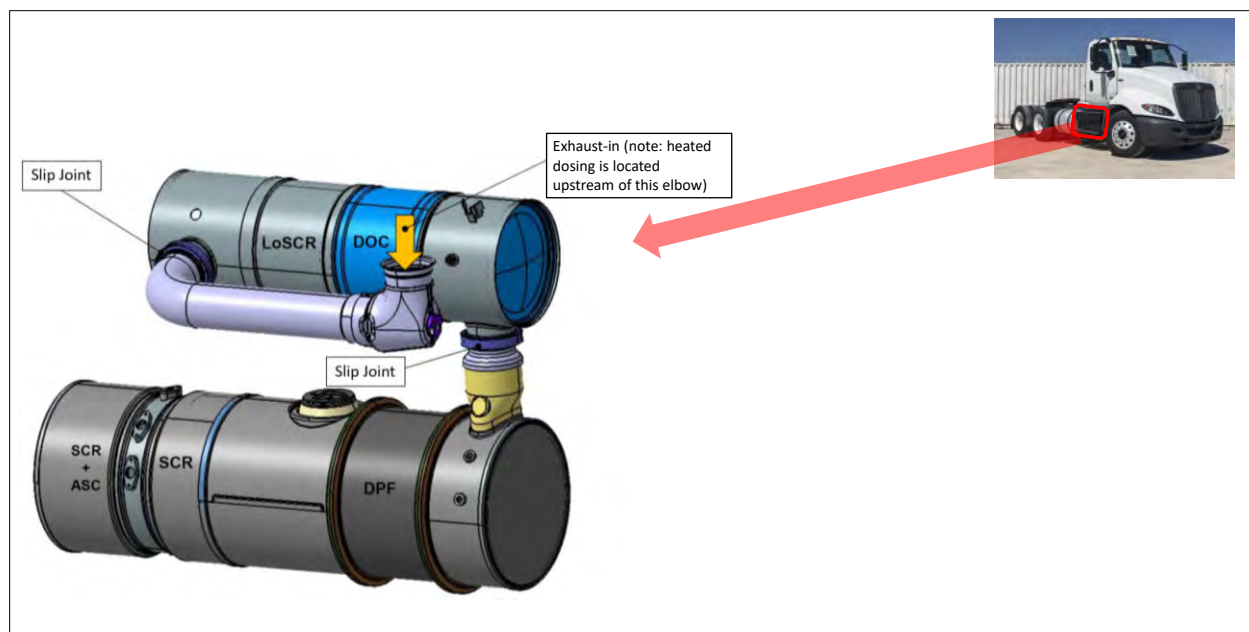


Figure 3-12: EAS with light-off SCR integrated into an under-cab mounting position. This system is designed to be installed in a Navistar Daycab which is shown in the upper right.

Table 3-14: Summary of catalyst specifications for developmental EAS with light-off SCR mounted under-cab.

Component	Substrate Dimensions, Dia. X Length (inches)	Substrate Volume (liters)	Cell Density (cpsi) / wall thickness (mil)	Notes
Light-off SCR/ASC	10.5 X 8	11.4	400/4	High porosity/low-mass substrate with ASC zone-coated to the rearmost 2"
DOC	10.5 X 6	8.5	400/4	High porosity/low-mass substrate
CDPF	13 X 7	15.2	300/7	
SCR+SCR/ASC	13 X 7	30.5	600/3	Two substrates in series - volume is for combined total. ASC is zone-coated to the rearmost 2" of SCR #3

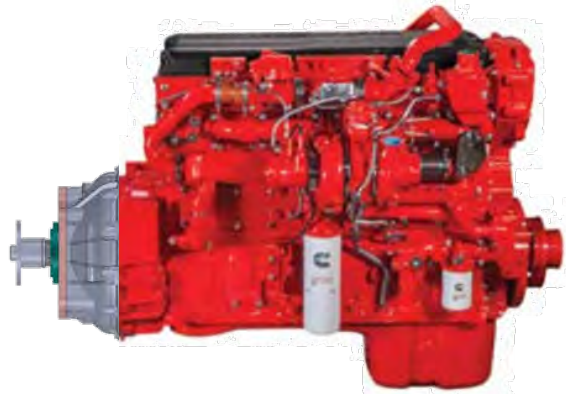


Figure 3-13: EPA developmental MY2018 Cummins X15 Heavy HDE.

Table 3-15: Major engine specifications for the MY2018 Cummins X15 engine used for EAS and CDA development by EPA

Engine Displacement	14.95 L
Bore X Stroke	137 X 169 mm
Rated Power @ Speed	373 kW @ 1800 rpm
Rated Torque @ Speed	2500 N·m @ 1000 rpm



Figure 3-14: Variable reluctance sensor for valve position measurement. The final installation will include valve position measurement at the valve bridges for each of the six cylinders.

Each EAS design will undergo accelerated aging using a "burner aging" version of the DAAAC.^{139,140} Burner aging uses a burner system fueled with diesel fuel and additized engine lubricant to expose the EAS to both accelerated thermal aging and accelerated chemical aging. The burner is operated over a series of controlled burner exhaust flow rates and burner exhaust temperature setpoints that match specific engine speed and engine load setpoints during operation of the targeted engine and EAS application (see Figure 3-15). A higher sulfur diesel fuel (>100 ppm) is also used during DAAAC burner aging in order to accelerate sulfur exposure. The DAAAC is designed to accelerate thermal and chemical effects by approximately 10 times normal engine operation (i.e., 1 hour of DAAAC is approximately equivalent to 10 hours of in-

use operation). Operation on the DAAAC for 1,000 hours is approximately equivalent to Heavy HDE operation in a truck application to the end of UL (435,000 miles).

Each EAS design will be tested using EPA's developmental X15 engine at the accelerated aging equivalents of 435,000, 600,000, and 800,000 miles of operation. The resulting data will provide a better understanding of the impacts of catalyst degradation at much longer in-use operation than captured by today's regulatory useful life. The systems under evaluation by EPA have also been specifically designed to meet longer useful life requirements.

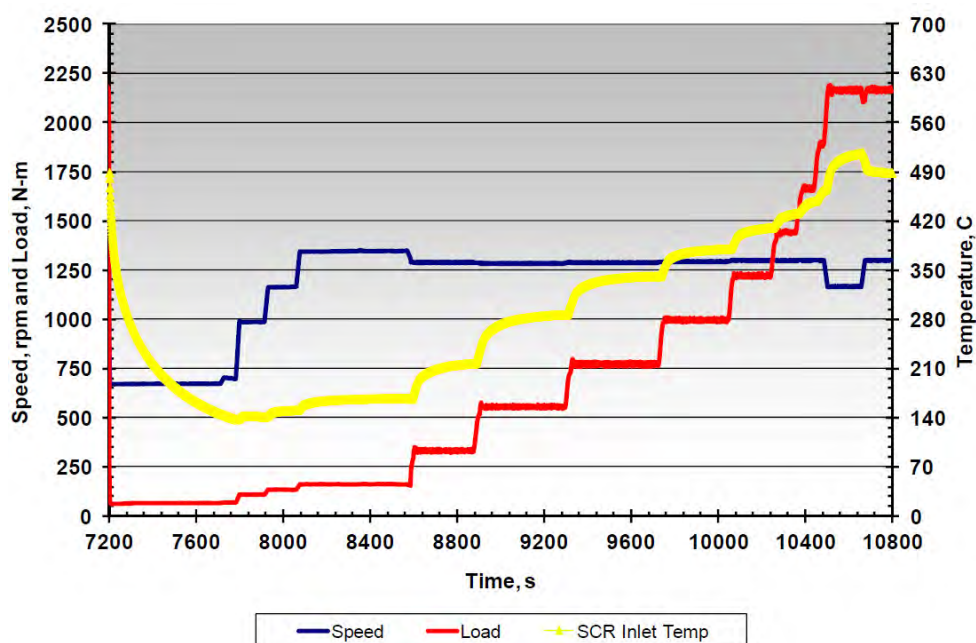


Figure 3-15: Example of engine-speed, engine load, and resulting SCR inlet temperature used over the DAAAC.

One of the design constraints that will be further explored within EPA's demonstration program is nitrous oxide (N₂O) emissions. N₂O emissions are affected by the temperature of the SCR catalyst, SCR catalyst formulation, urea dosing rates, and the makeup of NO and NO₂ upstream of the SCR catalyst. Limiting N₂O emissions is important because N₂O is a strong greenhouse gas and because highway heavy-duty engines are subject to a 0.10 g/hp-hr N₂O emissions standard set within the HD GHG Phase 1 rule.

3.1.2 Baseline Technology Effectiveness

The basis for our baseline technology assessment is the data provided by manufacturers as part of the heavy-duty in-use testing requirements. This data encompasses in-use operation from nearly 300 LHD, MHD, and HHD vehicles. Chapter 6 of the draft RIA describes how the data was used to update the MOVES model emissions rates for HD diesel engines. Chapter 3 of the draft RIA summarizes the in-use emissions performance of these engines.

To assess emissions levels of current production engines on the regulatory cycles we analyzed the certification data submitted to the agency. For this analysis we focused on MY2019 and newer engines.

Table 3-17 include the data for the certification results of the FTP and SET cycle. The certification results are the test results adjusted for IRAF and DF.

One observation from the data is the range of margin between the certification results and the standard. The margin for NO_x on the FTP cycle is as small as 0.02 g/hp-hr or 11% and as large as 0.15 g/hp-hr or 300%. For the SET the average compliance margin is slightly larger than the average margin for the FTP. For the other criteria pollutants the margin between the certification results and the applicable standards are much larger than for NO_x.

Table 3-16: Summary of certification data for FTP cycle

	NO _x (g/hp-hr)	PM (g/hp-hr)	NMHC (g/hp-hr)	CO (g/hp-hr)	N ₂ O (g/hp-hr)
Standard	0.2	0.01	0.14	15.5	0.1
Average	0.13	0.00	0.01	0.18	0.07
Minimum	0.05	0.00	0.00	0.00	0.04
Maximum	0.18	0.00	0.04	1.10	0.11

Table 3-17: Summary of certification data for SET cycle

	NO _x (g/hp-hr)	PM (g/hp-hr)	NMHC (g/hp-hr)	CO (g/hp-hr)
Standard	0.2	0.01	0.14	15.5
Average	0.11	0.00	0.01	0.00
Minimum	0.00	0.00	0.00	0.00
Maximum	0.18	0.00	0.04	0.20

In addition to analyzing the in-use data submitted by manufacturers, we also conducted and analyzed engine dynamometer data of three modern HD diesel engines. These engines include a 2018 Cummins B6.7, 2018 Detroit DD15 and 2018 Navistar A26. These engines were tested on cycles that ranged in power demand and included the LLC and the SET cycle defined in 40 CFR 1036.505. These results are summarized in Table 3-18, Table 3-19, and Table 3-20

For two of these engines both the SET in 40 CFR 1036.505 and 40 CFR 86.1333 were run. As can be seen from the data, there was not a measurable difference between the results of these two cycles. Both of these cycles were also run on the Stage 3 engine. These results are summarized in Chapter 3.1.1.1. The LLC cycle was also run for these engines to understand the performance of current engines on this cycle. The results from this cycle vary much more than the SET and FTP. The Cummins B6.7, which is the only non-tractor engine that was tested, had the lowest NO_x at 0.35 g/hp-hr. The other two engines including the Cummins X15 shown in Table 3-3 had results that were multiple times higher than the current standards for the FTP and SET.

Table 3-18: 2018 Detroit DD15 engine emissions in g/hp-hr

	Cold FTP	Hot FTP	FTP Composite	SET in 40 CFR 86.1333	SET in 40 CFR 1036.505	LLC
CO ₂	573	550	554	481	472	642
CO	0.54	0.04	0.11	0.01	0.01	0.07
THC	0.02	0.01	0.01	0.01	0.00	0.03
NO _x	0.43	0.05	0.10	0.01	0.01	0.61
NMHC	0.01	0.01	0.01	0.01	0.00	0.02

Table 3-19: 2018 Cummins B6.7 engine emissions in g/hp-hr

	Cold FTP	Hot FTP	FTP Composite	SET in 40 CFR 86.1333	SET in 40 CFR 1036.505	LLC
CO ₂	621	569	576	486	480	908
CO	0.09	0.04	0.05	0.01	0.02	0.03
THC	0.02	0.04	0.04	0.02	0.04	0.04
NO _x	0.48	0.10	0.15	0.05	0.05	0.35
NMHC	0.02	0.04	0.04	0.02	0.04	0.03
PM	0.00	0.00	0.00	0.00	0.00	

Table 3-20: 2018 Navistar A26 engine emissions in g/hp-hr

	Cold FTP	Hot FTP	FTP Composite	SET in 40 CFR 86.1333	LLC
CO ₂	546	527	529	459	710
CO	0.03	0.02	0.02	0.01	0.03
THC	0.01	0.00	0.00	0.00	0.05
NO _x	0.37	0.10	0.14	0.12	0.81
NMHC	0.01	0.00	0.00	0.00	0.05
PM	0.00	0.00	0.00	0.00	

3.1.3 Projected Heavy-Duty Diesel Technology Effectiveness

Based upon data from the EPA Heavy-duty Low NO_x Stage 3 Research Program (see Chapter 3.1.1.1), HDE NO_x reductions of approximately 90% from today's standards are technologically feasible when using CDA or other valvetrain-related air control strategies in combination with dual/light-off SCR systems. Emissions results for the EPA Heavy-duty Low NO_x Stage 3 Research Program after thermal and chemical aging of the EAS using the DAAAC are summarized in Figure 3-16 through Figure 3-17. The 1000 hours of engine and EAS operation

over the DAAAC is equivalent to approximately 435,000 miles. The SET results reflect changes to test procedures effective for MY2021 and later heavy-duty engines and thus better reflect SET results for MY2027 and later compliance. One thousand hours of DAAAC operation is approximately equivalent to the current Heavy HDE full useful life of 435,000 miles. After aging to the equivalent of 435,000 miles, NO_x emissions over the FTP composite and SET were 90% and 91% below today's standards, respectively. The projected NO_x emissions over the FTP composite, SET and LLC were all below the proposed Option 1 2031 full useful life standards. NO_x emissions over the FTP composite, and SET were at or just above the intermediate useful life standards, indicating that further calibration and development will be needed in order to meet the intermediate useful life standards. Aging of the EAS over DAAAC to the equivalent of the proposed Option 1 800,000-mile full useful life for 2031 Heavy HDE has been completed for the EPA Stage 3 Research Program, however testing with the aged EPA Stage 3 EAS was not completed in time to be included in this proposal. However, data from testing of the fully aged EPA Stage 3 engine will be added to the docket as it becomes available.¹⁴¹ As discussed Chapter 3.1.1.2, the testing of the CARB Stage 3 EAS was used to inform the design of a EAS with a full useful life design target of less than 30 mg/bhp-hr at 800,000 miles, an intermediate useful life design target of less than 20 mg/bhp-hr at 435,000 miles, and with further improvements in NO_x emissions reduction over the SET. The improved EAS design will be evaluated as part of the EPA Heavy-duty Diesel Low NO_x Demonstration Program.

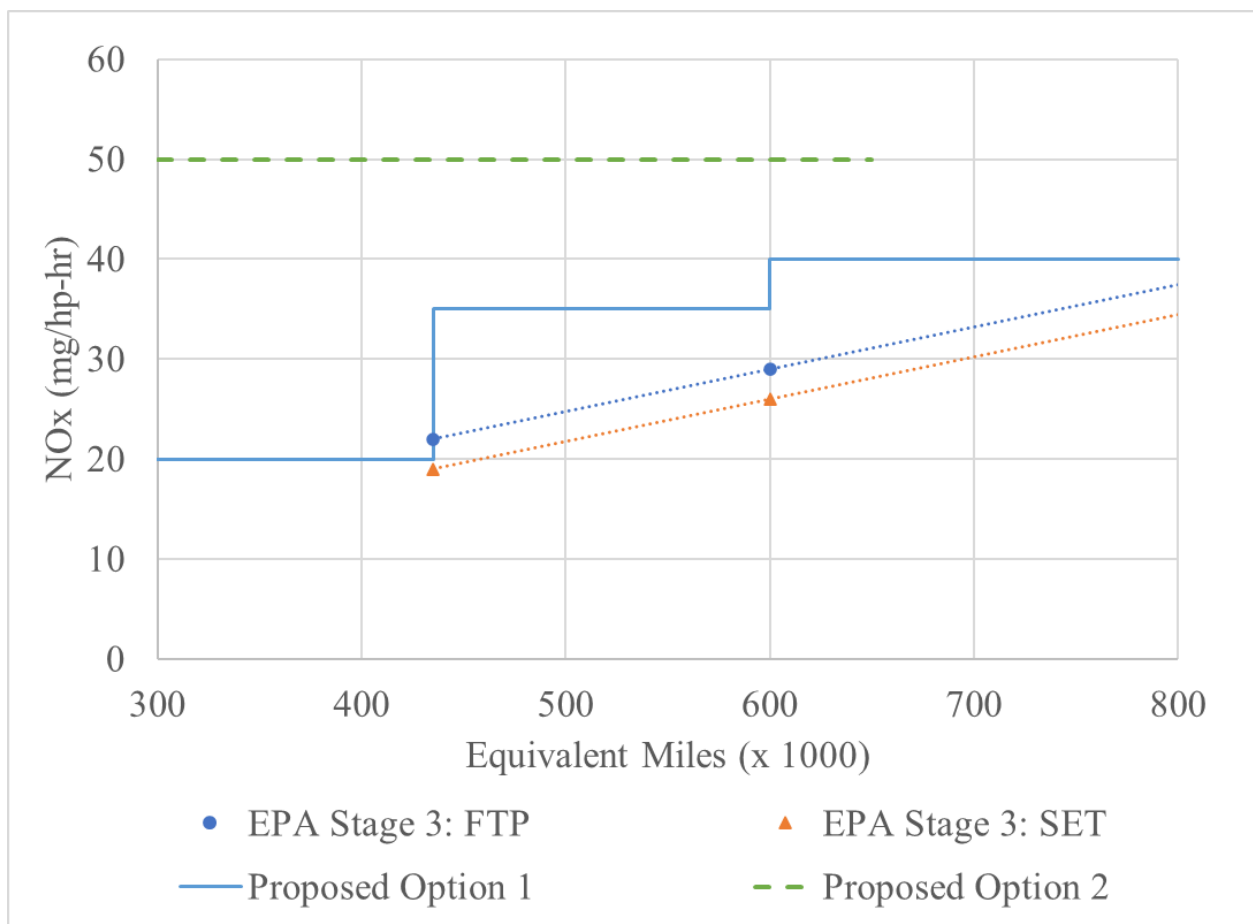


Figure 3-16: FTP composite and SET NO_x emissions results including IRAF for the EPA Stage 3 developmental engine and emissions control system versus equivalent miles of operation.

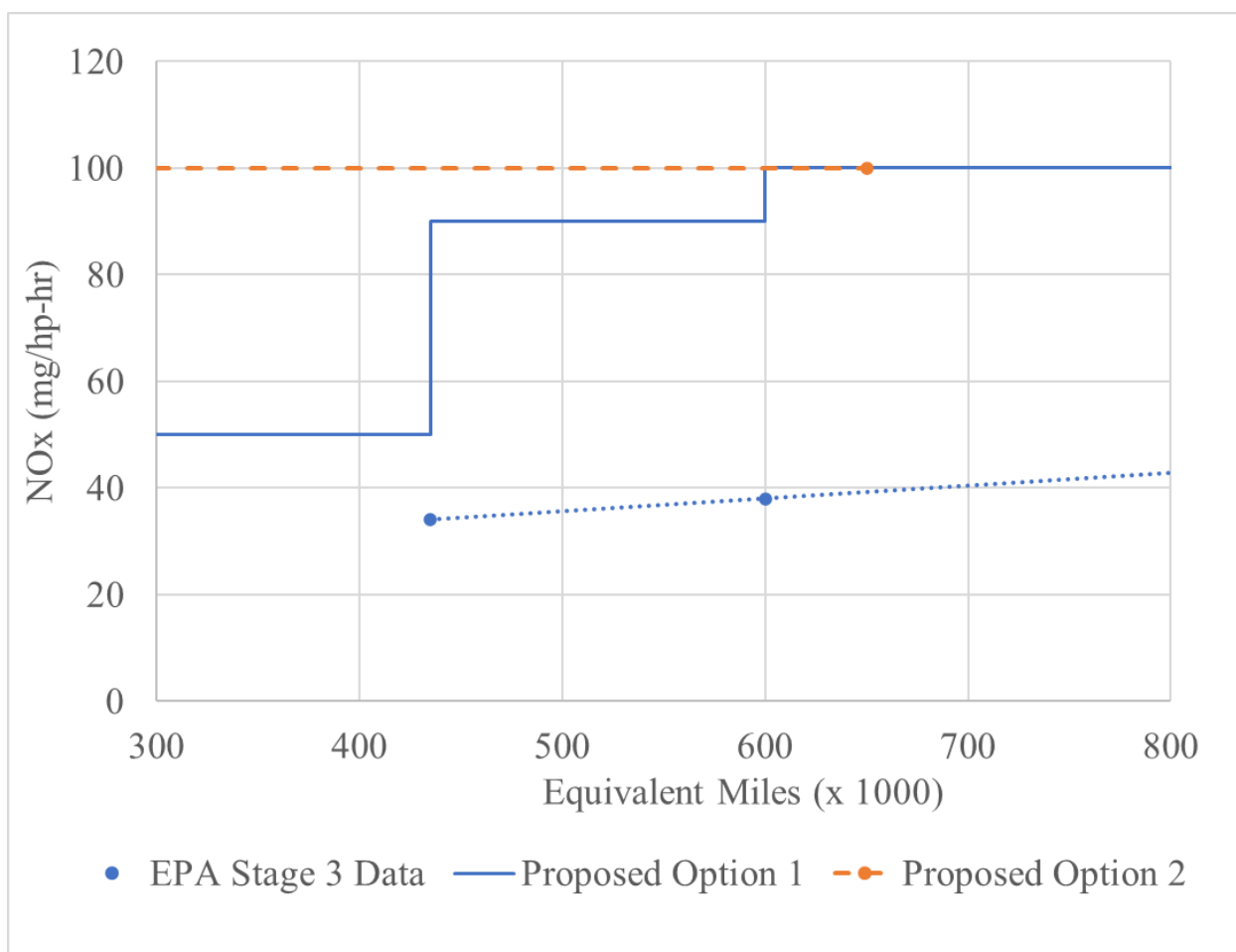


Figure 3-17: LLC NO_x emissions results including IRAF for the EPA Stage 3 developmental engine and emissions control system versus equivalent miles of operation.

EPA will continue to evaluate EAS durability via accelerated aging of advanced emissions control systems. When taking into consideration the proposed Option 1 longer useful life (UL) and the anticipated additional degradation in SCR NO_x reduction between 600,000 miles and 800,000 miles, when taking lead time into consideration to 2027 and 2031, the proposed Option 1 MY 2031 and later emissions standards of 40 mg/hp-hr for FTP composite and SET, 100 mg/hp-hr for the LLC, and the respective off-cycle standards are feasible at a useful life of 800,000 miles beginning in MY 2031.

3.1.4 GHG Impacts

The combination of active and passive thermal management anticipated for meeting the proposed standards can be designed and developed in a manner that does not pose an additional burden for meeting the heavy-duty engine GHG standards in 40 CFR 1036.108 or the heavy-duty vehicles GHG standards in 40 CFR 1037 Subpart B. As described in section 3.1.1.1, the design

and calibration of the CARB Stage 3 system achieved significant NO_x reductions that were GHG neutral. The system design and calibration strategy of that system took advantage of GHG improvements at light-load conditions from CDA and calibration changes at higher load conditions (e.g., injection timing) that approximately offset the impact of increased backpressure from the additional SCR catalyst volume.

3.1.5 Technology Cost

The final program is based on the need to obtain significant emissions reductions from the heavy-duty transportation sector, and the recognition that there are technically feasible, cost effective technologies to achieve such reductions in the 2027-2031 timeframe at reasonable cost per vehicle, with no compromise to vehicle utility or safety. As in many prior mobile source rulemakings, the decision on what standard to set is largely based on the effectiveness of the emissions control technology, the cost (both per manufacturer and per vehicle) and other impacts of implementing the technology, and the lead time needed for manufacturers to employ the control technology. EPA also considered the need for reductions of greenhouse gases, the degree of reductions achieved by the standards, and the impacts of the standards in terms of costs, quantified and unquantified benefits, safety, and other impacts. The availability of technology to achieve reductions and the cost and other aspects of this technology are therefore a central focus of this rulemaking.

3.1.5.1 Heavy-duty Diesel Exhaust Aftertreatment System (EAS) Costs

Costs for baseline MY2019 EAS were estimated primarily based upon cost data published by Dallman et al.¹⁴² combined with manufacturer's technical descriptions of EAS components that were submitted as part of engine certification packages for MY2019. Manufacturer's data was then combined into projected-sales-weighted averages for diesel engines by primary intended service class (Light HDE, Medium HDE, and Heavy HDE) in order to account for diesel EAS system differences by HDE category and to protect any data for individual EAS system component specifications claimed as confidential business information. Projected-sales-weighted average engine displacements, EAS component sizing, DOC and CDPF PGM loadings, and other specifications are shown in Table 3-21 for all HDE categories except urban buses. The small number of manufacturers producing engines for urban buses raised a possibility that reverse engineering of sales-weighted-average data could occur and thus derivation of more detailed information on individual urban bus EAS specifications. For that reason, component level details for MY2019 urban buses were not included within publicly available data for this analysis, but such details were included within the cost analysis for MY2019 urban bus EAS.¹⁴³ In general, average engine displacement, component sizing, DOC and CDPF PGM loading, and other EAS properties urban bus applications were generally similar to the weighted-average values found for diesel Medium HDE. Most MY2019 Heavy HDE diesel applications used a separate ASC downstream of the SCR, while most MY2019 diesel Light HDE, Medium HDE and urban bus applications used zone-coating of ASC onto the outlet of the SCR substrate. In MY2019, the majority of DPF substrates were made of extruded cordierite, but there were also a significant number of CDPFs made from silicon carbide (SiC) and aluminum titanate (Al₂TiO₅). A sales-weighted-average material cost scaling factor was derived for each engine class to account for the additional cost of SiC and Al₂TiO₅ DPF substrates relative to the cost of cordierite substrates. The scaling factor was applied as a multiplicative correction to the DPF

substrate costs derived from Dallman et al., which had assumed exclusive use of cordierite material for DPF substrates.

Table 3-21: MY2019 average engine displacement and diesel EAS specifications for Light HDE, Medium HDE, and Heavy HDE applications based on projected-sales-weighted-averages from EPA heavy-duty diesel engine certification data.

EAS Components		Light HDE	Medium HDE	Heavy HDE
DOC	Average Engine Displacement (L)	6.65	7.54	13.23
	Displacement-specific Substrate Volume (L/L)	0.56	0.61	0.74
	Pt Loading (g/L)	1.01	0.93	0.73
	Pd Loading (g/L)	1.16	0.35	0.27
CDPF	Displacement-specific Substrate Volume (L/L)	1.31	1.39	1.49
	Material Cost Scaling Factor*	1.10	1.03	1.20
	Pt Loading (g/L)	0.10	0.10	0.09
	Pd Loading (g/L)	0.03	0.03	0.03
SCR	Displacement-specific Substrate Volume (L/L)	2.40	2.11	2.24
ASC*	Displacement-specific Substrate Volume (L/L)	0.43	0.38	0.40
	Pt Loading (g/L)	0.064	0.054	0.077

*ASC was typically zone-coated to the SCR substrate for MY2019 Light HDE and Medium HDE that reported specific details regarding ASC. Use of a separate ASC substrate was more typical for MY2019 Heavy HDE applications that reported specific details regarding ASC.

Catalyst substrate sizes were scaled by engine displacement based on certification data. The scaling of EAS component costs by catalyst size and/or engine displacement and for costs that were approximately constant across different engine platforms (e.g., NO_x and NH₃ sensors) were based upon Dallman et al. for the following components: DOC, DPF, SCR, and ASC substrate costs, washcoating costs, and mounting accessories; scaling and cost of DEF dosing system components including the storage tank, level sensor, heating system, mounting accessories, pump, injector, tubing, dosing control unit (DCU), exhaust decomposition tube/mixer; and other components such as temperature sensors, NO_x sensors, NH₃ sensors and associated electronics. The EPA used costs that differed from Dallman et al. for catalyst substrate canning costs (\$10/L-catalyst-volume) and for SCR combined substrate and wash-coating costs (\$28/L-catalyst-volume). EPA estimates of these costs were based upon direct manufacturing cost data provided by component manufacturers that were claimed as confidential.¹⁴³ PGM cost estimates also differ from Dallman et al. within the EPA analysis. EPA substituted 5-year average commodity prices for PGM. PGM commodity prices were averaged between August 1, 2014 and August 6, 2019.¹⁴⁴ Scaling for DOC, DPF, SCR and ASC by engine displacement was based upon MY2019 HD engine certification data.

Estimated costs and approximate catalyst scaling and volume data for MY2019 DOCs, CDPFs, and SCR systems are shown in Table 3-22, Table 3-23, and Table 3-24, respectively. Total MY2019 EAS costs are summarized in Table 3-25. Note that the costs estimated for MY2019 systems include the improvements described in draft RIA Chapter 1.1.1 that have resulted in substrate size reduction and cost reductions between MY2010 and MY2019. These MY2019 engine and aftertreatment costs estimates are used as the MY2027 baseline cost presented in draft RIA 7.1.1 after conversion to 2017 dollars.

Table 3-22: MY2019 DOC System Costs for Light HDE, Medium HDE, & Heavy HDE Applications.

EPA HD Engine Class	Light HDE	Medium HDE	Heavy HDE	Urban Bus
Sales-weighted average engine displacement (L)	6.65	7.54	13.23	
DOC catalyst volume scaling factor by engine displacement	0.561	0.607	0.744	
Catalyst volume (L)	3.7	4.6	9.8	
Platinum costs	\$ 119	\$ 135	\$ 226	
Palladium costs	\$ 123	\$ 45	\$ 75	
Total PGM Costs	\$ 241	\$ 180	\$ 301	
Substrate costs	\$ 25	\$ 31	\$ 66	
Washcoat	\$ 48	\$ 59	\$ 128	
Total PGMs + substrate + washcoat	\$ 315	\$ 270	\$ 495	
Canning	\$ 37	\$ 46	\$ 98	
Accessories—brackets	\$ 13	\$ 13	\$ 16	
Total direct manufacturing cost (2019 \$):	\$ 365	\$ 329	\$ 610	\$ 327

Table 3-23: MY2019 CDPF System Costs for Engine-dynamometer Certified Light HDE, Medium HDE, Heavy HDE, and Urban Bus Applications.

EPA HD Engine Class	Light HDE	Medium HDE	Heavy HDE	Urban Bus
Sales-weighted average engine displacement (L)	6.65	7.54	13.23	
CDPF volume scaling factor by engine displacement	1.31	1.39	1.49	
Catalyst volume (L)	8.7	10.5	19.7	
Platinum	\$ 28	\$ 34	\$ 56	
Palladium	\$ 7	\$ 7	\$ 19	
Total PGMs	\$ 35	\$ 42	\$ 74	
Substrate	\$ 201	\$ 241	\$ 454	
Adjustment for substrate material cost for alternatives to cordierite (SiC, Al-titanate)	\$ 221	\$ 248	\$ 546	
Washcoat	\$ 87	\$ 105	\$ 197	
Total PGMs + substrate + washcoat	\$ 344	\$ 395	\$ 817	
Canning	\$ 87	\$ 105	\$ 197	
Accessories—brackets	\$ 13	\$ 13	\$ 16	
Active regeneration system (ΔP sensor, piping, electronic hardware)	\$ 81	\$ 81	\$ 81	
Total direct manufacturing cost (2019 \$):	\$ 525	\$ 594	\$ 1,112	\$ 591

Table 3-24: MY2019 SCR System Costs for Engine-dynamometer Certified Light HDE, Medium HDE, Heavy HDE, and Urban Bus Applications.

EPA HD Engine Class	Light HDE	Medium HDE	Heavy HDE	Urban Bus
Sales-weighted average engine displacement (L)	6.65	7.54	13.23	
SCR catalyst volume scaling factor by engine displacement	2.40	2.11	2.24	
SCR Catalyst volume (L)	15.95	15.90	29.65	
SCR substrate and washcoat costs	\$ 459	\$ 456	\$ 830	
SCR canning costs	\$ 164	\$ 163	\$ 297	
SCR Catalyst Cost	\$ 622	\$ 619	\$ 1,127	\$ 641
ASC volume scaling factor by engine displacement	0.43	0.38	0.40	
ASC Catalyst Volume (L)	2.84	2.89	5.30	
ASC Substrate Canning Costs	N/A*	N/A*	\$ 26.51	
ASC Substrate Costs	N/A*	N/A*	\$ 35.52	
ASC Washcoating Costs	N/A*	N/A*	\$ 68.92	
Pt Costs	\$ 5.72	\$ 4.92	\$ 12.88	
ASC Cost	\$ 5.72	\$ 4.92	\$ 143.84	\$ 4.66
Urea tank volume (L)	39.9	45.2	79.4	
Urea tank cost	\$ 210	\$ 228	\$ 332	
Urea level sensor	\$ 48	\$ 48	\$ 48	
Urea tank accessories (brackets, bolts, spacers)	\$ 37	\$ 38	\$ 42	
Urea pump	\$ 78	\$ 81	\$ 98	
Urea injector	\$ 52	\$ 54	\$ 65	
Tubing, stainless steel	\$ 109	\$ 124	\$ 217	
Urea injection mounting parts (brackets, bolts, gaskets, spacers, tubing connectors)	\$ 30	\$ 32	\$ 42	
Urea heating system, 200 W, 12 V DC	\$ 60	\$ 62	\$ 75	
Temperature sensor (4 per system)	\$ 84	\$ 84	\$ 84	
Decomp/mixer	\$ 39	\$ 39	\$ 53	
Dosing control unit	\$ 200	\$ 200	\$ 200	
NO _x sensor cost (2 per system)	\$ 340	\$ 340	\$ 340	
Total urea system	\$ 1,287	\$ 1,330	\$ 1,595	
Total direct manufacturing cost – short term (2019 \$):	\$ 1,915	\$ 1,954	\$ 2,866	\$ 2,011

*ASC assumed to be zone-coated onto SCR substrate for Light HDE & Medium HDE. Use of a separate ASC substrate assumed for Heavy HDE applications.

Table 3-25: Summary of MY2019 EAS Costs for Engine-dynamometer Certified Light HDE, Medium HDE, Heavy HDE, and Urban Bus Applications.

EPA HD Engine Class	Light HDE	Medium HDE	Heavy HDE	Urban Bus
Sales-weighted average engine displacement (L)	6.65	7.54	13.23	8.26
DOC - total direct manufacturing cost – short term (2019 \$):	\$ 365	\$ 329	\$ 610	\$ 327
CDPF - total direct manufacturing cost – short term (2019 \$):	\$ 525	\$ 594	\$ 1,112	\$ 591
SCR - Total direct manufacturing cost – short term (2019 \$):	\$ 1,915	\$ 1,954	\$ 2,866	\$ 2,011
Total EAS costs (2019 \$)	\$ 2,804	\$ 2,877	\$ 4,587	\$ 2,929

The analytical approach developed for estimating MY2019 costs was also used for estimating the costs of proposed Option 1 MY2027-2030, MY2031 and later, and the proposed Option 2 EAS (see Table 3-26 and Table 3-27). For the proposed Option 1 and 2 standards we assumed the same aftertreatment technology. For analyzing the costs, both SCR catalyst volume and DOC, DPF and SCR canning costs were increased in part to account for greater useful life requirements. For example, Heavy HDE total SCR+ASC catalyst substrate volume increased from 2.64 times engine displacement for MY2019 systems to 3.0 times engine displacement and 4.0 times engine displacement for the analysis of the proposed Option 1 and 2 standards^{MM}. The SCR catalyst volume and urea injection systems also reflect implementation of dual-SCR in order to meet more stringent NO_x emissions standards both in-use and over regulatory engine-dynamometer test cycles. The proposed Option 1 and 2 standards include addition of an NH₃ sensor, one additional NO_x sensor, and the addition of a fuel dosing system located downstream of the light-off SCR and upstream of the DOC. The system costs for the proposed Option 1 and 2 standards assume the use of zone-coated ASC for all HD diesel engine classes. We would also anticipate the use of either high-porosity or thin-wall substrates for both the light-off SCR and DOC for the proposed Option 1 and 2 standards. The change in bulk density would reduce substrate mass and improve catalyst warmup. The scaling of individual EAS components for the proposed Option 1 and 2 standards represent the upper bounds of component sizing for developmental EAS systems designed for the EPA Heavy-duty Diesel Low NO_x Demonstration Program (see Chapter 3.1.1.2). Total SCR volume increases by approximately 79% relative to MY2019 systems. We assume the use of light-off SCR within the cost estimates for either the proposed Option 1 and 2 standards, with total SCR catalyst volume split between the light-off SCR and the downstream SCR. The light-off SCR is estimated to account for approximately 25% of total SCR volume, with the downstream SCR accounting for the remaining 75% of SCR volume. We assume the use of a single pump for both urea dosing systems within EAS using light-off SCR. The cost of substrate canning for the DOC and DPF was increased within the cost analyses for the proposed Option 1 and 2 standards in order to account for improvements to substrate matting and other materials necessary for the longer useful life requirements.

^{MM} Note that MY2019 Heavy HDE system costs assume the use of separate SCR and ASC substrates, while the cost analysis for the proposed Option 1 and 2 standards are based upon ASC zone-coated to the final 2" of SCR substrate volume. Other engine categories assumed the use of zone-coated ASC for MY2019 and the proposed Option 1 and 2 standards.

Table 3-26: Proposed Option 1 and 2 SCR System Costs for Engine-dynamometer Certified Light HDE, Medium HDE, Heavy HDE, and Urban Bus Applications

EPA HD Engine Class	Light HDE	Medium HDE	Heavy HDE	Urban Bus
Sales-weighted average engine displacement (L)	6.65	7.54	13.23	
SCR1 catalyst volume scaling factor by engine displacement	1.07	0.940	1.00	
SCR2 catalyst volume scaling factor by engine displacement	3.21	2.83	3.00	
SCR1 catalyst volume (L)*	7.1	7.1	13.2	
SCR2 catalyst volume (L)*	21.4	21.3	39.7	
Total SCR catalyst volume scaling factor by engine displacement	4.3	3.8	4.0	
Total SCR catalyst volume (L)*	28.5	28.4	53.0	
SCR1 Substrate and washcoat cost	\$ 199	\$ 199	\$ 370	
SCR1 canning cost	\$ 89	\$ 89	\$ 165	
SCR2 substrate and washcoat cost	\$ 610	\$ 607	\$ 1,124	
SCR2 canning cost	\$ 272	\$ 271	\$ 502	
Cost for canning improvements for longer FUL	\$ 90	\$ 90	\$ 167	
SCR Catalyst Cost	\$ 1,261	\$ 1,255	\$ 2,328	\$ 1,303
ASC1 volume scaling factor by engine displacement	0.190	0.171	0.179	
ASC1 Catalyst Volume (zone-coated) (L)†	1.27	1.29	2.36	
ASC2 volume scaling factor by engine displacement	0.427	0.384	0.401	
ASC2 Catalyst Volume (zone-coated) (L)†	2.84	2.89	5.30	
ASC1 Pt Costs	\$ 2.55	\$ 2.20	\$ 5.75	
ASC2 Pt Costs	\$ 5.72	\$ 4.92	\$ 12.88	
ASC Cost	\$ 8.28	\$ 7.12	\$ 18.63	\$ 6.73
Urea tank volume	39.9	45.2	79.4	
Urea tank cost	\$ 210	\$ 228	\$ 332	
Urea level sensor	\$ 48	\$ 48	\$ 48	
Urea tank accessories (brackets, bolts, spacers)	\$ 37	\$ 38	\$ 42	
Urea pump	\$ 78	\$ 81	\$ 98	
Urea-injector-1 (heated dosing)	\$ 78	\$ 81	\$ 98	
Urea-injector-2	\$ 52	\$ 54	\$ 65	
Tubing, stainless steel	\$ 153	\$ 174	\$ 304	
Urea injection mounting parts (brackets, bolts, gaskets, spacers, tubing connectors)	\$ 59	\$ 63	\$ 83	
Urea heating system, 200 W, 12 V DC (SCR1-only)	\$ 60	\$ 62	\$ 75	
Temperature sensor (4 per system)	\$ 105	\$ 105	\$ 105	
Mixers	\$ 89	\$ 89	\$ 121	
Dosing control unit	\$ 220	\$ 220	\$ 220	
NO _x sensors (3 per system)	\$ 510	\$ 510	\$ 510	
NH ₃ sensor	\$ 170	\$ 170	\$ 170	
Total urea system	\$ 1,869	\$ 1,924	\$ 2,272	\$ 1,968
Total direct manufacturing cost – short term (2019 \$):	\$ 3,139	\$ 3,187	\$ 4,618	\$ 3,278
Incremental SCR Cost from 2019 to 2031 (2019 \$):	\$ 1,224	\$ 1,233	\$ 1,752	\$ 1,267

*Total SCR volume includes 2" of zone-coated ASC onto the outlet of SCR1 and SCR2

†ASC volume is included within total SCR volume

Table 3-27: Summary of proposed Option 1 and 2 EAS Costs* for Engine-dynamometer Certified Light HDE, Medium HDE, Heavy HDE, and Urban Bus Applications.

EPA HD Engine Class	Light HDE	Medium HDE	Heavy HDE	Urban Bus
Sales-weighted average engine displacement (L)	6.65	7.54	13.23	
DOC - total direct manufacturing cost (2019 \$):	\$ 365	\$ 329	\$ 610	
CDPF - total direct manufacturing cost (2019 \$):	\$ 525	\$ 594	\$ 1,112	
Increased DOC+CDPF Canning Costs for longer FUL:	\$ 31	\$ 38	\$ 74	
HC dosing system (2019 \$):	\$ 225	\$ 225	\$ 225	
SCR - Total direct manufacturing cost (2019 \$):	\$ 3,139	\$ 3,187	\$ 4,618	
Total EAS costs (2019 \$)	\$ 4,285	\$ 4,373	\$ 6,638	\$ 4,460
Total EAS Incremental Cost from 2019 to 2027 (2019 \$):	\$ 1,481	\$ 1,495	\$ 2,051	\$ 1,531

Table Notes:

* Proposed Option 1 and 2 standards were both assumed to use comparable EAS system designs, which includes increased DOC/DPF costs to account for increased useful life requirements and use of dual SCR systems with heated urea injection for the light-off SCR position.

3.1.5.2 Cost Teardown Studies

Publicly available information regarding the engineering cost of new engine and vehicle technologies is a subject of considerable interest. A number of cost analyses in the past few years have utilized supplier price quotes on designated bills of materials as a methodology for estimating the increased cost of vehicle improvements. In general, the actual price quotes provided by suppliers were claimed as confidential business information and have not been released. In addition, supplier price quotes are typically provided for near-term (e.g., 3-5 years) estimation, as these are how contracts between OEMs and suppliers are typically written.

This methodology for estimating technology costs to the consumer has several deficiencies. The lack of transparency regarding the data provided by suppliers does not provide an opportunity for a full public evaluation of the information. In addition, these near-term price quotes may not be appropriate for estimating the long-term costs of a regulatory program implemented in the future. A large fraction of the near-term fixed costs may be recovered and no longer part of the costs to consumers. EPA is required to evaluate the near- and long-term costs to consumers that may result from proposed regulatory requirements. To effectively estimate and communicate those costs, EPA requires a transparent engineering analysis that separates direct and indirect costs for each major component in the technologies it projects will be implemented to meet the new requirements.

EPA previously directed contractual work to develop an analytical methodology that is based on technical knowledge of the engineering, design, and development of advanced vehicle technology components, systems, and subsystems. In addition, the previous contractual work performed pilot studies to demonstrate the methodology on representative vehicle categories.

A key objective for these studies was transparency-- methodologies, assumptions, and inputs well-documented, clearly explained, and releasable to the public, except to the extent that those essential inputs included information claimed as confidential.

3.1.5.2.1 EPA HDE Cylinder Deactivation and Variable Geometry Valvetrain Teardown Cost Study

The cost of CDA for Light HDE, Medium HDE, Heavy HDE, and Urban Buses was estimated based upon a detailed, tear-down study of heavy-duty diesel valvetrains, the Heavy-Duty Engine Valvetrain Technology Cost Assessment (or “FEV Valvetrain Study”).¹⁴⁵ The study was conducted by FEV North America, Inc. under a contract with EPA^{NN} and was submitted to an independent peer review.^{146, 147} The FEV Valvetrain Study investigated design modifications to a production engine cylinder head from the Cummins X15 engine. These design modifications allowed the addition of a variable-geometry valvetrain system in one of two different configurations. One configuration was implementation of individual CDA with an integrated exhaust brake. The other configuration was implementation of late intake valve closing (LIVC). The final objective was to evaluate the incremental cost of CDA and LIVC hardware as two distinct technology packages.

The cost of the CDA and LIVC technology packages were evaluated relative to a baseline valvetrain technology represented by a 2019 Cummins X15 engine. FEV also investigated other valvetrain designs used by diesel HDE in order to develop fleet average per-cylinder costs for these valvetrain technologies. The baseline and new technology packages were required to have similar overall performance with respect to service life and other functional objectives. For this study, estimates for direct, indirect, and operating costs other than fuel costs were considered. Table 3-1 shows estimated costs for application of CDA to diesel HDE based on costs derived from the FEV study. For purposes of EPA’s cost analysis of CDA applied to diesel HDE, Light HDE costs were based on application of CDA hardware to 8-cylinder engines while Medium HDE, Heavy HDE, and Urban Bus costs were based on application of CDA hardware to 6-cylinder engines. Both costs, airflow control, and thermal management appeared to roughly comparable for both CDA and LIVC within the analysis, with some advantages with respect to higher BMEP CO₂ reduction for LIVC at slightly higher cost. For more details regarding the FEV Valvetrain Study, please refer to the final report for the study within the docket for this rule. The costs for CDA were assumed as the cost for active thermal management via valvetrain system improvements within EPA’s costs for diesel HDE for the proposed Option 1 and 2 standards.

Table 3-28: Summary of CDA Costs from Teardown Study

EPA HD Engine Class	Light HDE	Medium HDE	Heavy HDE	Urban Bus
CDA Valvetrain Hardware - Tier 1 Supplier Cost to Manufacturer (2019 \$):	204.16	153.12	214.56	153.12

3.1.5.2.2 EPA Advanced EAS Teardown Cost Study

EPA also sponsored an additional study to examine in detail an advanced heavy-duty diesel EAS technology package utilizing a dual-SCR system with heated dosing for the light-off SCR and capable of approximately 90% NO_x reduction relative to post-2010 heavy-duty diesel emission control systems, the Heavy-Duty Vehicles Aftertreatment Systems Cost Assessment (FEV EAS Study)¹⁴⁸. As with the valvetrain study, this was also conducted by FEV North

^{NN} U.S. EPA Contract No. 68HERC19D0008, Task Order No. 68HERH20F0041.

America, Inc. The FEV EAS Study was not completed in time for inclusion within the cost analysis for the proposed standards but our intention is to update EAS costs for the final rule based upon this study. The costs associated with the advanced EAS technology packages were evaluated relative to a baseline OE (MY2018) EAS technology representative of the current state of design. The costs from the FEV EAS Study are summarized within Table 3-29. The incremental costs for the advanced system were approximately \$108 to 316 higher for the FEV Study relative to the costs for systems meeting the proposed standards from the EPA analysis presented Chapter 3.1.1.3. For details regarding the FEV EAS Study, please refer to the final report for the study within the docket for this rule.¹⁴⁸

Table 3-29: Summary of Costs from the FEV Exhaust Aftertreatment System Study

EPA HD Engine Class	Light HDE	Medium HDE	Heavy HDE	Urban Bus
Total MY2019 EAS costs estimated by the FEV EAS Study (2019 \$)	\$2,698.69	\$2,649.28	\$3,934.77	\$2,729.61
Total MY2027 and later EAS costs estimated by the FEV EAS Study (2019 \$)	\$4,494.79	\$4,350.83	\$6,093.82	\$4,464.79
Total EAS Incremental Cost from 2019 to 2027 and later costs estimated by FEV EAS Study (2019 \$):	\$1,796.10	\$1,701.55	\$2,159.05	\$1,735.18
Difference in Incremental Cost for FEV EAS Study relative to the EPA Analysis in Chapter 3.1.1.3, Table 3-27	\$315.56	\$206.06	\$107.89	\$204.39

Note: Costs from the FEV Study were originally calculated on a 2020\$ basis and were converted to a 2019\$ basis for this table to allow direct comparison with other costs within this draft RIA. Costs for the advanced system studied by FEV would be equally applicable to the costs of systems designed to meet the proposed Option 1 and 2 standards.

3.1.5.3 Closed Crankcase Systems Technology Costs

We project that this proposed requirement to close the crankcase on turbocharged engines that do not have closed crankcase systems already will force manufacturers to rely on engineered closed crankcase ventilation systems that filter oil from the blow-by gases prior to routing them into either the engine intake or the exhaust system downstream of the turbocharger but upstream of the exhaust aftertreatment system. We have estimated the initial cost of these systems to be approximately \$41 (2002\$).¹⁴⁹ To estimate the baseline cost, we multiplied \$41 (2002\$) by the percentage of engines that already have closed crankcase systems, which resulted in a baseline cost of \$13 (2002\$). We estimated the percentage of engines that already have closed crankcase systems at 32.5%, based on the certification data. For our cost analysis, we converted these estimates to 2017 dollars, which resulted in \$18 (2017\$) for the baseline cost and the same cost of \$37 to implement closed crankcases in the remaining CI engines for our proposed Option 1 and 2 standards.

3.2 Spark-Ignition Technology Feasibility

3.2.1 Baseline Technology Effectiveness

3.2.1.1 EPA Baseline Real World Test Program for Exhaust Emissions

In 2018 EPA evaluated heavy-duty gasoline Class 3 and 4 vehicles from three different manufacturers to better understand the state of criteria pollutant control technology incorporated on gasoline engines used in these applications¹⁵⁰. Evaluations were conducted using laboratory chassis dynamometer testing and real-world Portable Emissions Measurement System (PEMS) testing.

Most chassis-certified heavy-duty vehicles are subject to EPA's light-duty Tier 3 program and these vehicles have adopted many of the emissions technologies from their light-duty counterparts (79 FR 23414, April 28, 2014). To meet these Tier 3 emission standards, manufacturers have been required to reduce the time needed for the catalyst to reach operational temperature by implementing cold-start calibration strategies to reduce light-off time, and they have also moved the catalyst closer to the engine. Manufacturers have not widely adopted the same strategies for their heavy-duty engine-certified products, and purpose of this test program was to observe differences between emissions performance for technologies that are available in the market today and establish a baseline to evaluate the performance of advanced technologies to further reduce criteria emissions.

3.2.1.1.1 Baseline Vehicles Tested

Three vehicles were chosen for evaluation based on majority market share. Two vehicles, Class 4 (GVWR 14,001 – 16,000 pounds), with powertrains produce by General Motors (GM) and Ford respectively, utilized engines that that were dyno certified. The third vehicle, produced by Fiat Chrysler Automobiles (FCA), was a Class 3 (GVWR 10,001 – 14,000 pounds) chassis certified truck that meets the Federal HDV2 Tier 3 Bin 570 standards, and has the same powertrain (engine and transmission) that FCA uses in their Class 4 engine certified trucks. The FCA test article had comparable gross combined vehicle weight (GCWR) as the Class 4 vehicles tested but employed aftertreatment technology tailored for Tier 3 chassis certification. Table 3-30 lists the major specifications of the three vehicle/powertrain combinations considered in this study.

Table 3-30: Heavy-Duty Gasoline Vehicle Emissions Investigation Vehicle Specifications

	G.M.	Ford	FCA
Configuration	Box Truck	Box Truck	Pickup
Certification	HDGE	HDGE	Tier 3 Bin 570
Model Year	2015	2016	2017
Odometer	48,000	37,000	43,000
Eng. System	NA/PFI/TWC	NA/PFI/TWC	NA/PFI/EGR/TWC
Displacement	6.0L V8	6.8L V10	6.4L V8
Power	297 hp @ 4,300 rpm	305 hp @ 4,250 rpm	410 hp @ 4,600 rpm
Torque	372 lbft @ 4,000 rpm	420 lbft @ 3,250 rpm	429 lbft @ 4,000 rpm
Transmission	6 spd Auto	6 spd Auto	6 spd Auto
GVWR (lbs)	14,500	14,500	13,300
GCWR (lbs)	20,500	22,000	19,900

3.2.1.1.2 Baseline Tests Performed

As previously stated, two of the vehicles tested were equipped with dyno certified engines for use in vehicles with a GVWR over 14,000 lbs while the third vehicle was a chassis certified HDV2. These vehicles were chosen as the engines represent the bulk of the HD SI vehicle market. The lighter HDV2 vehicle was chosen because of its chassis certification resulting in its aftertreatment system more closely resembling what is commonly found on Tier III light-duty vehicle.

The purpose of this particular program was to investigate the current state of emissions performance of HD SI engine criteria emissions performance. Because cold start emissions are not strongly emphasized in HD SI engine test, manufacturers generally locate three-way catalysts for exhaust aftertreatment significantly downstream from the exhaust manifold. Because chassis certification places a higher weighting on cold start results, the HDV2 vehicle we tested was designed to reach light-off temperature sooner, and its catalyst were significantly closer to the exhaust manifold than they would be in an engine certified configuration. Table 3-31 shows the average distance, in meters, from the outlet of the exhaust manifold to the front face of the catalyst substrate. Where two catalyst are used, one for each bank of cylinders on a V8 or V10 engine, the value represents the average of the two distances.

Table 3-31: Average distance from exhaust manifold to catalyst.

Manufacturer	Average Exhaust Manifold to Catalyst Distance (meters)
G.M./Isuzu	2
Ford	1.6
FCA	0.9

Location of the catalyst relative to the exhaust manifold has a significant impact on overall tailpipe emissions, as a shorter distance will enable more rapid heating and catalytic reduction after cold start, and a longer distance reduces the maximum catalyst temperature during high

load operation, protecting the washcoat from thermal degradation. The assumptions investigated in this test program were as follows:

1. Gasoline stoichiometric operation and advanced three-way catalyst can provide a high level of efficiency and nearly zero warmed-up emissions rates.
2. Vehicle weights and loads can drive high exhaust gas temperatures.
3. High exhaust gas temperatures can lead to need for fuel enrichment, to protect engine components and the catalyst.
4. Location of the catalyst is partially dictated by exhaust gas temperature.
5. Rearward catalyst locations can hinder catalyst light-off as well as performance under extended low-load operation.

3.2.1.1.3 On Road PEMS testing

Each vehicle was subject to real world emissions testing and driven during the workday on several routes EPA uses to collect real world drive emissions. During these drive evaluations, each vehicle was equipped with a portable emissions measurement system (PEMS). These PEMS unit are CFR 1065 compliant, with independent emissions measurement for CO, CO₂, NO, NO₂ and NMHC emissions. Additionally, data is collected for exhaust flow, GPS location, environmental conditions and selected CAN signals via the vehicles OBD connector. Temperatures within the exhaust system were also recorded during these drive cycles: exhaust gas temperature at the exhaust manifold outlet and catalyst inlet cone, and catalyst substrate temperature 1-inch reward of the front face of the catalyst.

Where possible, each vehicle was tested across a range of test weights: curb weight plus instrumentation; 90% GVRW (gross vehicle weight rating); and where possible, 90% GCWR (gross combined weight rating, which represents truck and trailer weight.) Each real-world drive schedule was on public roads and subject to varying traffic loads dependent on the time of day as well as all variation as a result of traffic control. When possible, each vehicle was driven on each route on three different days. Table 3-32 describes the routes used for collection of real-world drive emissions.

Table 3-32: Description of Real-world PEMS Testing Routes

Route	Distance (mi)	Avg. Speed (mph)	Description
A	7	21	Low speed, light load
B	12	24	Medium speed, short duration high load
C	32	45	High speed, short duration high load
D	84	63	High speed, sustained high load
E	30	40	Medium speed, high load

3.2.1.1.4 Laboratory Chassis Testing

The vehicles described previously were tested at EPA's Ann Arbor, MI National Vehicle and Fuel Emissions Laboratory (NVFEL). Laboratory testing was conducted to remove the

variability inherent in real world PEMS testing such as engine coolant start temperature, load and traffic conditions. Both the Ford and the GM/Isuzu vehicles engines were, as previously noted, certified to HD engine standards on an engine dynamometer, while the FCA vehicle was chassis certified as a complete vehicle to HDV2 standards. By testing engine certified vehicles on the chassis rolls, it was possible to highlight the emphasis each type of certification places on the vehicle, engine, and catalyst system design considerations. For testing purposes, each vehicle was subjected to both cold start and hot start testing using Tier 3 (10% ethanol) certification fuel. Each vehicle was tested at an estimated test weight (ETW) condition that represented the vehicle's curb weight plus the weight of instrumentation, as well as 90% GVWR condition. Because the FCA vehicle was certified as a Tier 3 HDV2 it was tested at curb weight plus 1/2 payload. Table 3-33 are the test weight and dynamometer coefficients used for this testing.

Table 3-33: Test weights and dynamometer coefficients used for NVFEL HD gasoline testing.

	Test #1	Test #2	Test #3 (FCA only)
ETW (lbs)	9,320	14,000	11,000
Target A (lbf)	123.23	87.54	87.54
Target B (lbf/mph)	0	1.399	1.399
Target C (lbf/mph ²)	0.0917	0.1215	0.1215

Each vehicle-engine combination was subject to four distinct test cycles, two of which were cold starts, with the remaining two warm starts. Each test cycle is described below:

Cold Start, Federal Test Procedure (FTP-75). The FTP-75 is used for emissions certification and fuel economy testing of light-duty vehicles in the United States. The FTP-75 consists of three phases; a cold transient phase (ambient temperature 20-30 deg. C), a stabilized phase and a hot start transient phase. The FTP-75 was used to understand the differences in cold start strategies and catalyst architectures resulting from the differences in certification testing between HD dynamometer and HD chassis. Figure 3-18 illustrates the FTP-75 three-phase test cycle.

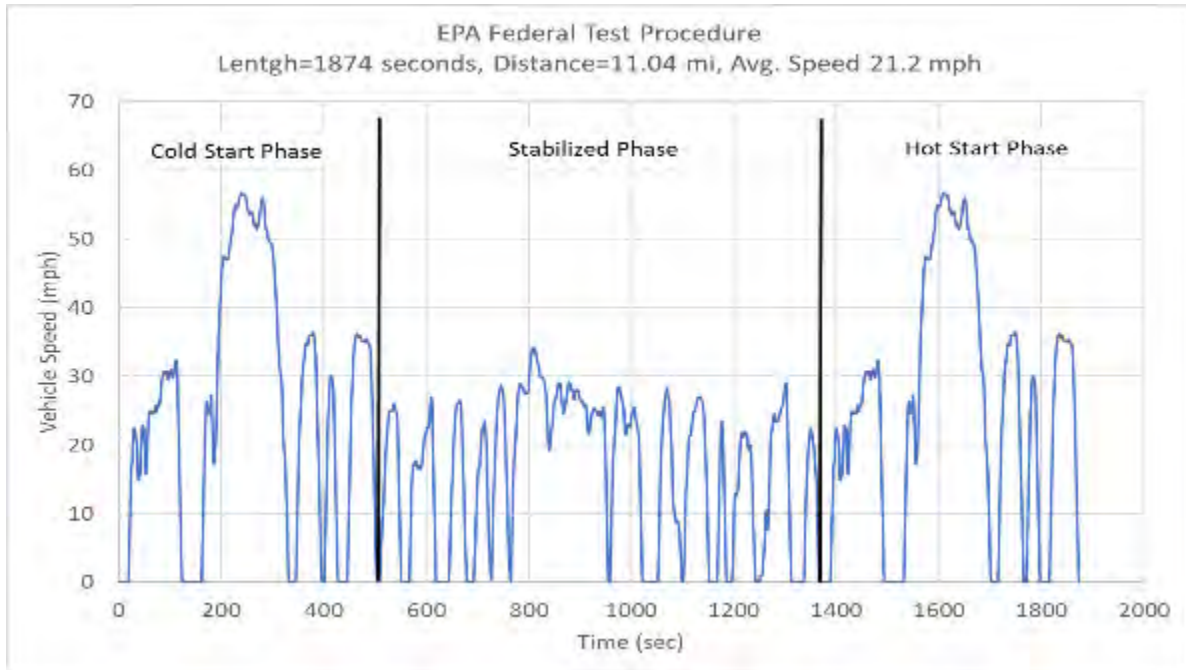


Figure 3-18: FTP-75, Cold start three phase test cycle

Highway Fuel Economy Driving Schedule (HWFE). This cycle was run as double HWFE cycles, where the first cycle is used as a warmup, or prep, and there is no emissions sampling or recording during. This cycle was chosen to compare emissions performance under simulated urban driving conditions, and Figure 3-19 illustrates the HFE test cycle that was used.

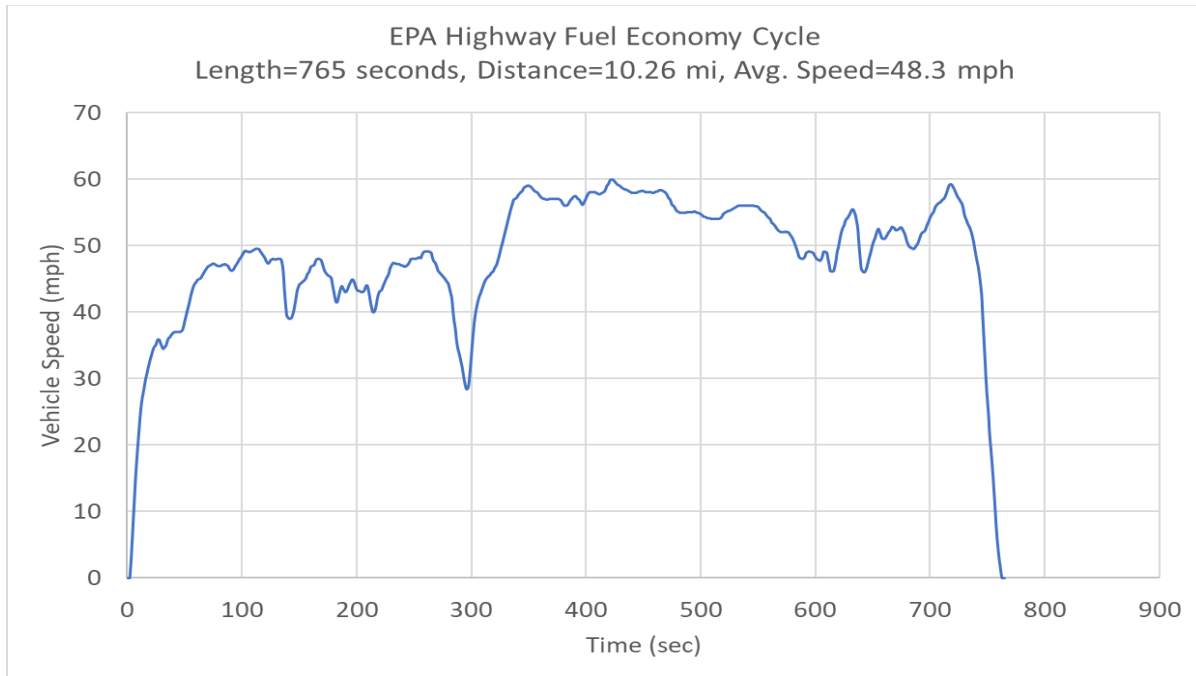


Figure 3-19: EPA Highway Fuel Economy Cycle

Phase LA92 drive cycle. The LA92 drive cycle is a CARB-developed dynamometer schedule. The LA92 was originally developed as an inventory improvement tool, and compared to the FTP, it has a higher top speed, a higher average speed, less idle time, fewer stops per mile, and higher rates of acceleration. For the purposes of this comparison testing, two back-to-back LA 92 cycles were utilized, doubling the distance and creating a 4-phase test. Phase 1, a warm start, was followed by a warmed-up Phase 2, followed by a 30-minute engine off soak. Phase 3 is a warm start after the engine off soak and is a repeat of the earlier Phase 1 drive cycle, and Phase 4 is a repeat of Phase 2.

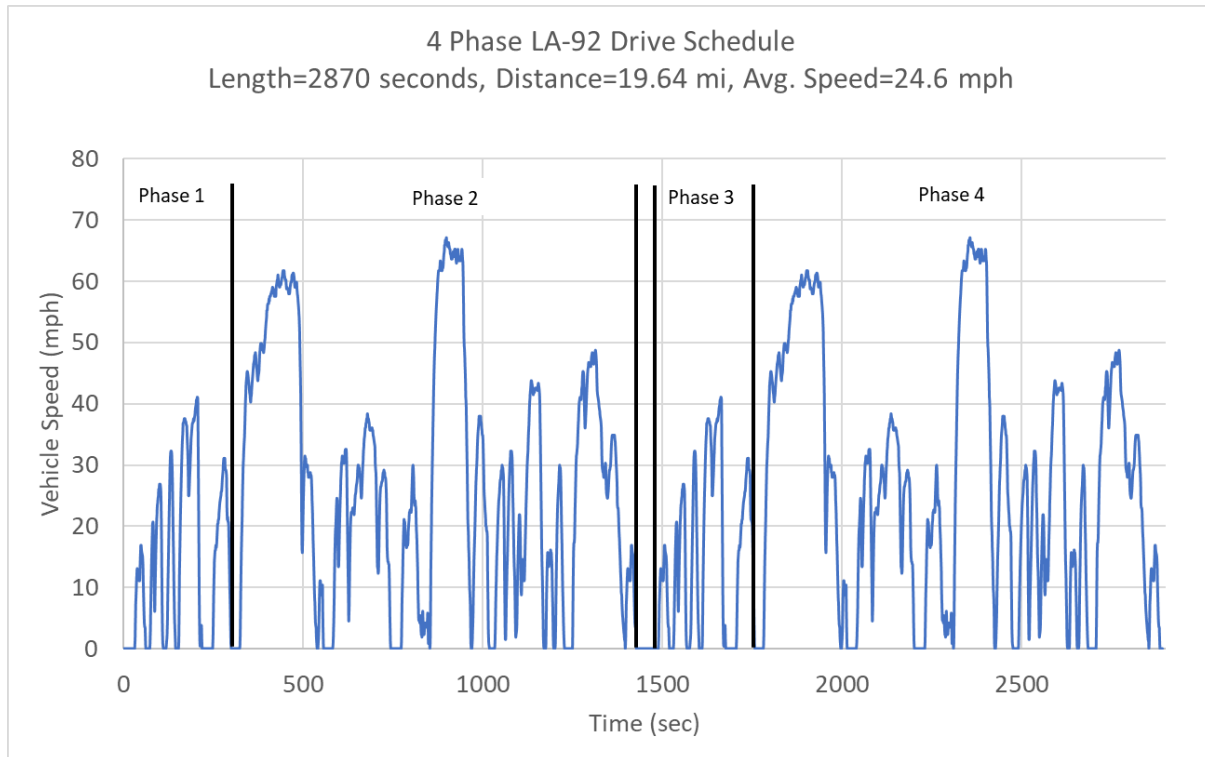


Figure 3-20: EPA 4 phase LA92 test cycle.

HD GEM Cycle (i.e. Super Cycle). This cycle is a composite of the many cycles used in the process of certifying trucks to HD GHG vehicle standards. The super cycle drive cycle consists of a combination of low speed, low load cycles followed by a 10-minute idle, and a return-to-service portion consisting of 55 and 65 mph cruise conditions. Phases 1 and 2 are consecutive ARB Heavy Heavy-Duty Diesel Truck transient modes from the ARB HHDDT schedule, are 14.3 miles in combined length, and represent an average speed 15.4 mph. Phases 1 and 2 are followed immediately by Phase 3, a 10-minute idle. Phase 4 is a return-to-service cycle consisting of an acceleration from idle to a 55-mph cruise, followed by another acceleration to a 65 mph cruise, and a return to idle. Phase 4 for has an average speed of 55.8 mph, is 29.2 miles in length, and both acceleration and deceleration rates are 0.5 mph/sec. The purpose of this cycle was to investigate how the lower exhaust gas temperature resulting from low-load operation affect catalyst activity and the emissions generated during a high-load, return-to-service event.

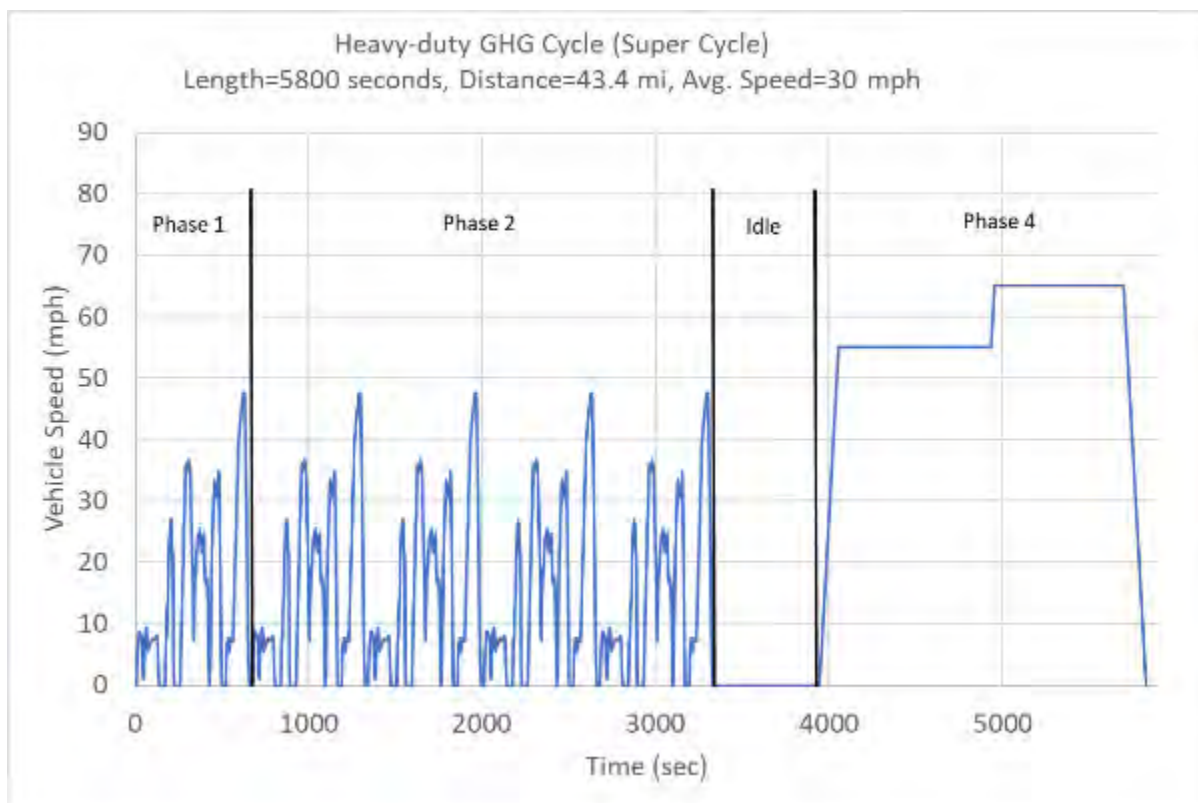


Figure 3-21: Super cycle, GEM greenhouse gas cycle

3.2.1.1.5 Baseline Results

Due to the inherent variability of real-world driving conditions, as well as the absence of defined test cycles or in-use emission standards for HD gasoline engines, direct comparisons of the onroad PEMS and chassis testing results cannot be used to classify the emissions performance of any one vehicle as above or below an applicable HD standard. However, comparisons of emission rates observed under similar conditions, time to catalyst light-off, and overall performance of each configuration relative to the others, can be made.

Most illustrative are the test results and data acquired in the laboratory employing the FTP-75 cold start test procedure. Figure 3-22 and Figure 3-23 show cumulative hydrocarbons and NO_x respectively for each vehicle at each test weight. Each figure clearly shows that once catalyst light-off is achieved, the sharp knee in the curve between 20 seconds and 140 seconds, emissions rates decline significantly and remain so for the remainder of the test. The top lines in the figures also illustrate how quickly the emissions can accumulate if catalyst light-off is delayed, allowing most of the emissions totals to be achieved in the first minutes of operation.

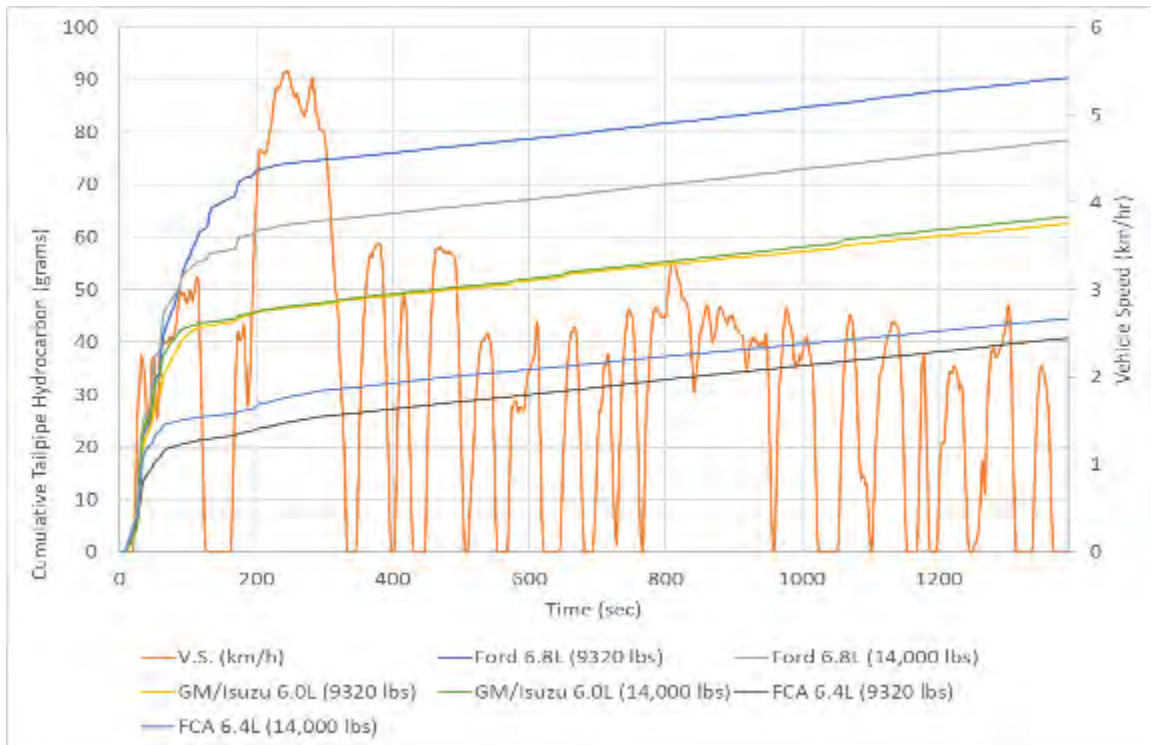


Figure 3-22: FTP-75 Cold start cumulative HC comparison

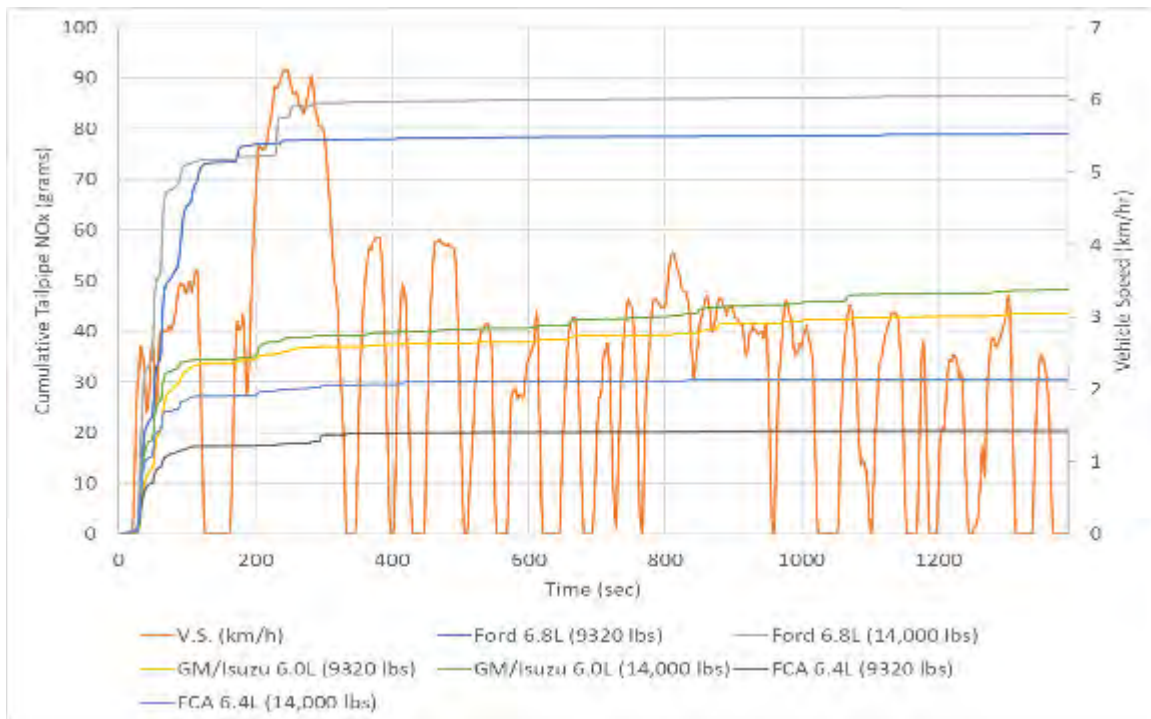


Figure 3-23: FTP-75 Cold start cumulative NOx comparison

Figure 3-24 sharpens the focus on catalyst architecture as well as possible calibration techniques driven by the particular certification tests. Figure 3-24 shows the effect that engine load has on the exhaust temperature of the Ford 6.8L and the GM/Isuzu 6.0L, both of which are dyno certified with little emphasis on cold start emissions. In contrast the FCA 6.4L which is a Tier 3 Bin 570 chassis certified vehicle shows no impact on catalyst light-off time, exhaust gas temperature, due to increased load. The FCA 6.4L was certified to the FTP-75 which emphasizes cold start emissions. This emphasis results in catalyst architecture, shorter exhaust manifold to catalyst distance, as well as cold start controls and calibrations more closely related to light-duty trucks and passenger cars.

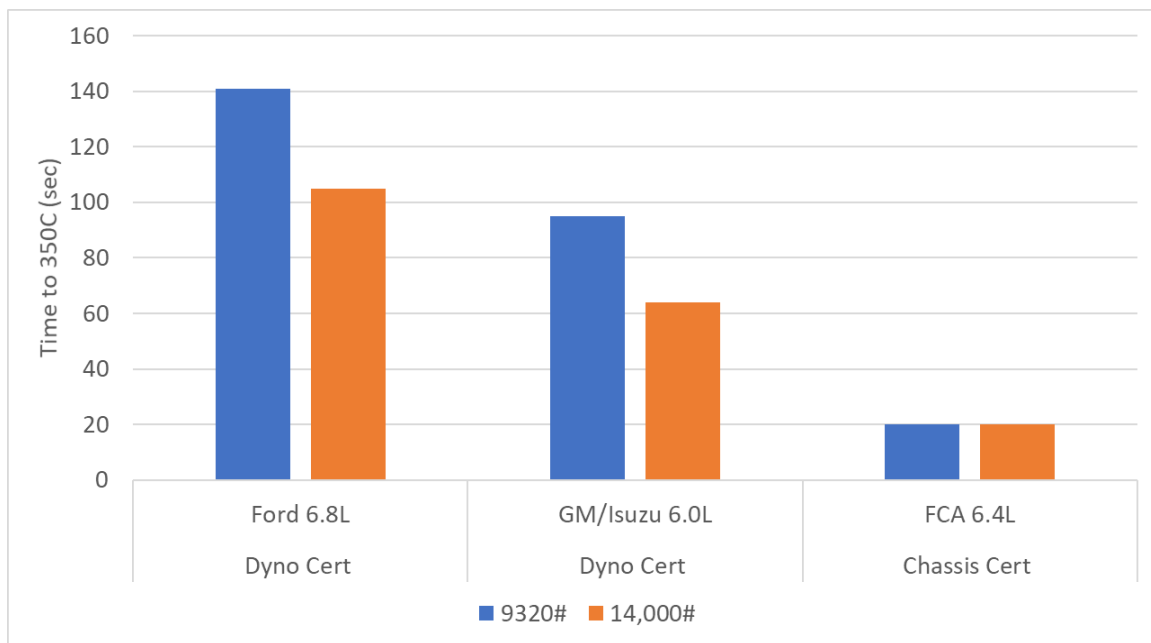


Figure 3-24: FTP-75 Catalyst light-off time comparison

Catalyst location cannot only affect light-off but also effects catalyst temperature during extended periods of idle. If idle conditions are long enough catalyst temperatures may fall below 350 C, a temperature associated with reduced conversion efficiency and emissions spikes when load is applied, and the vehicle returns to service. Figure 3-25 illustrates this condition during the 10-minute idle portion of the Super Cycle (Figure 3-21). Each vehicle enters the idle with a catalyst temperature of approximately 500 C. Over the course of the idle, catalyst temperatures decline and those vehicle with the largest distances from manifold to catalyst (Table 3-31) falling below 300 C.

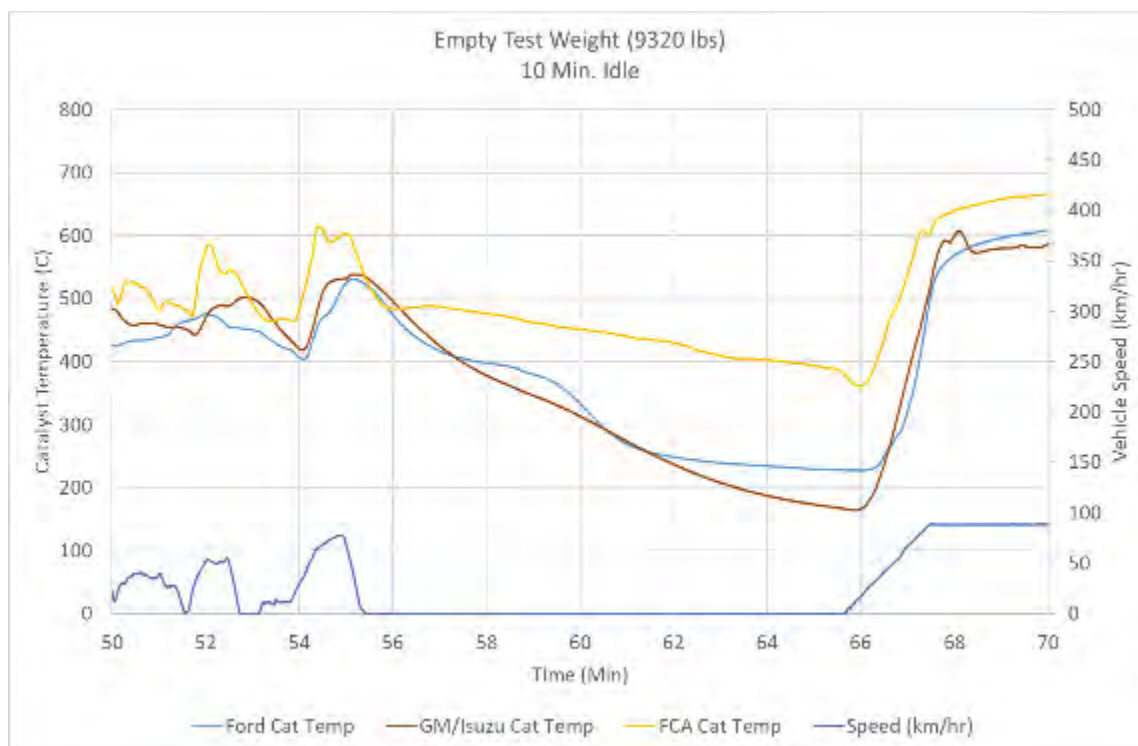


Figure 3-25: Extended idle catalyst cool down comparison

3.2.1.2 Baseline Technology for Evaporative Emissions

As mentioned in Chapter 3.3.2.3 of this draft RIA, these vehicles are subject to evaporative emission standards, but have no refueling requirements. We are unaware of any HD SI engines certified for incomplete vehicles that implement ORVR technologies today. For our feasibility analysis, we believe these HD SI engines would not implement ORVR without a regulatory driver and assumed zero adoption of ORVR technology in our baseline.

3.2.2 Projected Technology Effectiveness

The emissions performance of the advanced catalyst technologies were evaluated in EPA's HD SI demonstration program. We also evaluated a combination of additional data sources including MY 2019 compliance data and engine mapping data to project the effectiveness of these technologies and inform the level of stringency in our proposed standards. A description of these data and our analysis of them is presented in this section.

We project the effectiveness of implementing ORVR for incomplete HD SI vehicles based on the performance of complete vehicles subject to the Tier 3 evaporative and refueling requirements applying assumptions to account for increased fuel tank sizes.

3.2.2.1 MY 2019 HD SI Compliance Data for FTP Emission Performance

Four engine manufacturers certified HD SI engines in MY 2019. These manufacturers certified six engine families ranging in displacement from 6.0 to 8.8 liters.¹⁵¹ Table 3-34 presents the MY 2019 FTP-based emission levels reported for the three pollutants addressed by a TWC: NO_x, NMHC and CO. We labeled the engines by descending NO_x level. One engine, labeled "Cert Engine 6", is below the proposed Option 1 NO_x standard for MY 2027-2030 while

maintaining relatively low NMHC and CO emissions. While this high performing engine, which is available today, demonstrates that it is possible to meet the proposed Option 1 MY 2031 and later NO_x standard, we acknowledge that these certification results are representative of a shorter useful life period than we are proposing. PM emissions for most of these engines were undetectable and reported as zero for certification, suggesting the 5 mg/hp-hr standard proposed for CI engines is feasible for HD SI as well.⁰⁰

Table 3-34: Family Emission Limits Reported for the Six Certified HD SI Engines in MY 2019; NO_x and NMHC values are converted from g/hp-hr to mg/hp-hr to match the units of our proposed standards

	Cert Engine 1	Cert Engine 2	Cert Engine 3	Cert Engine 4	Cert Engine 5	Cert Engine 6
NO _x (mg/hp-hr)	160	120	104	89	70	29
NMHC (mg/hp-hr)	50	60	80	42	80	42
CO (g/hp-hr)	3.7	6.6	8.6	1.5	12.7	2.3
Fraction of MY 2019 HD SI Sales	2%	20%	4%	20%	48%	5%

In order to evaluate the NMHC and CO emissions, we calculated an overall average emission rate for each pollutant that includes all engines, and separately averaged a smaller subset of three engines with the lowest NO_x levels. Table 3-35 compares these two averages with the EPA 2010 standards and results from the engine family with the best NO_x emission performance of the MY 2019 compliance data.

Table 3-35: Average emission performance for Certified HD SI Engines in MY 2019

Pollutant	EPA 2010 Standard	Overall Average	Subset Average	Best NO _x Performance
NO _x (mg/hp-hr)	200	95	63	29
NMHC (mg/hp-hr)	140	59	55	42
CO (g/hp-hr)	14.4	5.9	5.5	2.3

Figure 3-26 compares the NO_x, NMHC, and CO emission performance of the six engines and displays the current EPA 2010 standard, overall average of the six engines, and average of the subset of three engines. When calibrating their engines, SI manufacturers experience a tradeoff in emissions performance for the three pollutants in their TWCs and each manufacturer will optimize their emission controls differently. As expected, the table shows no clear trend in NMHC and CO emissions related to the reduced NO_x. However, the overall average NMHC and CO levels are both met by three engine families today and likely achievable by two additional engine families with minor calibration changes, such as incorporation of cold start catalyst light-off strategies and refinement of the catalyst protection fuel enrichment levels. These results suggest FTP standards of 60 mg NMHC/hp-hr and 6 g CO/hp-hr, consistent with the overall average NMHC and CO levels achieved today, are feasible. These emission levels would be a low cost first step that could establish consistent emission performance across all certified HD SI

⁰⁰ One engine reported a 0.005 g/hp-hr PM FEL.

engines, and also serve as anti-backsliding standards, as manufacturers optimize their TWCs to reduce NO_x and improve component durability to meet the increased useful life periods we are proposing.

As we consider NMHC and CO FTP standards for MY 2031, we note that one MY 2019 engine family was certified below the proposed Option 1 MY 2031 NO_x standard while NMHC and CO emissions for that family remained below the overall average across the range of families certified. Using this low NO_x engine's performance as a basis, an NMHC standard of 40 mg/hp-hr and CO standard of 4 g/hp-hr are feasible in the 2031 timeframe. While this engine's CO performance is below 4 g/hp-hr, a balance is needed to account for uncertainty in durability over longer useful life periods. We expect advanced catalyst formulations would provide substantial emission reductions beyond the performance demonstrated by technologies on engines certified today. Additionally, manufacturers have a range of other strategies from their chassis-certified products that they can employ from improve emissions performance (see Chapter 1.2). Consequently, it is reasonable to project all HD SI engine families should be capable of achieving emission levels comparable to today's best performing engines.

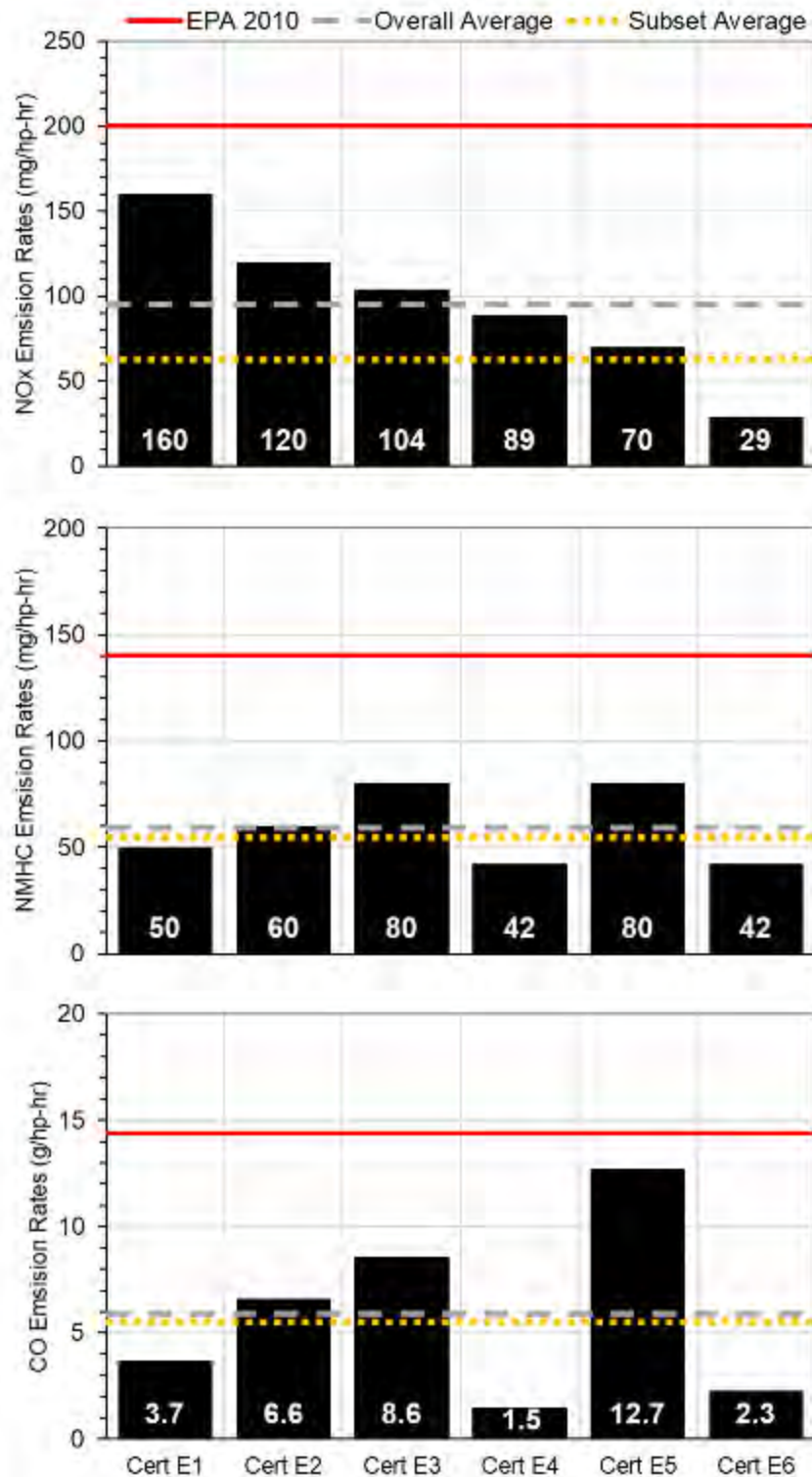


Figure 3-26: Comparison of emissions performance for MY 2019 certified HD SI engines; Overall Average (grey dash) includes data from all six engines, Subset Average (yellow dash) includes data from the three engines with the best NO_x performance (Cert E4-E6)

3.2.2.2 EPA Engine Mapping Test Program for SET Emissions Estimation

To assess the potential for emission reductions in HD gasoline engines over sustained loads, EPA evaluated engine fuel mapping data from a testing program previously performed by the agency as part of the HD GHG Phase 2 rule. EPA contracted SwRI to test a production MY 2015 Ford 6.8L V10 gasoline engine to assess CO₂ emissions and to evaluate the new fuel mapping test procedures developed for that rulemaking. As part of that work, the engine was run on an early version of 40 CFR 1036.535, which is the steady state fuel mapping procedure that requires the engine to be run at nearly 100 speed and torque points for 90 seconds. The first 60 seconds is for the engine and fuel consumption to reach stability and the last 30 seconds are averaged to create the fuel map.

Since continuous dilute criteria emissions were also collected for the test, we recently directed SwRI to reevaluate those results and create three versions of the data that summarized fuel consumption and emissions (NO_x, CO, NMHC and CO₂) versus engine speed and torque. The first version analyzed conditions where the engine went into power enrichment, consistent with strategy used in the production application of the engine. The second version analyzed the conditions where the engine controller activated a catalyst protection fuel enrichment strategy but did so before a power enrichment strategy was activated (this is due to a programmed delay for power enrichment of approximately one minute in the production engine controller.) The third version analyzed only conditions where the engine maintained stoichiometric air-fuel ratio, achieved by limiting engine load to keep exhaust temperatures slightly below the level that would activate the thermal protection strategy programmed into the production software.

These three analyses of the data differed only in the peak torque portions of the map, as in other portions, the engines maintained stoichiometric air-fuel ratio control for a majority of the points (below about 90 percent throttle). For each of the maps the peak torque points were used to calculate the A, B and C speeds as well as the torque values, so there were three unique sets of surrogate SET test points. Emission mass rates for CO, NMHC, NO_x, and CO₂ and fuel consumption were calculated from each map by interpolation of the maps at each of the SET test points. Finally, the results were weighted according to the existing CI-based weighting factors outlined in 40 CFR 1036.510. The engine and emission control components were not aged to the useful life requirements in this proposal.

The data analysis below includes operation at three distinct engine speeds described above and at several different loads, consistent with the approximate test points that would be required to perform the SET test procedure and then calculate a composite emissions level for the engine. The data presented includes the emission levels, fuel consumption rates, and engine power observed at the required SET test points, while operating in three distinct modes as allowed by production software controls: power enrichment mode, catalyst protection enrichment mode, and stoichiometric operation.

While not typically observed during the transient FTP test or torque mapping procedure, the engine controller activated a power enrichment mode after approximately one minute when throttle openings above 90%, where the extra fuel resulted in a slight increase in power. Power enrichment is sometimes used on gasoline engines to produce approximately 5% additional power beyond what is made when the air to fuel ratio is maintained at stoichiometry. Stoichiometric operation is the fundamental operating mode needed for three-way catalyst

systems to simultaneously reduce HC, CO and NO_x emissions, but as described above, it is not the mode that produces peak power.

Another operating mode observed in the data is catalyst protection fuel enrichment. When the catalyst or other critical engine components are exposed to high exhaust gas temperatures, damage can occur that affects the durability of these components, and manufacturers typically implement control strategies that use a limited amount of fuel enrichment to cool the exhaust gas and protect critical components. The fuel enrichment reduces the amount of excess oxygen that supports the exothermic (heat releasing) reaction in the catalyst and also reduces the temperature of the combustion gases exiting the engine. The combination of these two temperature-reducing strategies effectively provides control of exhaust gas temperatures and protects critical exhaust components from irreversible damage. Other strategies that maintain effective emission control, expand the area of stoichiometric operation, and still provide protection of critical engine and catalyst components are discussed in Chapter 2 of the RIA.

As observed in the composite SET test data below, any enrichment mode, whether for power or catalyst protection purposes, can result in substantial emission increases and higher fuel consumption. As seen in Table 3-36, when the engine is commanded into power enrichment mode and is no longer maintaining stoichiometric operation, the NMHC and CO increase substantially, and the engine consumes more fuel. The NMHC emissions are more than 10 times higher while the CO emissions are almost 50 times higher than the stoichiometric operating mode. NO_x emissions are reduced about 60% in power enrichment mode as expected because of the rich operation, however stoichiometric emissions NO_x emissions can be improved with catalyst design and calibration. Since this is a MY 2015 production engine, it was not designed or calibrated for optimum emissions for sustained high load operation at mid operating speeds such as demonstrated over the SET cycle. Improved NO_x emission control required over the FTP test cycle with this proposal is expected to also result in improvements in the NO_x levels over the SET cycle. It is important to note that this power enrichment mode is not typically observed during the transient FTP test due to the short periods of time spent at full power loads, which limits any power related enrichment features from activating like observed in the sustained full power test points in the SET testing described above.

Table 3-36: Comparison of Simulated 6.8L V10 SET Composite Emissions to Proposed Standards

	NO _x (mg/hp-hr)	NMHC (mg/hp-hr)	CO (g/hp-hr)	CO ₂ (g/hp-hr)	BSFC (lb/hp-hr)
Power Enrichment Allowed	11	110	45.2	587.3	0.479
Catalyst Protection with No Power Enrichment	19	30	11.4	617.7	0.463
Stoichiometric Operation	28	10	0.97	626.6	0.457
Proposed Option 1 Spark- Ignition Exhaust Emission Standards for SET Duty Cycle MY2027 - MY2030	35	60	6	-	-
Proposed Option 1 Spark- Ignition Exhaust Emission Standards for SET Duty Cycle MY2031 and later	20	40	6	-	-

As discussed above and illustrated in Figure 3-27, NO_x emissions remain reasonably controlled under all operating modes; however, NMHC and CO emissions increases are closely tied to enrichment events. The MY 2027 and MY 2031 NMHC and CO standards we are proposing for the FTP cycle are achieved in stoichiometric operation, but CO begins to approach today's FTP standard when catalyst protection is enabled. Power enrichment causes drastic spikes in both NMHC and CO. We are proposing to include the SET duty cycle to incentivize manufacturers to expand the stoichiometric operation of their HD SI engines and maintain the maximum TWC effectiveness. The FTP standards considered in Chapter 3.1.1.8 for NMHC and CO would require manufacturers to significantly reduce the frequency of fuel enrichment events, yet would allow for some necessary catalyst protection and power enrichment operation. We are proposing to apply the same numeric values for FTP and SET duty cycles for NMHC and CO standards. As with FTP, we are proposing to maintain fuel neutral standards, such that the NMHC and CO standards developed based on HD SI engine performance would apply to CI engines and the NO_x standards proposed for HD CI engines would apply to HD SI. These proposed SET standards are summarized in Table 3-37.

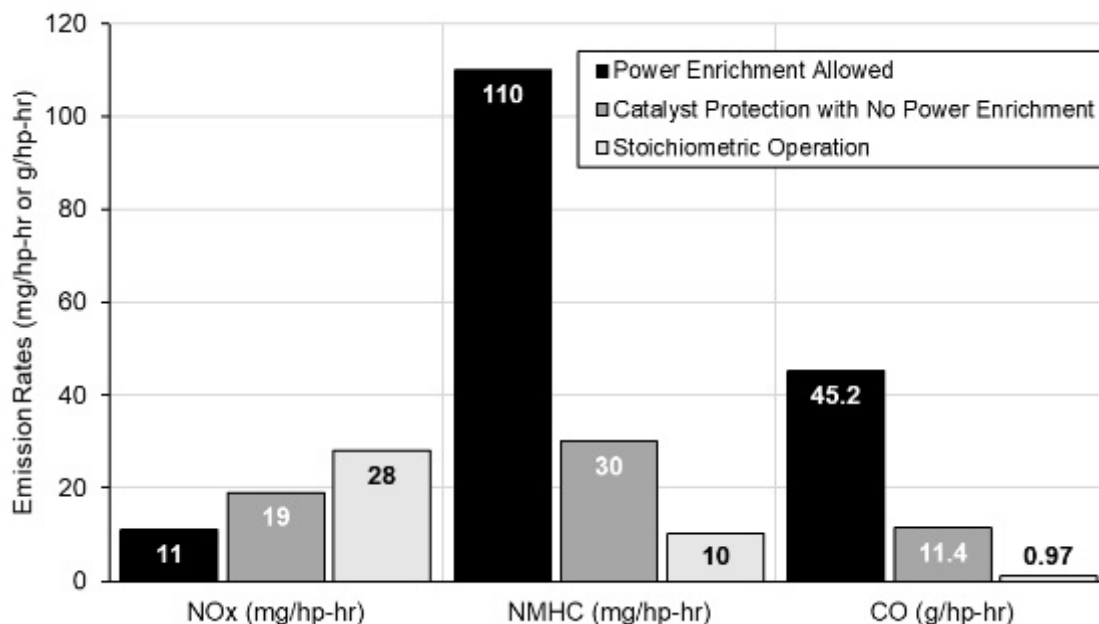


Figure 3-27: Comparison of operating modes in the fuel mapping-based SET

Table 3-37: Proposed Option 1 Spark-Ignition Exhaust Emission Standards for SET Duty Cycle

	NO _x (mg/hp-hr)	NMHC (mg/hp-hr)	CO (g/hp-hr)
MY 2027-2030	35	60	6
MY 2031 and later	20	40	6

The standards we are proposing in Table 3-37 represent levels we believe are feasible, based on our analysis of the performance of products currently in the market, the use of current high-

temperature-tolerant catalyst washcoats, and the design and calibration strategies available to ensure rapid catalyst light-off and reduce HC and CO emissions under high load. As indicated in the results of the SET composite analysis in Table 3-36, where emission results for three distinct modes of fuel control under high load operation were simulated, the emission levels for each can vary significantly.

First, the current power enrichment mode, which is allowed solely for the purpose of providing a modest increase in power, can produce emission results that exceed two of the proposed Option 1 composite SET standards (see Table 3-38 below.) This fuel enrichment approach does indeed increase power, but produces higher CO and NMHC emissions as a result, in addition to increasing fuel consumption. Reducing the amount of time spent in this enrichment mode, or eliminating it entirely, could result in a significant reduction in emissions. Second, the catalyst thermal protection mode, where fuel enrichment is used solely for catalyst thermal protection (to limit temperatures inside the catalyst to a value specified by manufacturers). This enrichment mode, controlled by software-based temperature models in the engine control module (ECM), also results in increased emissions, but is necessary to prevent irreversible damage to the catalyst. As indicated in Chapter 2 technology discussion, catalyst washcoats and other related exhaust components have progressed in recent light-duty applications and are able to tolerate significantly higher exhaust gas temperatures while still achieving acceptable component durability and catalytic deterioration targets. The use of these improved materials, along with the more robust temperature models or temperature measurement devices discussed in Chapter 2.2.1.5 should result in significant reductions in CO emissions and allow engines to meet the proposed emission standards. Also discussed in Chapter 2.2.1.7 is the use of engine down speeding, which can avoid the high speed, high exhaust gas temperature conditions that typically result in fuel enrichment due to engine component durability and catalyst thermal concerns. With the integration of modern multi-speed electronically controlled transmissions, this down speeding approach is extremely feasible and likely to also reduce engine wear and improve fuel consumption with little perceived effect on performance under commercial and vocational operation. Note that in order to meet GHG and fuel consumption goals, this engine has already implemented some degree of down speeding as evident in the reduced maximum test speeds reported by one manufacturer. The agency believes that the more recent introduction of 10-speed transmissions provides additional opportunities for down speeding that have not yet been explored.

Finally, the third mode of operation, where the ECM maintains a stoichiometric fuel-to-air ratio throughout all of the SET cycle test points, and potentially, under high load in-use operation as well, results in the greatest degree of emission control. Under stoichiometric operation, NMHC, CO, and NO_x emissions are simultaneously reduced, and the three-way catalyst can be optimized to reduce all three pollutants. This strategy is discussed in chapter 2.2.1.6, and our analysis of MY 2019 certification data indicates that NMHC and CO emissions are well below the proposed Option 1 SET standards, and NO_x emissions meet the proposed Option 1 MY 2027-2030 standards, and are slightly higher than the proposed Option 1 MY 2031 and later standards. This level of NO_x control was achieved without any improvements or refinements to the calibration and control strategies that we believe manufacturers will utilize to meet the proposed FTP standards. As observed in the analysis in Table 3-38, a slight drop in power is observed at the three SET test points as fuel enrichment is decreased, however, this slight power loss is also accompanied by a noticeable decrease in fuel consumption, which can be a

potentially important operational cost benefit in a commercial vehicle applications. Similar to the previous discussion, the agency believes that several engine hardware and control technologies, in addition to the additional gear ratios in current transmission designs, will provide the opportunity for maintaining stoichiometric fuel-air control under all load and speed conditions.

Table 3-38: 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
Catalyst Protection with No Power Enrichment	211	182	141	542	554	524
Stoichiometric Operation	201	179	137	522	551	526

3.2.2.3 Spark-Ignition Technology Demonstration Program

EPA initiated a program with Southwest Research Institute to better understand the emissions performance limitations of current heavy-duty spark-ignition (SI) engines as well as investigate the feasibility of advanced three-way catalyst aftertreatment and technologies and strategies to meet our proposed exhaust emission standards. In addition to investigating emission performance on the FTP duty cycle, the test program evaluated the proposed SET duty cycle that are not currently required for certification. This section describes the results of the SI demonstration program at the time of this proposal. See Chapter 1.2 for an expanded description of these and other technologies and strategies to address exhaust emissions for HD SI engines.

A MY 2019-certified heavy-duty gasoline engine was used for this evaluation. This particular engine was chosen because it represented the newest design among the three most-common engines in the market and includes technologies not normally found in HD SI engines, such as variable valve timing (VVT) and cooled EGR. Additional considerations for selecting this engine were the availability of chassis-certified trucks with the options and driveline configuration desired, as well as the ability to install and operate the engine in a dynamometer test cell. Table 3-39 describes the HD SI engine that was used for this evaluation.

Table 3-39: Major engine specifications of the MY2019 HD SI gasoline engine used for the EPA demonstration program

Engine Component	Specification
Engine Displacement (L)	6.4
Configuration / Type	90° Pushrod V-8
Bore (mm)	103.9
Stroke (mm)	94.8
Aspiration	Naturally aspirated
Injection	Sequential multi-port fuel injected
Compression Ratio	10.0:1
Engine Block Material	Cast Iron
Cylinder Head Material	Cast Aluminum, Hemispherical combustion chamber
Valve Train	2 valve per cylinder, Cam-in-block, VVT, Hydraulic roller lifters
Ignition	8 individual coils, 16 spark plugs, 2 per cylinder
Exhaust Gas Recirculation	Cooled EGR
Fuel Requirement	89 Octane recommended
Peak Horsepower	360 HP @ 4715 rpm
Peak Torque	408 lb-ft @ 4000 rpm

This program includes a baseline evaluation of emissions performance as well as a demonstration of the reductions possible through the application of advanced catalyst designs that included decreased substrate wall thickness and increased cell density, a washcoat formulation that is more tolerant of high exhaust gas temperatures, and forward placement of the catalyst substrate (i.e. moving a portion of the total catalyst volume closer to the engine). The catalysts were artificially aged to represent performance equivalent of 250,000 miles of real-world operation in a manner approved by the engine manufacturer.

We also investigated the impact of engine down-speeding and calibration changes to demonstrate further emission reduction potential of both the baseline and advanced catalyst configurations on the FTP and SET. As noted in Chapter 1.2.1.7, this engine down-speeding strategy is currently used by at least one HD gasoline engine manufacturer and this lower speed is made possible by transmission strategies preventing over-speeding, which allows the emission controls to operate in a much more desirable and lower emitting area of engine operation. For the down-speed testing in our demonstration program, the maximum test speed (MTS) was lowered from the manufacturer's stated MTS of 4715 rpm to 4000 rpm.

Finally, engine calibration parameters affecting air-fuel enrichments and biasing ($\lambda < 1.0$) were manipulated to further reduce CO emissions on the SET. Because of the limited abilities of aftermarket vehicle engine control module programmers and the complexity of OEM engine calibrations and control strategies, this effort was met with limited success. We do however believe that manufacturers with access to the latest tools for calibration and complete access to engine control strategies and calibrations will be able to optimize λ biasing as well as any necessary air-fuel enrichments for catalyst and engine protection. With the capabilities previously mentioned we believe that the that through a combination of engine down-speeding and calibration optimization that the emissions goals proposed are achievable.

Installation of the engine in the test cell included instrumenting the engine's aftertreatment with thermocouples at exhaust manifold exit, catalyst inlet, and 1-inch rearward of the catalyst

front face. For all engine tests, CAN data from the engine control module, including, but not limited to engine speed, short and long-term fuel correction, and spark advance were recorded.

We evaluated the following test procedures, performing three repeats of each cycle:

- HD SI FTP cycle (40 CFR 1036.510(a)(1))
- Engine mapping (40 CFR 1036.535 and 1036.540)
- HD SET (40 CFR 1036.505)

In all tests, we measured NO_x, CO, PM, and NMHC, as well as the GHG-related parameters of brake-specific fuel consumption (BSFC), CH₄ and CO₂. Emissions were measured from two locations throughout each test cycle: before the catalytic aftertreatment and at the tailpipe.

Table 3-40 and Table 3-41 present results representing application of advanced catalyst technology and engine down-speeding and a combination of engine down-speeding and calibration for the FTP and SET duty cycles. In all test cases, FTP and SET, the results show NO_x and NMHC to be at or below the proposed Option 1 standards for both MY 2027-2030 and MY 2031 and later. For the FTP results in Table 3-40, with regards to the 4715 rpm MTS, CO is below the proposed Option 1 MY 2027 standards but slightly above the 2031 proposed limit. For the 4000 rpm MTS, CO is significantly below each proposed standard. Figure 3-28 illustrates the CO breakthrough associated with the 4715 MTS. The lambda excursions seen in Figure 3-28 are a direct result of catalyst protection lambda enrichment. Please see the discussion in Chapter 1.2 regarding engine operating modes and possible calibration philosophy to address excess CO emissions. Calibration changes to address the borderline NO_x and SET CO levels, richer lambda bias and no throttle-based enrichment, resulted in slight increases in NO_x and CO.

Table 3-40: Spark-Ignition Demonstration Program Preliminary FTP Results

	NO_x (mg/hp-hr)	CO (g/hp-hr)	NMHC (mg/hp-hr)	PM (mg/hp-hr)	BSFC (lb/hp-hr)
Proposed Option 1 MY 2027-2030	35	6.0	60	5	
Proposed Option 1 MY 2031 and later	20	4.0	40	5	
250k Catalysts 4715 RPM MTS	19	4.9	32	4.8	0.456
250k Catalysts 4000 RPM MTS	18	0.25	35	4.5	0.448
250k Catalysts 4000 RPM MTS Modified Cal	21	0.99	1	4.4	0.448

4715 rpm Vs. 4000 rpm MTS Comparison FTP CO Reduction

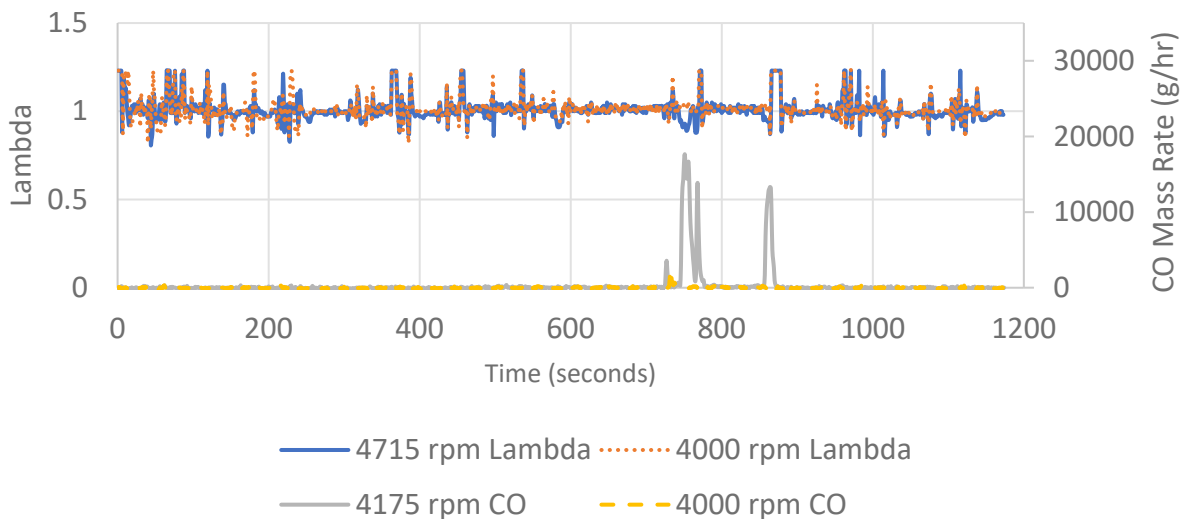


Figure 3-28: Engine RPM Down-Speeding FTP CO Comparison

Table 3-41 compares the emissions results for the SET cycle at MTSs of 4715 rpm and 4000 rpm. Like the FTP results NMHC and NO_x are well below the proposed standards. Unlike the FTP results both the 4715 rpm and 4000 rpm MTS operation show CO above the proposed standards. Calibration changes, described above, were then applied to attempt further reducing the CO. In the first two cases there was no calibration attempted to decrease the amount of air-fuel enrichment during operation, Figure 3-29. Because no calibration was attempted the decrease in all emissions constituents is due to the lower operating loads and the need for air-fuel enrichments commensurate with the lower MTS. When calibration changes to richer lambda biasing and removal of throttle-based enrichments were applied NO_x did decrease while CO increased even higher above goal.

Table 3-41: Spark-Ignition Demonstration Program Preliminary SET Results

	NO _x (mg/hp-hr)	CO (g/hp-hr)	NMHC (mg/hp-hr)	PM (mg/hp-hr)	BSFC (lb/hp-hr)
Proposed Option 1 MY 2027-2030	50	6.0	60		
Proposed Option 1 MY 2031 and later	20	4.0	40	5	
250k Catalysts 4715 RPM MTS	8	36.7	6	7	0.462
250k Catalysts 4000 RPM MTS	5	7.21	1	3	0.437
250k Catalysts 4000 RPM MTS Modified Cal	1	9.65	1	3	0.438

4715 rpm Vs. 4000 rpm MTS Comparison SET CO Reduction

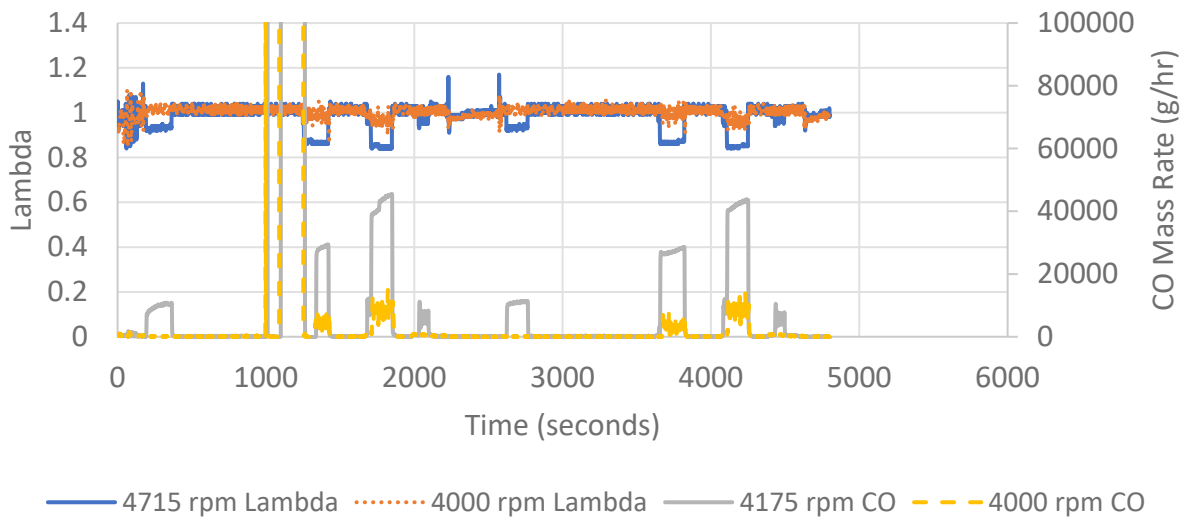


Figure 3-29: Engine RPM Down-Speeding SET CO Comparison

As mentioned previously, SwRI undertook a calibration effort to address the level of CO witnessed, 7.21 g/hp-hr, during SET testing and lower NO_x for both the FTP and SET. Because of the limited abilities of aftermarket vehicle engine control module programmers and the complexity of OEM engine calibrations and control strategies, this effort was met with limited success. We do however believe that manufacturers with access to the latest tools for calibration and complete access to engine control strategies and calibrations will be able to optimize lambda biasing as well as any necessary air-fuel enrichments for catalyst and engine protection. With the capabilities previously mentioned we believe that the that through a combination of engine down-speeding and calibration optimization that the emissions goals proposed are achievable.

3.2.2.4 Refueling Emissions Technology Effectiveness

As described Chapter 2.3.2 of this draft RIA, HD SI engines certified as incomplete heavy-duty vehicles are not currently required to meet ORVR. The technology package we considered for these engines is based on the technologies implemented by chassis-certified complete vehicles to meet the evaporative and refueling requirements of Tier 3. The technology package includes four main equipment components and strategies that incomplete heavy-duty vehicles would need to update to implement ORVR: increased working capacity of the carbon canister to handle additional vapors volumes, 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. Chapter 1.2.4 includes descriptions of these technologies. The assumptions we applied to account for the larger fuel tanks and other considerations for larger incomplete vehicles are summarized in Section 3.1.1.13 where we present our projected costs.

The proposed refueling controls would result in 29.2% lower VOC and Benzene by 2031, 80.2% lower by 2040 and 88.5% lower by 2045 for heavy duty gasoline vehicles over 14,000 lbs. See the discussion and table in Chapter 5, Section 5.3.3.

3.2.3 Technology Cost

For this analysis of the aftertreatment costs, heavy-duty spark-ignition (HD SI) engines are categorized by the type of fuel they use: liquid fuels (i.e., gasoline, gasoline-ethanol blends, and ethanol) or gaseous fuels (i.e., compressed natural gas and liquified petroleum gas). The gaseous-fueled category includes engines derived from SI platforms and engines converted to SI from heavy-duty CI engines. The heavy-duty SI engine category is further divided into heavy heavy-duty (HHD) and urban bus. We projected the costs of achieving the proposed HD SI engine exhaust emission standards based on the technologies we evaluated in our demonstration program (see Chapter 3.1.1.10).

3.2.3.1 Spark Ignition Exhaust Aftertreatment System Cost Analysis

Manufacturers will optimize the design of their aftertreatment systems specific to their different vehicles. Primary considerations include cost, light-off performance, warmed-up conversion efficiency, and the exhaust temperatures encountered by the vehicle during high-load operation. Vehicles having low power-to-weight ratios will tend to have higher exhaust gas temperatures and exhaust gas flow which will result in a different design when compared to vehicles having higher power-to-weight ratios.

Manufacturers and catalyst suppliers perform detailed studies evaluating the cost and emission performance of aftertreatment systems. It is anticipated that manufacturers will optimize their aftertreatment systems to achieve the proposed heavy-duty emission standards and meet the durability criteria for all vehicle classes.

Similar to the CI engine cost analysis, costs for baseline HD SI engine aftertreatment systems were estimated using cost data published by Dallman et al.¹⁵², Pasoda et al.¹⁵³ as well as data from manufacturer's technical descriptions of aftertreatment catalyst components submitted as part of engine certification packages for MY2019. Manufacturer's data was then combined into projected sales-weighted averages by type of fuel (liquid and gaseous fuels), including two distinct categories for gaseous-fueled engines identified as heavy heavy-duty and urban bus that have distinctly different aftertreatment demands.

Baseline projected sales-weighted average engine displacements, catalyst volumes, PGM loadings and costs are shown in Table 3-42 for both liquid and gaseous fueled SI engines. As mentioned previously, these are based on certification data from MY 2019. These MY2019 engine and aftertreatment costs estimates are used as the MY2027 baseline cost presented in draft RIA Chapter 7.1.1 after conversion to 2017 dollars.

Table 3-42: 2019 MY Sales-Weighted Baseline SI Engine Technology Costs (2019\$)

	Liquid Fueled SI Engine	Gaseous Fueled SI Engine
Engine Displacement (L)	6.6	7.2
Total TWC Volume (L)	4.3	5.1
CATv/ENGd Ratio (L/L)	0.65	0.72
Total Pt (\$)	\$0	\$0
Total Pd (\$)	\$53	\$68
Total Rh (\$)	\$172	\$179
Substrate cost (\$)	\$56	\$68
Washcoat cost (\$)	\$26	\$31
Canning cost (\$)	\$15	\$19
<i>Total cost (\$2019)</i>	<i>\$322</i>	<i>\$365</i>

We separately evaluated two distinct categories for the three gaseous-fueled HD SI engines that certified to California's optional and more stringent 0.02 g/hp-hr NO_x standard in MY 2019: HHD and urban bus. One engine is derived from a traditional SI gasoline-fueled engine and two are converted from CI diesel-fueled engines. Given the small number of engines in each of these categories, we are not publicly releasing the component-level details for MY 2019 HD SI, HHD and urban bus engines, but summarize the total costs for these categories. Table 3-43 shows the baseline aftertreatment cost for HHD and urban bus gaseous-fueled engines.

Table 3-43: 2019 MY HHD and Urban Bus Gaseous-fueled Technology Baseline Costs (2019\$)

	Gaseous Fueled SI Engine	Gaseous Fueled HHD Engine	Gaseous Fueled Urban Bus Engine
Engine Displacement (L)	6.8	11.9	8.9
<i>Total cost (\$2019)</i>	<i>\$641</i>	<i>\$3,348</i>	<i>\$2,511</i>

As mentioned previously, the three MY2019 gaseous-fueled HD SI, HHD and urban bus engines currently meet a 0.02 g/hp-hr NO_x standard, and we assumed that additional technology would not be needed for these engines to meet the proposed standards in future model years. However, it is reasonable to believe that improvements in the materials and design of the catalyst substrate support structure (e.g., can material, mat, seals, etc.) will be needed to achieve durability over the longer useful life and we estimated a nominal addition per-engine cost for these engine categories.

For the other gaseous fueled engines category, we assumed the same technologies would be used to meet the proposed Option 1 MY 2027-2030 and MY 2031 and later standards and that manufacturers would update calibration to achieve lower emissions in the final step of the rule. Table 3-44 shows the MY 2027 and later gaseous-fueled engine technology costs adjusted for improved catalyst and component durability.

Table 3-44: Projected Gaseous Fueled Engine Technology Cost based on Proposed Standards (2019\$)

	Gaseous Fueled SI Engine	Gaseous Fueled HHD Engine	Gaseous Fueled Urban Bus Engine
<i>MY 2027 and later Total cost (\$2019)</i>	\$646	\$3,376	\$2,531

The MY2027 and MY2031 technology cost for the liquid fueled SI engines are based on the demonstration engine described in Chapter 3.1.1.10. Costs were estimated using the same Dallman et al.¹⁵⁴ and Pasoda et al.¹⁵⁵ data as our baseline estimates and data from the specific aftertreatment catalyst components used for the HD SI demonstration program. We did not make any specific cost adjustments to account for the lengthened useful life, since the aftertreatment system used in the demonstration program represented catalysts aged to 250,000 miles. Table 3-45 contains the details of this analysis.

Table 3-45: Projected Liquid Fueled SI Engine Technology Cost to meet Proposed Standards (\$2019\$)

Technology Description	MY 2027 and later Liquid Fueled SI Engine
Total TWC Volume (L)	5.8
CATv/ENGd Ratio (L/L)	0.91
Light-off Catalyst	
Number of Catalysts	2
L.O. Catalyst Volume (L)	0.82
Total Pt (\$)	\$0.0
Total Pd (\$)	\$268
Total Rh (\$)	\$40
Substrate Cost (\$)	\$21
Washcoat Cost (\$)	\$10
Canning Cost (\$)	\$6
Underfloor Catalyst	
Number of Catalyst	2
U.F. Catalyst Volume (L)	2.1
Total Pt (\$)	\$0
Total Pd (\$)	\$187
Total Rh (\$)	\$102
Substrate Cost (\$)	\$55
Washcoat Cost (\$)	\$25
Canning Cost (\$)	\$18
<i>Total Demonstration TWC Cost (\$2019)</i>	<i>\$732</i>

Table 3-46 summarizes the costs for each of the HD SI engine categories evaluated in this analysis. These technologies costs are used in the analysis to determine the overall costs of the proposed program, as detailed in Chapter 7 of this draft RIA.

Table 3-46: Summary of HD SI Engine Technology Cost Comparison

Cost Packages (2019\$)	Liquid Fueled SI Engine	Gaseous Fueled		
		SI Engine	SI HHD	SI Urban Bus
Baseline Technology	\$322	\$365	\$3,348	\$2,511
MY 2027 Technology	\$732	\$646	\$3,376	\$2,531
<i>MY 2027 Incremental</i>	<i>\$410</i>	<i>\$281</i>	<i>\$28</i>	<i>\$20</i>

3.2.3.2 Onboard Refueling Vapor Recovery Anticipated Costs

As described Chapter 2.3.2 of this draft RIA, HD SI engines certified as incomplete heavy-duty vehicles are not currently required to meet ORVR. There are four main equipment components and strategies incomplete heavy-duty vehicles would need to update to implement ORVR: increased working capacity of the carbon canister to handle additional vapors volumes, 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. Chapter 1.2.4 includes more information on these technologies. The associated costs for these updates are summarized below. We are proposing to have ORVR requirements extend to heavy-duty gasoline engines in incomplete vehicles starting in model year 2027. For our cost analysis, we assumed all heavy-duty gasoline engines that are identified as LHD, MHD and HHD in MOVES will have an average of a 70-gallon fuel tank.

Capturing the increased vapor volume from the vapor displaced during a refueling event will require canisters to increase vapor or "working" capacity approximately 15%-40% 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 5.1 liters of conventional carbon to capture overnight diurnal evaporative emissions for a 70-gallon fuel tank. An increase in required capacity to allow refueling vapors to be captured would result in the need for an additional 1.9 liters of conventional carbon. A change in canister volume to accommodate additional carbon could include increased costs for retooling and additional canister plastic material, as well as design considerations to fit the larger canister on the vehicle.

An alternative to retooling for a larger single canister could 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% reduction in carbon volume required if a mechanical seal is used at the filler neck versus a liquid seal approach. Typically, mechanical seals have not been a preferred approach because it introduces another wearable part that can deteriorate and would

potentially need to be monitored under OBD requirements, as well as requiring replacement during the useful life of the vehicle if it wears prematurely. 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, it may be more economical to choose a mechanical seal design to avoid excess canister carbon requirements and possible retooling charges, but we share our assumptions and cost estimates for both seal options in Table 3-47 and Table 3-48. A mechanical seal approach costs approximately \$10.00 per seal. 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 costs effectively nothing for the seal, but would require approximately \$15 of new hardware modifications to provide enough back pressure to stop the refueling nozzle fuel flow when tank reaches full capacity to avoid spitback of the liquid fuel.

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. 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 canister as observed in dual tank single canister light-duty applications.

Table 3-47 shows our calculations estimating the amount of extra canister size for conventional carbon for a 70-gallon tank, using Tier 3 requirements as a baseline. Currently under Tier 3 requirements the canister and purge strategy is 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% efficiency. 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% efficiency mainly because 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% 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.

In order for carbon in the canisters to be effective at managing vapors for diurnals and refueling events, the vehicle engine must sufficiently purge the canister during engine operation

in preparation for future events that will require vapor adsorbing capacity. The purge requirements are shown in Table 3-47. The diurnal drive cycle is only 30 minutes and targets 200 bed volumes of purge to clean the canister before the evaporative emissions test. When the bed volumes of purge are multiplied by the canister volume, the total purge volume can be calculated. The total purge volume divided by the number of minutes driving gives us the average purge rate. An ORVR test requires proper conditioning for a very clean canister in order to pass the ORVR test. To clean out the canister over the 97 minutes of driving cycles for the ORVR prep, there is a much higher amount of bed volumes necessary, therefore the purge rate required is also higher. Table 3-48 shows cost estimations for the different approaches. For our cost analysis described in Chapter 7, we used \$25, which is the average of all approaches considered, as the cost estimate for the additional canister capacity and hardware for our proposed ORVR requirements.

Table 3-47: Assumptions for gasoline-fueled heavy-duty spark-ignition vehicles for conventional carbon requirements to meet the proposed ORVR

	Tier 3 Baseline	Proposed Requirements	
		Mechanical Seal	Liquid Seal
	Diurnal	ORVR	
Diurnal Heat Build	72-96°F	80°F	
RVP	9 psi		
Nominal Tank Volume	70 gallons		
Fill Volume	40%	10% to 100%	
Air Ingestion Rate		0%	13.50%
Mass Vented per heat build, g/day	120		
Mass Vented per refueling event		255	315
Hot Soak Vapor Load	5		
Mass Vented over 48-hour test	227.2		
Mass Vented over 72-hour test	323.3		
1500 GWC, g/L (Efficiency) ^a	70	50	50
Excess Capacity	10%	10%	10%
Canister Volume, liters ^b			
48-hour	3.6		
72-hour	5.1		
ORVR ^c		5.6	6.9
Limiting Drive Cycle, minutes	30	97	97
Bed Volumes Purge	200	646	646
Total Purge Volume, liters ^d	1020	3618	4457
Average Purge Rate, LPM ^e	34	37	46
BETP Purge		37	46

^a Efficiency of conventional carbon

^b Canister Volume = 1.1(mass vented)/ 1500 GWC (Efficiency)

^c ORVR adds .5 liters and 1.8 liters for Mechanical Seal and Liquid Seal respectively

^d Total Purge Volume, liters = canister volume, liters * Bed Volumes Purge represent the potential volume of purge for the 97 minute drive cycle used for the ORVR test procedure. Required purge volume to clean out the canister of fuel vapors for the larger ORVR canisters is likely much lower, approximately the ratio of new canister volume to the previous canister volume multiplied by the target bed volumes (220 bed volumes for a mechanical seal and 271 bed volumes for a liquid seal)

^e Average Purge Rate, LPM = Total Purge Volume, liters / Limiting Drive Cycle, minutes however as noted in (d), this is not necessarily the required purge volumes or rates

Table 3-48: Estimated Costs for ORVR Over Tier 3 as Baseline

	Liquid Seal		Mechanical Seal	
	New Canister	Dual Existing Canisters in Series	New Canister	Dual Existing Canisters in Series
Additional Canister Costs	\$20	\$15	\$8	\$8
Additional Tooling ^a	\$0.50		\$0.50	
Flow Control Valves	\$6.50		\$6.50	
Seal	\$0	\$0	\$10	
Total ^b	\$27	\$22	\$25	

^a Assumes the retooling costs will be spread over a five-year period

^b Possible additional hardware for spitback requirements

Chapter 4 Health and Environmental Impacts

4.1 Health Effects Associated with Exposure to Pollutants

Heavy duty vehicles emit pollutants that contribute to ambient concentrations of ozone, PM, NO₂, CO, and air toxics. A discussion of the health effects associated with exposure to these pollutants is presented in this section of the draft RIA. The following discussion of health impacts is mainly focused on describing the effects of air pollution on the population in general. Additionally, children are recognized to have increased vulnerability and susceptibility related to air pollution and other environmental exposures; this and effects for other vulnerable and susceptible groups are discussed below.

4.1.1 Ozone

4.1.1.1 Background on Ozone

Ground-level ozone pollution forms in areas with high concentrations of ambient NO_x and VOCs when solar radiation is high. Major U.S. sources of NO_x are highway and nonroad motor vehicles and engines, power plants, and other industrial sources, 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, NO₂, 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 NO₂ 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 and even in VOC-limited areas, NO_x reductions are not expected to increase ozone levels if the NO_x reductions are sufficiently large - large enough to become NO_x-limited.

4.1.1.2 Health Effects Associated with Exposure to Ozone

This section provides a summary of the health effects associated with exposure to ambient concentrations of ozone.^{PP} The information in this section is based on the information and conclusions in the April 2020 Integrated Science Assessment for Ozone (Ozone ISA).¹⁵⁶ 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.^{QQ} The discussion below highlights the Ozone ISA's conclusions pertaining to health effects associated with both short-term and long-term periods of exposure to ozone.

For short-term exposure to ozone, the Ozone ISA concludes that respiratory effects, including lung function decrements, pulmonary inflammation, exacerbation of asthma, respiratory-related hospital admissions, and mortality, are causally associated with ozone exposure. It also concludes that metabolic effects, including metabolic syndrome (i.e., changes in insulin or glucose levels, cholesterol levels, obesity and blood pressure) and complications due to diabetes are likely to be causally associated with short-term exposure to ozone, and that evidence is suggestive of a causal relationship between cardiovascular effects, central nervous system effects and total mortality and short-term exposure to ozone.

For long-term exposure to ozone, the Ozone ISA concludes that respiratory effects, including new onset asthma, pulmonary inflammation and injury, are likely to be causally related with ozone exposure. The Ozone ISA characterizes the evidence as suggestive of a causal relationship for associations between long-term ozone exposure and cardiovascular effects, metabolic effects, reproductive and developmental effects, central nervous system effects and total mortality. The evidence is inadequate to infer a causal relationship between chronic ozone exposure and increased risk of cancer.

Finally, interindividual variation in human responses to ozone exposure can result in some groups being at increased risk for detrimental effects in response to exposure. In addition, some 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

^{PP} Human exposure to ozone varies over time due to changes in ambient ozone concentration and because people move between locations which have notable different ozone concentrations. Also, the amount of ozone delivered to the lung is not only influenced by the ambient concentrations but also by the breathing route and rate.

^{QQ} 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.

greater fraction of air through the mouth.^{RR} Children also have a higher asthma prevalence compared to adults. Recent epidemiologic studies provide generally consistent evidence that long-term ozone exposure is associated with the development of asthma in children. Studies comparing age groups reported higher magnitude associations for short-term ozone exposure and respiratory hospital admissions and emergency room visits among children than for adults. Panel studies also provide support for experimental studies with consistent associations between short-term ozone exposure and lung function and pulmonary inflammation in healthy children. Additional children's vulnerability and susceptibility factors are listed in Section XII of the Preamble.

4.1.2 Particulate Matter

4.1.2.1 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.¹⁵⁷ 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 ($\text{PM}_{2.5}$; 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 $\text{PM}_{2.5}$ and PM_{10} , are referred to as "thoracic coarse particles" ($\text{PM}_{10-2.5}$, particles with a nominal mean aerodynamic diameter greater than 2.5 μm and less than or equal to 10 μm). EPA currently has standards that regulate $\text{PM}_{2.5}$ and PM_{10} .^{SS}

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 $\text{PM}_{2.5}$, which often remains in the atmosphere for days to weeks before being removed by wet or dry deposition.¹⁵⁸ In contrast, atmospheric lifetimes for UFP and $\text{PM}_{10-2.5}$ are shorter. Within hours, UFP can undergo coagulation and condensation that lead to formation of larger particles in the accumulation mode, or can be removed from the atmosphere by evaporation, deposition, or

^{RR} Children are more susceptible than adults to many air pollutants because of differences in physiology, higher per body weight breathing rates and consumption, rapid development of the brain and bodily systems, and behaviors that increase chances for exposure. Even before birth, the developing fetus may be exposed to air pollutants through the mother that affect development and permanently harm the individual.

Infants and children breathe at much higher rates per body weight than adults, with infants under one year of age having a breathing rate up to five times that of adults. In addition, children breathe through their mouths more than adults and their nasal passages are less effective at removing pollutants, which leads to a higher deposition fraction in their lungs.

^{SS} 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., $\text{PM}_{10-2.5}$).

reactions with other atmospheric components. PM_{10-2.5} are also generally removed from the atmosphere within hours, through wet or dry deposition.¹⁵⁹

Particulate matter consists of both primary and secondary particles. Primary particles are emitted directly from sources, such as combustion-related activities (e.g., industrial activities, motor vehicle operation, biomass burning), while secondary particles are formed through atmospheric chemical reactions of gaseous precursors (e.g., sulfur oxides (SO_x), nitrogen oxides (NO_x) and volatile organic compounds (VOCs)). From 2000 to 2017, national annual average ambient PM_{2.5} concentrations have declined by over 40 percent,^{TT} largely reflecting reductions in emissions of precursor gases.

4.1.2.2 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 (PM ISA), which was finalized in December 2019.¹⁶⁰ 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.^{UU} Within this characterization, the PM ISA summarizes the health effects evidence for short- and long-term exposures to PM_{2.5}, PM_{10-2.5}, and ultrafine particles, and concludes that human exposures to ambient PM_{2.5} are associated with a number of adverse health effects. The discussion below highlights the PM ISA's conclusions 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 2020 Policy Assessment for the review of the PM NAAQS.¹⁶¹

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 mortality and cardiovascular effects and a “likely to be causal relationship” between long- and short-term PM_{2.5} exposures and respiratory effects.¹⁶² 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. In addition, EPA noted that there was more limited and uncertain evidence 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,

TT See <https://www.epa.gov/air-trends/particulate-matter-pm25-trends> and <https://www.epa.gov/air-trends/particulate-matter-pm25-trends#pmnat> for more information.

UU The causal framework draws upon the assessment and integration of evidence from across scientific disciplines, spanning atmospheric chemistry, exposure, dosimetry and health effects studies (i.e., epidemiologic, controlled human exposure, and animal toxicological studies), and assess the related uncertainties and limitations that ultimately influence our understanding of the evidence. This framework employs a five-level hierarchy that classifies the overall weight-of-evidence with respect to the causal nature of relationships between criteria pollutant exposures and health and welfare effects using the following categorizations: causal relationship; likely to be causal relationship; suggestive of, but not sufficient to infer, a causal relationship; inadequate to infer the presence or absence of a causal relationship; and not likely to be a causal relationship (U.S. EPA. (2019). Integrated Science Assessment for Particulate Matter (Final Report). U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-19/188, Section P. 3.2.3).

and short-term exposure and nervous system effects resulting in the ISA concluding "suggestive of, but not sufficient to infer, a causal relationship".

As discussed extensively in the 2019 PM ISA, recent studies continue to support and extend the evidence base linking short- and long-term PM_{2.5} exposures and mortality.¹⁶³ For short-term PM_{2.5} exposure, recent 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, with the strongest evidence for exacerbations of chronic obstructive pulmonary disease (COPD) and asthma, provide biological plausibility for cause-specific mortality and ultimately total 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 (CHD), 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.

A large body of recent studies examining both short- and long-term PM_{2.5} exposure and cardiovascular effects supports and extends the evidence base evaluated in the 2009 PM ISA. Some of the strongest evidence from both experimental and epidemiologic studies examining short-term PM_{2.5} exposures are for ischemic heart disease (IHD) and heart failure. The evidence for cardiovascular effects is coherent across studies of short-term PM_{2.5} exposure that have observed associations with 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 studies continue to provide evidence of a relationship between both short- and long-term PM_{2.5} exposure and respiratory effects. Epidemiologic and animal toxicological studies examining short-term PM_{2.5} exposure provide consistent evidence of asthma and COPD exacerbations, in children and adults, respectively. This evidence is supported by epidemiologic studies examining asthma and COPD emergency department visits and hospital admissions, as well as respiratory mortality. However, there is inconsistent evidence of respiratory effects, specifically lung function declines and pulmonary inflammation, in controlled human exposure

studies. Epidemiologic studies conducted in the U.S. and abroad provide evidence of a relationship between long-term PM_{2.5} exposure and 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. 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 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 (ASD) 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, epidemiologic studies of neurodevelopmental effects 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 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 in analyses limited to never smokers. The epidemiologic evidence is supported by both experimental and epidemiologic evidence of genotoxicity, epigenetic effects, carcinogenic potential, and that PM_{2.5} exhibits several characteristics of carcinogens, which collectively provides biological plausibility for cancer development.

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.”¹⁶⁴

For both PM_{10-2.5} and UFPs, for all health effects categories evaluated, the 2019 PM ISA concluded that the evidence was “suggestive of, but not sufficient to infer, a causal relationship” or “inadequate to determine the presence or absence of a causal relationship.” For PM_{10-2.5}, although a Federal Reference Method (FRM) was instituted in 2011 to measure PM_{10-2.5} concentrations nationally, the causality determinations reflect that the same uncertainty identified in the 2009 PM ISA with respect to the method used to estimate PM_{10-2.5} concentrations in epidemiologic studies persists. Specifically, across epidemiologic studies, different approaches are used to estimate PM_{10-2.5} concentrations (e.g., direct measurement of PM_{10-2.5}, difference between PM₁₀ 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, 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 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.”^{165,166} 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. 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, populations that are of low socioeconomic status, and current/former smokers could be at increased risk for adverse PM_{2.5}-related health effects.

4.1.3 Nitrogen Oxides

4.1.3.1 Background on Nitrogen Oxides

Oxides of nitrogen (NO_x) refers to nitric oxide (NO) and nitrogen dioxide (NO₂). Most NO₂ 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 4.1.1 and 4.1.1 respectively.

4.1.3.2 Health Effects Associated with Exposure to Nitrogen Oxides

The most recent review of the health effects of oxides of nitrogen completed by EPA can be found in the 2016 Integrated Science Assessment for Oxides of Nitrogen - Health Criteria (Oxides of Nitrogen ISA).¹⁶⁷ The primary source of NO₂ is motor vehicle emissions, and ambient NO₂ concentrations tend to be highly correlated with other traffic-related pollutants. Thus, a key issue in characterizing the causality of NO₂-health effect relationships consists of evaluating the extent to which studies supported an effect of NO₂ 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 NO₂ exposure. The strongest evidence supporting an independent effect of NO₂ exposure comes from controlled human exposure studies demonstrating increased airway responsiveness in individuals with asthma following ambient-relevant NO₂ exposures. The coherence of this evidence with epidemiologic findings for asthma hospital admissions and ED visits as well as lung function decrements and increased pulmonary inflammation in children with asthma describe a plausible pathway by which NO₂ 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 NO₂ exposure and respiratory effects. This conclusion is based on new epidemiologic evidence for associations of NO₂ 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 NO₂ exposure and cardiovascular effects and mortality and between long-term NO₂ 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 NO₂ 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 NO₂ is copollutant confounding, particularly by other roadway pollutants. The available evidence for non-respiratory health effects does not adequately address whether NO₂ 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 NO₂-related health effects. In these groups and lifestages, NO₂ is consistently related to larger effects on outcomes related to asthma exacerbation, for which there is confidence in the relationship with NO₂ exposure.

4.1.4 **Carbon Monoxide**

4.1.4.1 **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.

4.1.4.2 **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).¹⁶⁸ The CO ISA presents conclusions regarding the presence of causal relationships between CO exposure and categories of adverse health effects.^{vv} This section provides a summary of the health effects associated with exposure to ambient concentrations of CO, along with the CO ISA conclusions.^{ww}

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 suggestive of a causal relationship between long-term exposures to CO and developmental effects and birth outcomes.

^{vv} 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.

^{ww} 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.

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, SO₂, and PM in two-pollutant models and found that CO risk estimates were generally robust, although this limited evidence makes it difficult to disentangle effects attributed to CO itself from those of the larger complex air pollution mixture. Controlled human exposure studies have not extensively evaluated the effect of CO on respiratory morbidity. Animal studies at levels of 50-100 ppm CO show preliminary evidence of altered pulmonary vascular remodeling and oxidative injury. The CO ISA concludes that the evidence is suggestive of a causal relationship between short-term CO exposure and respiratory morbidity, and inadequate to conclude that a causal relationship exists between long-term exposure and respiratory morbidity.

Finally, the CO ISA concludes that the epidemiologic evidence is suggestive of a causal relationship between short-term concentrations of CO and mortality. Epidemiologic evidence suggests an association exists between short-term exposure to CO and mortality, but limited evidence is available to evaluate cause-specific mortality outcomes associated with CO exposure. In addition, the attenuation of CO risk estimates which was often observed in 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.

4.1.5 Diesel Exhaust

4.1.5.1 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 lifetime of the components present in diesel exhaust ranges from seconds to days.

4.1.5.2 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.^{169,170} 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 $5 \mu\text{g}/\text{m}^3$ 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 $\text{PM}_{2.5}$ NAAQS of $15 \mu\text{g}/\text{m}^3$. In 2012, EPA revised the annual $\text{PM}_{2.5}$ NAAQS to $12 \mu\text{g}/\text{m}^3$ and this was retained in 2020 and is being reconsidered as of June 10, 2021.^{XX} 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 $\text{PM}_{2.5}$ NAAQS is designed to provide protection from the noncancer health effects and premature mortality attributed to exposure to $\text{PM}_{2.5}$. The contribution of diesel PM to total ambient PM varies in different regions of the country and also, within a region, from one area to another. The contribution can be high in near-roadway environments, for example, or in other locations where diesel engine use is concentrated.

XX <https://www.epa.gov/pm-pollution/national-ambient-air-quality-standards-naaqs-pm>

Since 2002, several new studies have been published which continue to report increased lung cancer risk associated with occupational exposure to diesel exhaust from older engines. Of particular note since 2011 are three new epidemiology studies which have examined lung cancer in occupational populations, including, truck drivers, underground nonmetal miners and other diesel motor-related occupations. These studies reported increased risk of lung cancer related to exposure to diesel exhaust, with evidence of positive exposure-response relationships to varying degrees.^{171,172,173} 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."¹⁷⁴ This designation was an update from its 1988 evaluation that considered the evidence to be indicative of a "probable human carcinogen."

4.1.6 **Air Toxics**

Heavy-duty engine emissions contribute to ambient levels of air toxics that are known or suspected human or animal carcinogens, or that have noncancer health effects. The population experiences an elevated risk of cancer and other noncancer health effects from exposure to the class of pollutants known collectively as "air toxics."¹⁷⁵ These compounds include, but are not limited to, benzene, formaldehyde, acetaldehyde, and naphthalene. These compounds were identified as national or regional risk drivers or contributors in the 2014 National-scale Air Toxics Assessment and have significant inventory contributions from mobile sources.^{176,177}

4.1.6.1 **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.^{178,179,180} 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 2.2×10^{-6} to 7.8×10^{-6} per $\mu\text{g}/\text{m}^3$ as the unit risk estimate (URE) for benzene.^{YY,181} 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.^{182,183}

^{YY} A unit risk estimate is defined as the increase in the lifetime risk of an individual who is exposed for a lifetime to $1 \mu\text{g}/\text{m}^3$ benzene in air.

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.^{184,185} The most sensitive noncancer effect observed in humans, based on current data, is the depression of the absolute lymphocyte count in blood.^{186,187} 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.^{188,189,190,191} 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.^{192,ZZ}

4.1.6.2 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.¹⁹³ 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.^{194,195,196}

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.^{197,198,199} 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.²⁰⁰ 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.²⁰¹ Finally, a study of embalmers reported formaldehyde exposures to be associated with an increased risk of myeloid leukemia but not brain cancer.²⁰²

Health effects of formaldehyde in addition to cancer were reviewed by the Agency for Toxic Substances and Disease Registry in 1999, supplemented in 2010, and by the World Health Organization.^{203,204,205} 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.²⁰⁶ That draft assessment reviewed more recent research from animal and

^{ZZ} 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.

human studies on cancer and other health effects. The NRC released their review report in April 2011.²⁰⁷ EPA's draft assessment, which addresses NRC recommendations, was suspended in 2018.²⁰⁸ The draft assessment was unsuspended in March 2021.

4.1.6.3 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.²⁰⁹ The URE in IRIS for acetaldehyde is 2.2×10^{-6} per $\mu\text{g}/\text{m}^3$.²¹⁰ 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.^{211,212}

The primary noncancer effects of exposure to acetaldehyde vapors include irritation of the eyes, skin, and respiratory tract.²¹³ In short-term (4 week) rat studies, degeneration of olfactory epithelium was observed at various concentration levels of acetaldehyde exposure.^{214,215} Data from these studies were used by EPA to develop an inhalation reference concentration of $9 \mu\text{g}/\text{m}^3$. Some asthmatics have been shown to be a sensitive subpopulation to decrements in functional expiratory volume (FEV1 test) and bronchoconstriction upon acetaldehyde inhalation.²¹⁶ 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.²¹⁷

4.1.6.4 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.²¹⁸ Chronic (long term) exposure of workers and rodents to naphthalene has been reported to cause cataracts and retinal damage.²¹⁹ EPA released an external review draft of a reassessment of the inhalation carcinogenicity of naphthalene based on a number of recent animal carcinogenicity studies.²²⁰ The draft reassessment completed external peer review.²²¹ Based on external peer review comments received, EPA was developing a revised draft assessment that considers all routes of exposure, as well as cancer and noncancer effects; this reassessment was suspended in 2018.²²² 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.²²³ 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.²²⁴

Naphthalene also causes a number of chronic non-cancer effects in animals, including abnormal cell changes and growth in respiratory and nasal tissues.²²⁵ The current EPA IRIS assessment includes noncancer data on hyperplasia and metaplasia in nasal tissue that form the basis of the inhalation RfC of $3 \mu\text{g}/\text{m}^3$.²²⁶ The ATSDR MRL for acute exposure to naphthalene is 0.6 mg/kg/day.

4.1.6.5 Health Effects Associated with Exposure to Other Air Toxics

In addition to the compounds described above, other compounds found in gaseous hydrocarbon and PM emissions from engines will be affected by this proposed rule. Mobile source air toxic compounds that would potentially be affected include acrolein, ethylbenzene, propionaldehyde, toluene, and xylene. Information regarding the health effects of these compounds can be found in EPA's IRIS database.²²⁷

4.1.7 Exposure and Health Effects Associated with Traffic

In addition to health concerns resulting from specific air pollutants, a large number of studies have examined the health status of populations near major roadways. These studies frequently employ exposure metrics that are not specific to individual pollutants, but rather reflect the large number of different pollutants found in elevation near major roads.

In this section of the draft RIA, information on health effects associated with air quality near major roads or traffic in general is summarized. The information presented in this section relies on a systematic literature review performed by the Health Effects Institute (HEI) Panel on the Health Effects of Traffic-Related Air Pollution, *Traffic-Related Air Pollution: A Critical Review of the Literature on Emissions, Exposure, and Health Effects* published in 2010.^{AAA,228} Other systematic reviews of relevant literature are also cited where appropriate.

It should be noted that HEI has another expert review underway of the literature on health studies associated with near-road air pollution. The publication of that review is currently planned for early 2022.

4.1.7.1 Sociodemographic Characteristics of Populations near Major Roads

A number of studies and data sets address the size and composition of the population living in close proximity of major roads.^{229,230,231,232} The studies vary in how they describe what constitutes a major road, and in the distance considered to be near enough to report. Consistently, the studies demonstrate that there are tens of millions of Americans living near major roads, key examples follow.

Rowangould (2013) used population data from the 2010 and 2000 decennial U.S. Census along with traffic data from 2008 to estimate the size and sociodemographic composition of populations living near roads.²³³ Considering as "high volume" roads with great than 25,000 annual average daily traffic (AADT), an estimated 59.5 million people lived within 500 meters. Fourteen counties had more than 50 percent of the population within 500 meters of roads with at least 25,000 AADT, and counties with the largest share of population living near high volume roads were mostly in urban areas. Considering a distance of 100 meters from roads with >25,000 AADT, about 3 percent of the population or about 10 million people lived there. Considering the highest-volume roads (AADT over 250,000), about 0.1 percent of the population, or about 0.4

^{AAA} It should be noted that there are no peer reviewed EPA-authored reviews of traffic-related health studies. The HEI panel primarily used epidemiology studies for inferring whether there was sufficient evidence of a causal association existing between a particular health effect and traffic-related air pollution. In its weight-of-evidence determinations, the panel also placed "considerable weight" on controlled human exposure studies. However, it restricted consideration of other toxicological studies to whether or not the studies provided "general mechanistic support" for the inferences of causality made on the basis of epidemiology.

million people, lived within 100 meters of these largest roads, while about 1 percent of the population lived within 500 meters. According to Rowangould, being a member of a "racial minority group" (as defined in the study) or living in a location with lower household income was associated with a higher likelihood of living near a high-volume road. For example, while 19.3 percent of the population lived within 500 meters of roads with >25,000 AADT, 23.7 percent and 29.4 percent of Black and Latino populations (as defined in the study) lived in such locations. These demographic and economic differences were somewhat attenuated when controlling for population density.

EPA recently conducted a study to estimate the number of people living near truck freight routes in the United States.²³⁴ Based on a population analysis using the U.S. Department of Transportation's (USDOT) Freight Analysis Framework 4 (FAF4), an estimated 41 million people live within 100 meters of these freight routes, 72 million within 200 meters, 148 million within 500 meters, and 215 million within 1000 meters.^{BBB} In addition, relative to the rest of the population, people living near FAF4 truck routes are more likely to live in areas with higher population density (e.g., cities) and with higher percentages of people of color and lower income residents. Every two years from 1997 to 2009 and in 2011, the U.S. Census Bureau's American Housing Survey (AHS) conducted a survey that includes data on whether housing units are within 300 feet of an "airport, railroad, or highway with four or more lanes."^{CCC,235} The 2013 AHS also included that question, but that was the last AHS that included that question. The 2013 survey reports that 17.3 million housing units or 13 percent of all housing units in the U.S., were located in such areas. Assuming that populations are in the same locations as housing units, this corresponds to a population of more than 41 million U.S. residents in close proximity to 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.²³⁶ As such, highways represent the overwhelming majority of transportation facilities described by this factor in the AHS. Chapter 6.3.9 of the DRIA also includes a discussion about how human exposure to future air quality varies with sociodemographic characteristics relevant to potential environmental justice concerns in scenarios with and without the proposed rule in place.

4.1.7.2 Premature Mortality

The HEI panel report concluded that evidence linking traffic-associated air pollution with premature mortality from all causes was "suggestive but not sufficient" to infer a causal relationship. This conclusion was based largely on several long-term studies that "qualitatively" examined whether or not someone was exposed to traffic-associated air pollution. In addition, based on several short-term studies of exposure, the panel concluded that there was "suggestive but not sufficient" evidence to infer a causal relation between traffic-related exposure and cardiovascular mortality.

^{BBB} FAF4 is a model from the USDOT's Bureau of Transportation Statistics (BTS) and Federal Highway Administration (FHWA), which provides data associated with freight movement in the U.S. It includes data from the 2012 Commodity Flow Survey (CFS), the Census Bureau on international trade, as well as data associated with construction, agriculture, utilities, warehouses, and other industries. FAF4 estimates the modal choices for moving goods by trucks, trains, boats, and other types of freight modes. It includes traffic assignments, including truck flows on a network of truck routes. https://ops.fhwa.dot.gov/freight/freight_analysis/faf/

^{CCC} The variable was known as "ETTRANS" in the questions about the neighborhood.

4.1.7.3 Cardiovascular Effects

4.1.7.3.1 *Cardiac Physiology*

Exposure to traffic-associated pollutants has been associated with changes in cardiac physiology, including cardiac function. One common measure of cardiac function is heart rate variability (HRV), an indicator of the heart's ability to respond to variations in stress, reflecting the nervous system's ability to regulate the heart.^{DDD} Reduced HRV is associated with adverse cardiovascular events, such as myocardial infarction, in heart disease patients. The HEI panel concluded that available evidence provides evidence for a causal association between exposure to traffic-related pollutants and reduced control of HRV by the nervous system. Overall, the panel concluded that the evidence was "suggestive but not sufficient" to infer a causal relation between traffic-related pollutants and cardiac function. Studies suggest that HRV changes from traffic-related air pollution result in changes to heart rhythms, which can lead to arrhythmia.^{237,238}

4.1.7.3.2 *Heart Attack and Atherosclerosis*

The HEI panel report concluded that epidemiologic evidence of the association between traffic-related pollutants and heart attacks and atherosclerosis was "suggestive but not sufficient" to infer a causal association. In addition, the panel concluded that the toxicology studies they reviewed provided "suggestive evidence that exposure to traffic emissions, including ambient and laboratory-generated [PM] and diesel- and gasoline-engine exhaust, alters cardiovascular function." The panel noted there are few cardiovascular studies of human volunteers exposed to real-world traffic mixture, which were not entirely consistent. The panel notes that, taken together, the studies reviewed provide consistent evidence for exposure to PM and impaired cardiovascular responses. In addition to the HEI panel report, several other reviews of available evidence conclude that there is evidence supporting a causal association between traffic-related air pollution and cardiovascular disease, including one from the American Heart Association (AHA).²³⁹

A number of mechanisms for cardiovascular disease are highlighted in the HEI panel report, including modified blood vessel endothelial function (e.g., the ability to dilate), atherosclerosis, and oxidative stress. The HEI panel report cites "two well executed studies" in which hospitalization for acute myocardial infarction (i.e., heart attack) were associated with traffic exposures, and a prospective study finding higher rates of arterial hardening and coronary heart disease near traffic.

4.1.7.4 Respiratory Effects

4.1.7.4.1 *Asthma*

Pediatric asthma and asthma symptoms are the effects that have been evaluated by the largest number of studies in the epidemiologic literature on near-roadway exposure. In general, studies consistently show effects of residential or school exposure to traffic and asthma symptoms, and the effects are frequently statistically significant. Studies have employed both short-term and

^{DDD} The autonomic nervous system (ANS) consists of sympathetic and parasympathetic components. The sympathetic ANS signals body systems to "fight or flight." The parasympathetic ANS signals the body to "rest and digest." In general, HRV is indicative of parasympathetic control of the heart.

long-term exposure metrics, and a range of different respiratory measures. The HEI panel report concluded that there is sufficient evidence for a causal association between exposure to traffic-related air pollution and exacerbation of asthma symptoms in children.

While there is general consistency in studies examining asthma incidence in children, the available studies employ different definitions of asthma (e.g., self-reported vs. hospital records), methods of exposure assessment, and population age ranges. As such, the overall evidence, while supportive of an association between traffic exposure and new onset asthma, are less consistent than for asthma symptoms. The HEI report determined that evidence is between “sufficient” and “suggestive” of a causal relationship between exposure to traffic-related air pollution and incident (new onset) asthma in children (HEI Panel on the Health Effects of Traffic-Related Air Pollution, 2010). A recent meta-analysis of studies on incident asthma and air pollution in general, based on studies dominated by traffic-linked exposure metrics, also concluded that available evidence is consistent with HEI’s conclusion.²⁴⁰ The study reported excess main risk estimates for different pollutants ranging from 7-16 percent per 10 $\mu\text{g}/\text{m}^3$ of long-term exposure (random effects models). Other qualitative reviews (Salam et al., 2008; Braback and Forsberg, 2009) concluded that available evidence is consistent with the hypothesis that traffic-associated air pollutants are associated with incident asthma.^{241,242}

4.1.7.4.2 *Chronic Obstructive Pulmonary Disease (COPD)*

The HEI panel reviewed available studies examining COPD in the context of traffic-associated air pollution. Because of how the panel selected studies for inclusion in review, there were only two studies that they used to review the available evidence. Both studies reported some positive associations, but not for all traffic metrics. The small number of studies and lack of consistency across traffic metrics led the panel to conclude that there is insufficient evidence for traffic-associated air pollution causing COPD.

4.1.7.4.3 *Allergy*

There are numerous human and animal experimental studies that provides strongly suggestive evidence that traffic-related air pollutants can enhance allergic responses to common allergens.^{243,244,245} However, in its review of 16 epidemiologic studies that address traffic-related air pollution’s effect on allergies, the HEI panel reported that only two such studies showed consistently positive associations. As a result, despite the strongly suggestive experimental evidence, the panel concluded that there is “inadequate/insufficient” evidence of an association between allergy and traffic-associated air pollution. As noted above, the HEI panel considered toxicological studies only based on whether they provide mechanistic support for observations and inferences derived from epidemiology.

4.1.7.4.4 *Lung Function*

Lung function is a term describing how well the lungs help a person breath. To detect conditions associated with reduced lung function, there are numerous measurements of breathing (spirometry) that indicate the presence or degree of airway diseases such as asthma and chronic obstructive pulmonary disease (COPD). Forced vital capacity (FVC) is measured when a patient maximally fills their lungs and then blows their hardest in completely exhaling. The peak expiratory flow (PEF) is the maximum air flow achievable during exhalation. The forced expiratory volume in the first second of exhalation is referred to as FEV1. FEV1 and PEF reflect

the function of the large airways. FVC and FEV1, along with their ratio (FVC/FEV1) are used to classify airway obstruction in asthma and COPD. Measurements of air flow at various times during forced exhalation, such as 25 percent, 50 percent, and 75 percent, are also used. The flow at 75 percent of forced exhalation (FEF75) reflects the status of small airways, which asthma and COPD affect.^{EEE}

The HEI panel concluded that the available literature suggests that long-term exposure to traffic-related air pollution is associated with reduced lung function in adolescents and young adults, and that lung function is lower in populations in areas with high traffic-related air pollutant levels. However, the panel noted the difficulty of disentangling traffic-specific exposures from urban air pollution in general. The studies reviewed that were more specifically oriented toward traffic were not consistent in their findings. As a result, the panel found that the evidence linking lung function and traffic exposure is “inadequate and insufficient” to infer a causal relationship.

4.1.7.5 Reproductive and Developmental Effects

Several studies have reported associations between traffic-related air pollution and adverse birth outcomes, such as preterm birth and low birth weight. At the time of the HEI review, the panel concluded that evidence for adverse birth outcomes being causally associated with traffic-related exposures was “inadequate and insufficient.” Only four studies met the panel’s inclusion criteria and they had limited geographic coverage. One study provided evidence of small but consistently increased risks using multiple exposure metrics. No studies that were available at that time examined traffic-specific exposures and congenital abnormalities. Since then, several studies investigating birth outcomes have been published, but no new systematic reviews. One new meta-analysis of air pollution and congenital abnormalities has been published, though none of the reviewed studies includes traffic-specific exposure information.

The HEI panel also reviewed toxicological studies of traffic-related air pollutants and fertility. While numerous studies examining animal or human exposure and sperm count have been published, the panel concluded that the generally high exposure concentrations employed in the studies limited the applicability to typical ambient concentration levels. Because there was no overlap in the effects studied by epidemiology and toxicology studies, no synthesis review of the combined literature was undertaken by the HEI panel.

Since the HEI panel’s publication, a systematic review and meta-analysis of air pollution and congenital abnormalities was published.²⁴⁶ In that review, only one study directly included nearby traffic in its exposure analysis. As such, there are no systematic reviews that specifically address traffic’s impact on congenital abnormalities.

^{EEE} It should be noted that there are no peer reviewed EPA-authored reviews of traffic-related health studies. The HEI panel primarily used epidemiology studies for inferring whether there was sufficient evidence of a causal association existing between a particular health effect and traffic-related air pollution. In its weight-of-evidence determinations, the panel also placed “considerable weight” on controlled human exposure studies. However, it restricted consideration of other toxicological studies to whether or not the studies provided “general mechanistic support” for the inferences of causality made on the basis of epidemiology.

4.1.7.6 Cancer

4.1.7.6.1 *Childhood Cancer*

In 2014, Boothe et al. published a systematic review and meta-analysis of studies of childhood leukemia risks associated for populations near major roads.²⁴⁷ The study concluded that childhood leukemia was positively associated with residential exposure during childhood, but not during the prenatal period. Other literature reviews have not concluded that available evidence supports an association between childhood leukemia and traffic exposure.^{248,249} For example, the HEI panel concluded that the available epidemiologic evidence was “inadequate and insufficient” to infer a causal relationship between traffic-related air pollution and childhood cancer.

4.1.7.6.2 *Adult Cancer*

Several studies have examined the risk of adult lung cancers in relation to exposure to traffic-related air pollutants. The HEI panel evaluated four such studies and rated the available evidence as “inadequate and insufficient” to infer a causal relation for non-occupational lung cancer.

4.1.7.7 Neurological Effects

The HEI panel found that current toxicologic and epidemiologic literature on the neurotoxicity of traffic-related air pollution was inadequate for their evaluation. The panel noted that there were a number of toxicologic studies of traffic-associated pollutants, but found them to have diverse exposure protocols, animal models, and endpoints, making them unsuitable for systematic evaluation.

4.2 Environmental Effects Associated with Exposure to Pollutants

This section discusses the environmental effects associated with pollutants affected by this proposed rule, specifically particulate matter, ozone, NO_x and air toxics.

4.2.1 Visibility Degradation

Visibility can be defined as the degree to which the atmosphere is transparent to visible light.²⁵⁰ 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.^{251,252} 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.²⁵³

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 4-1 for an illustration of the important factors affecting visibility.²⁵⁴

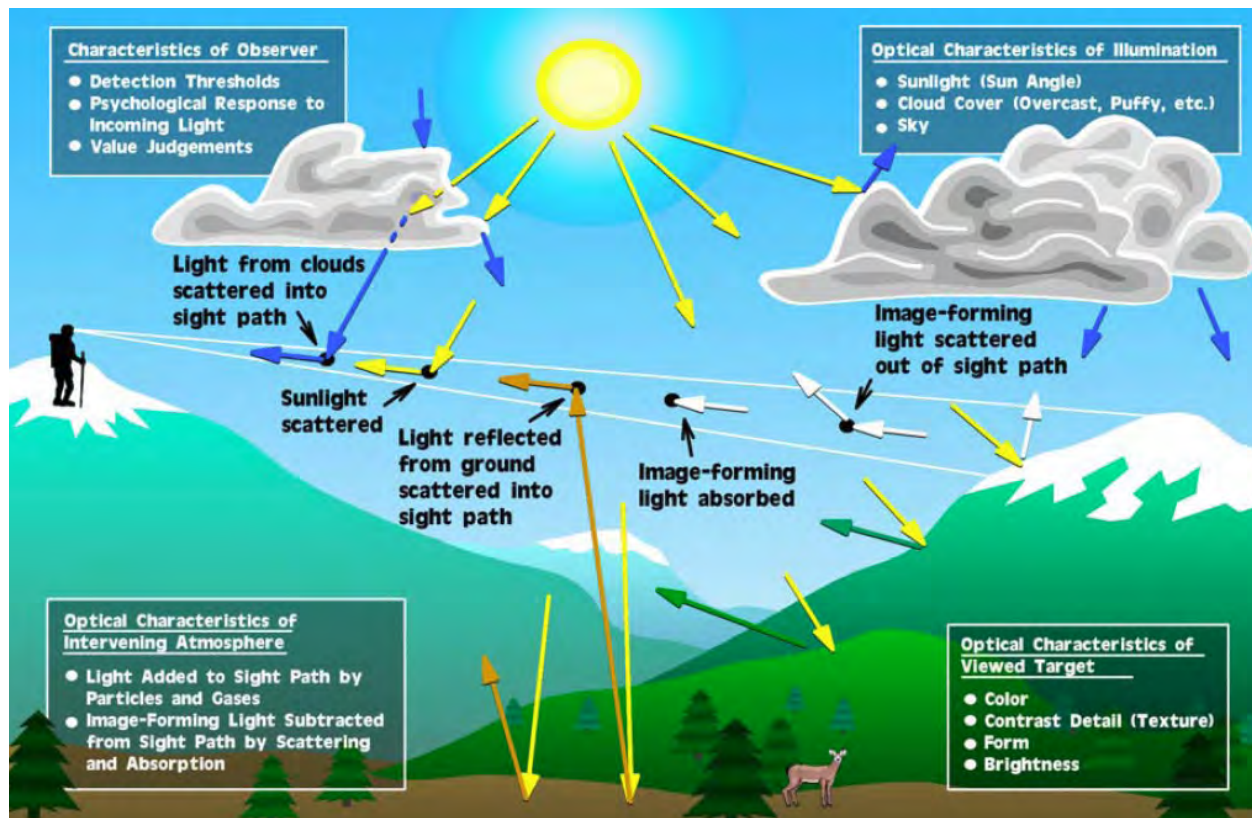


Figure 4-1: Important Factors Involved in Seeing a Scenic Vista (Malm, 2016)

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. 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 SO₂ and NO_x have decreased over time due to air pollution regulations such as the Acid Rain Program.²⁵⁵

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.²⁵⁶ 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 4-2 shows the location of the 156 Mandatory Class I Federal areas.



Figure 4-2: 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). EPA revised the $PM_{2.5}$ NAAQS in 2012, retained it in 2020, and established a target level of protection that is expected to be met through attainment of the existing secondary standards for $PM_{2.5}$.^{FFF}

4.2.1.1 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 4-2). 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

^{FFF} On June 10, 2021, EPA announced that it will reconsider the previous administration's decision to retain the PM NAAQS. <https://www.epa.gov/pm-pollution/national-ambient-air-quality-standards-naaqs-pm>.

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.²⁵⁷

4.2.2 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. Ozone effects that begin at small spatial scales, such as the leaf of an individual plant, when they occur at sufficient magnitudes (or to a sufficient degree), can result in effects being propagated 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.²⁵⁸ In those sensitive species^{GGG}, 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.^{259,HHH} 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

GGG 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.

HHH 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.

below ground, resulting in other, more subtle plant and ecosystems impacts.²⁶⁰ These latter impacts include increased susceptibility of plants to insect attack, disease, harsh weather, interspecies competition and overall decreased plant vigor. The adverse effects of ozone on areas with sensitive species could potentially lead to species shifts and loss from the affected ecosystems^{III}, resulting in a loss or reduction in associated ecosystem goods and services.²⁶¹ 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.²⁶² 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.²⁶³ 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.^{III} 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.

4.2.3 **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.^{264,265} This proposed rule would reduce emissions of nitrogen and PM but would not change emissions of sulfur.

4.2.3.1 **Deposition of Nitrogen and Sulfur**

Nitrogen and sulfur interactions in the environment are highly complex, as shown in Figure 4-3.²⁶⁶ 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

^{III} Per footnote above, ozone impacts could be occurring in areas where plant species sensitive to ozone have not yet been studied or identified.

^{III} 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.

ecosystems, excesses of nitrogen or sulfur can lead to acidification and nutrient enrichment.²⁶⁴ In addition, in aquatic ecosystems, sulfur deposition can increase mercury methylation.

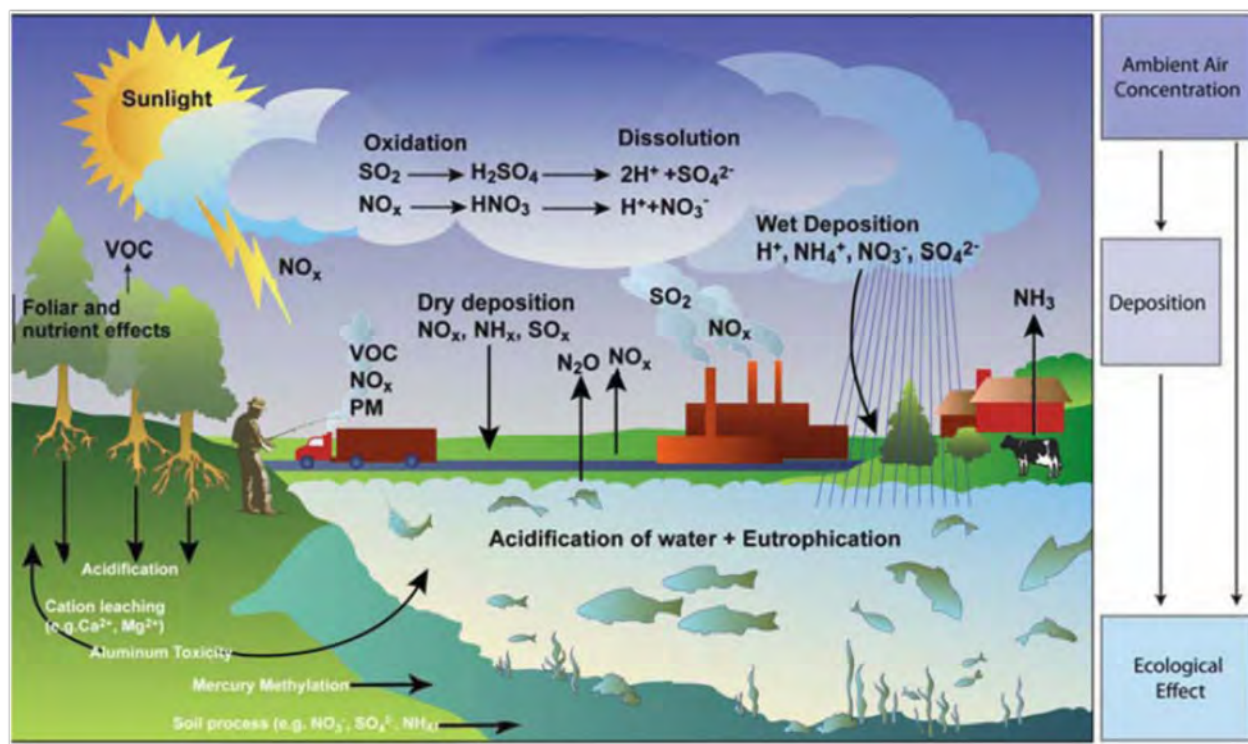


Figure 4-3: Nitrogen and Sulfur Cycling, and Interactions in the Environment

4.2.3.1.1 *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.²⁶⁴ Biological effects of acidification in terrestrial ecosystems are generally linked to aluminum toxicity and decreased ability of plant roots to take up base cations.²⁶⁴ 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.²⁶⁴

Geology (particularly surficial geology) is the principal factor governing the sensitivity of terrestrial and aquatic ecosystems to acidification from nitrogen and sulfur deposition.²⁶⁴ 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.²⁶⁴

4.2.3.1.1.1 *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. 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.^{267,268}

4.2.3.1.1.2 *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.²⁶⁴ 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.²⁶⁹ 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.²⁶⁴

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.²⁷⁰

4.2.3.1.2 *Ecological Effects from Nitrogen Enrichment*

4.2.3.1.2.1 *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.²⁷¹ 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.²⁷² 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.

4.2.3.1.2.2 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.

4.2.3.1.3 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.²⁶⁴ 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.²⁶⁴

Acute foliar injury from SO₂ 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 SO₂ exposures over the growing season. Besides foliar injury, chronic exposure to low SO₂ concentrations can result in reduced photosynthesis, growth, and yield of plants.²⁶⁴ 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. SO₂ is also considered the primary factor causing the death of lichens in many urban and industrial areas.²⁷³

Similarly, in sufficient concentrations, nitric oxide (NO), nitrogen dioxide (NO₂), peroxyacetyl nitrate (PAN), and nitric acid (HNO₃) 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 HNO₃ concentrations may be contributing to the decline in lichen species in the Los Angeles basin.²⁷⁴

4.2.3.1.4 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.²⁶⁴ Specifically, there appears to be a relationship between SO₄²⁻ 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 SO₄²⁻ 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.²⁶⁴

4.2.3.2 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.²⁶⁴ 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.²⁷⁵ 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.²⁶⁴ 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.²⁶⁴ 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.²⁶⁴ 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.²⁶⁴ 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.²⁷⁶

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.²⁶⁴ 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.²⁶⁴ 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.^{277,278} 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.²⁷⁹

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.^{280,281} 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.²⁶⁴ 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.²⁶⁴

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.²⁶⁴ 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.²⁶⁴ 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.²⁸² 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.

4.2.3.3 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.²⁸³ 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 (as monuments and building facings), and surface coatings (paints).²⁸⁴ 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.

4.2.4 Environmental Effects of Air Toxics

Emissions from producing, transporting and combusting fuel contribute to ambient levels of pollutants that contribute to adverse effects on vegetation. Volatile organic compounds (VOCs), some of which are considered air toxics, have long been suspected to play a role in vegetation damage.²⁸⁵ In laboratory experiments, a wide range of tolerance to VOCs has been observed.²⁸⁶ 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.²⁸⁷

Research suggests an adverse impact of vehicle exhaust on plants, which has in some cases been attributed to aromatic compounds and in other cases to nitrogen oxides.^{288,289,290} 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.

4.3. Climate-Related Effects from GHG Emissions

Elevated concentrations of carbon dioxide (CO₂), methane (CH₄), and other greenhouse gases (GHGs) in the atmosphere 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 well-documented atmospheric changes due to anthropogenic GHG emissions are changing the climate at a pace and in a way that threatens human health, society, and the natural environment.

Extensive information on climate change is available in the scientific assessments and 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 – CO₂, CH₄, nitrous oxide (N₂O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF₆) – “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. 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 the effects of climate change occurring outside the U.S. are reasonably expected to impact the U.S. population. (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. 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 change impacts have continued to intensify, with new observational records being set for several climate indicators such as global average surface temperatures, GHG concentrations, and sea level rise. Moreover, heavy precipitation events have increased in the eastern United States while agricultural and ecological drought has increased in the western United States along with more intense and larger wildfires.^{KKK} Recent assessment reports discuss how these observed trends are increasingly attributed to human-induced climate change^{LLL} and are expected to continue and worsen over the coming century, with stronger trends under higher warming scenarios.^{291,292,293} Climate impacts that occur outside U.S. borders also increasingly impact the welfare of individuals and firms that reside in the United States because of their connection to the global economy. This will occur through the effect of climate change on international markets, trade, tourism, and other activities. For example, supply chain disruptions are a prominent pathway through which U.S. business and consumers are, and will

^{KKK} See EPA’s November 2021 Proposed Standards of Performance for New, Reconstructed, and Modified Sources and Emissions Guidelines for Existing Sources: Oil and Natural Gas Sector Climate Review (<https://www.govinfo.gov/content/pkg/FR-2021-11-15/pdf/2021-24202.pdf>) for more discussion of specific examples. An additional resource for indicators can be found at <https://www.epa.gov/climate-indicators>.

^{LLL} For example, “[f]ield evidence shows that anthropogenic climate change has increased the area burned by wildfire above natural levels in western North America from 1984-2017 by double for the Western USA...(*high confidence*)” (AR6 WGII, p. 2-5).

continue to be, affected by climate change impacts abroad.^{291,294} Additional climate change induced international spillovers can occur through pathways such as damages across transboundary resources, economic and political destabilization, and global migration that can lead to adverse impacts on U.S. national security, public health, and humanitarian concerns.^{295,296} These and other trends highlight the increased risk already being experienced due to climate change as detailed in the 2009 and 2016 Endangerment Findings. Additionally, new major scientific assessments continue to 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 assessments include:

- U.S. Global Change Research Program's (USGCRP) 2016 Climate and Health Assessment and 2017–2018 Fourth National Climate Assessment (NCA4).^{297,298,291}
- IPCC's 2018 Global Warming of 1.5 °C, 2019 Climate Change and Land, and the 2019 Ocean and Cryosphere in a Changing Climate assessments, as well as the 2021 IPCC Sixth Assessment Report (AR6).^{299,300,301,302}
- The National Academies of Sciences, Engineering, and Medicine's 2016 Attribution of Extreme Weather Events in the Context of Climate Change, 2017 Valuing Climate Damages: Updating Estimation of the Social Cost of Carbon Dioxide, and 2019 Climate Change and Ecosystems assessments.^{303,304,305}
- National Oceanic and Atmospheric Administration's (NOAA) annual State of the Climate reports published by the Bulletin of the American Meteorological Society, most recently in August of 2020.³⁰⁶
- EPA Climate Change and Social Vulnerability in the United States: A Focus on Six Impacts (2021).³⁰⁷

Chapter 5 Emissions Inventory

5.1 Introduction

This chapter presents our analysis of the national emissions impacts of the proposed and alternative standards for calendar years 2027 through 2045. In addition to describing the national emission inventories, this chapter describes the methods used to estimate the spatially and temporally-resolved emission inventories in 2016 and 2045 that supported the air quality modeling analysis documented in Chapter 6.

The onroad national inventories were estimated using an updated version of EPA's Motor Vehicle Emission Simulator (MOVES) model, as described in detail in Chapter 5.2. The onroad national emission inventories were developed using a single national modeling domain, referred to as national-scale in MOVES. Using MOVES national-scale mode facilitates the estimation of national emission inventories for multiple scenarios and multiple calendar years within our available resource constraints. Inputs developed to model the national emission inventories for the proposed and alternative scenarios are discussed in Chapter 5.2.2. The national emissions inventory impacts on criteria and toxic air pollutants for calendar years 2030, 2040, and 2045 for proposed Option 1 and 2 and an alternative are presented in Chapter 5.3. In addition, the national emissions results for calendar years 2027 through 2045 are presented in Chapter 5.5.5 for criteria pollutants.

As described in Chapter 5.4, MOVES is also used to estimate the emission inventories for air quality modeling; however, the process is resource-intensive, requiring many sets of MOVES inputs and many MOVES runs to account for spatial and temporal differences in local vehicle activity and meteorology data. For this reason, we only used this method to estimate emissions for one scenario (proposed Option 1) in the two calendar years necessary for air quality analyses (2016 and 2045). The control scenario analyzed for air quality analysis differed from the proposed Option 1. Section 5.4 also compares the onroad emission inventories estimated from the national-scale runs to the emissions inventories estimated for the air quality analysis aggregated to the national-scale for calendar year 2045, in order to understand the impact of using different methods and control scenarios to estimate emissions inventories.

5.2 Model and Data Updates

To quantify the impacts of the proposed Options 1 and 2 and alternative on emissions, EPA developed an updated version of MOVES, referred to as "MOVES CTI NPRM", that includes significant updates to heavy-duty vehicle emission rates and activity from MOVES2014b, the public version of the model at the time of the analysis (see Table 5-1). Detailed descriptions of the underlying data and analyses that informed the model updates are documented in peer-reviewed technical reports referenced in Table 5-1. In addition, the MOVES CTI NPRM version used to generate the emissions inventories can be found in the docket.³⁰⁸

Table 5-1: Updates to MOVES CTI NPRM from MOVES2014b

MOVES updates	Description
Heavy-duty Greenhouse Gas Phase 2 Rulemaking ^{309,310}	Data updates and algorithm modifications to model the emission control technologies from the HD GHG Phase 2 Rulemaking. These include improvements in engine and vehicle efficiency, reductions in tire rolling resistance and aerodynamic drag, increased use of idle reduction technologies, and updated main engine and auxiliary power unit emission rates
Off-network idle ³⁰⁹	Update MOVES algorithms to incorporate off-network idling, which includes truck idle activity off the road network, such as at the curbside, parking lots, distribution centers, truck depots, ports, and construction sites. Incorporate idle data from instrumented truck studies
Heavy-duty start activity ³⁰⁹	Update MOVES algorithms and data to incorporate start data collected from instrumented truck studies
Hotelling activity ³⁰⁹	Update MOVES algorithms for modeling hotelling activity (rest periods for long-haul combination trucks)
Heavy-duty vehicle weights ³⁰⁹	Update heavy-duty vehicle weights by vehicle vocation and weight class
Heavy-duty running exhaust emission rates ³¹⁰	Update heavy-duty diesel running exhaust emission rates for 2010 and later model year vehicles using data from the Heavy-Duty In-Use Testing (HDIUT) Program
Heavy-duty start emission rates ³¹⁰	Update heavy-duty start emission rates using engine certification data submitted by engine manufacturers
Glider trucks ^{309,310}	Add glider trucks to MOVES. Incorporate emission rates based on NVFEL test program of glider trucks
Heavy-duty compressed natural gas (CNG) vehicles and emissions ^{309,310}	Update heavy-duty CNG exhaust emission rates based on HDIUT program, and update MOVES to include CNG fuel use in additional heavy-duty vehicle types
Heavy-duty gasoline vehicles ^{310,311}	Update heavy-duty gasoline tailpipe emission rates based on test program conducted at NVFEL, and update data regarding onboard refueling vapor recovery systems used in heavy-duty gasoline vehicles
Heavy-duty population and activity information ³⁰⁹	Update information on heavy-duty vehicle populations based on vehicle registration data, FHWA vehicle miles traveled data, and updated projections from the Annual Energy Outlook 2018 ³¹²
Speciation Updates ^{311,313}	Update speciation profiles (used to estimate total organic gases, volatile organic compounds, and individual organic compounds, such as methane and toxics) for model year 2010 and later heavy-duty diesel vehicles
Light-duty vehicle and other changes ^{309,311}	Other changes to MOVES, including updated gasoline fuel properties, light-duty vehicle emissions rates, light-duty activity, and other changes outlined in technical memo to the docket

5.2.1 **Methodology Overview**

We used MOVES CTI NPRM to estimate the emissions impacts of the proposed and alternative control scenarios. First, we estimated emissions for a baseline scenario in which there are no new heavy-duty engine emission standards. We then estimated emissions for each of the three control scenarios: the proposed Option 1, proposed Option 2, and the Alternative. For description of the proposed options and alternative program aspects, see Chapter 1. The emissions impacts of the proposed Options 1 and 2 and the Alternative control scenarios were estimated by calculating the difference between the emissions estimated in the baseline and each of the control scenarios. All of the model inputs, MOVES runspec files, and the scripts used for the analysis, as well as the version of MOVES used to generate the emissions inventories, can be found in the docket.³⁰⁸

For the baseline scenario, we used the heavy-duty exhaust emission rates in the default database for the MOVES CTI NPRM, which are described in detail in the MOVES CTI NPRM technical report.³¹⁰ Note that because the national emissions inventories used a single national modeling domain, the baseline scenario did not account for different emission standards in California or other states that have adopted the California emission standards, for either heavy-duty or light-duty vehicles. At the time of the analysis for this proposed rule, California had not finalized its proposed HD low NO_x Omnibus rule³¹⁴; thus, we modeled only the existing federal heavy-duty standards for all US States. For light-duty vehicles, MOVES can account for States that have adopted California's Low Emission Vehicle (LEV) program under Section 177 of the Clean Air Act. However, the single modeling domain used in national-scale modeling does not allow us to include the LEV program in California and Section 177 States emission estimates. Expanding the number of MOVES runs to include the state-by-state LEV programs would greatly increase the number of MOVES runs and was deemed outside the scope of this analysis^{MMM} because the purpose of this analysis is to estimate the emission reductions from the heavy-duty sector due to the proposed rule. Note that the LEV program in California and Section 177 States are included as inputs in the county-scale MOVES runs conducted to develop the emissions inventory used for air quality analyses documented in Chapter 5.4.

The vehicle activity and fuel inputs were kept the same for baseline and control scenarios. For vehicle activity, we used the default inputs in MOVES CTI NPRM (e.g., fleet age distributions, vehicle miles traveled by vehicle type and road type, vehicle speeds, off-network idling, hotelling hours, and start activity). The default activity data are described in detail in a recent MOVES model technical report.³⁰⁹ For example, as shown in Table 5-1 above, future year projections of vehicle populations and vehicle miles travelled were updated to reflect the estimates from the Department of Energy's Annual Energy Outlook 2018.³¹² Note that the vehicle activity data for the emissions inventory used for the air quality analyses included local activity data as documented in Chapter 5.4.

The fuel inputs used in the MOVES CTI NPRM emission inventory runs were updated from the default fuel database in MOVES2014b using revised assumptions and more recently available compliance data. These changes include setting the diesel fuel supply nationwide to B5 biodiesel, setting the gasoline fuel supply for calendar years 2012 and later to E10 nationwide (no E0 or E15 gasoline), updating gasoline fuel properties on latest available data from EPA's fuel compliance system and updating the characterizations of local fuel programs. We used the same fuel usage and fuel property data for all the MOVES runs for calendar years from 2027 through 2060.³¹¹ Additional details on updates to the fuels in MOVES CTI NPRM runs are documented in the MOVES CTI NPRM Technical Report.³¹¹

The same fuel inputs are used in both the national emission inventory runs and the emission inventory runs used for air quality modeling. The national emissions inventory runs aggregate the gasoline fuel properties into a single region representing the United States, whereas the county-level MOVES runs for the air quality modeling analysis account for county and regional differences in gasoline fuel properties. Diesel and CNG fuel properties are represented with one set of fuel properties to represent the entire nation for each calendar year and fuel type. As such,

^{MMM} The state-specific LEV programs are included in the emission inventories used for the air quality modeling analysis of the proposed rule as discussed in Section 5.4.

no precision on the diesel and CNG fuel effects are averaged when running MOVES in national-scale.

The emission rate inputs developed for modeling the control scenarios (proposed Option 1 and 2 and the Alternative) are discussed in detail in the following section.

5.2.2 MOVES Emission Rates for Control Scenarios

We developed separate MOVES emission rates for the proposed Options 1 and 2 and the Alternative (collectively referred to as the control scenarios). The methodologies used to develop the emission rates reflect the effects of this rulemaking's program elements (duty-cycle standards, off-cycle standards, closed crankcase requirements, refueling standards, regulatory useful life, and emissions warranty) on vehicles subject to the proposed rule as described below. We did not estimate the emission impacts of our proposed compliance provisions that target long-term compliance assurance. As we describe in Section IV of the preamble to this rule, we expect improved serviceability and updates to our current inducement policy will discourage owners from tampering their engines or emission control systems; however, we had insufficient data to estimate the impact of these proposals.

MOVES has separate emission rates for heavy-duty vehicles according to three different fuel types—diesel, gasoline, and natural gas (NG)—and six different regulatory vehicle classes, shown in Table 5-2. The proposed rule includes new duty-cycle standards for all heavy-duty vehicles in the LHD45, MHD, HHD, and Urban Bus regulatory classes for all fuel types. The Urban Bus regulatory class was modeled using the same zero-mile emission rates as HHD for the control scenarios.^{NNN}

Light heavy-duty Class 2b and 3 trucks (LHD2b3) are composed of vehicles that are both chassis- and engine-certified. The proposed standards would apply to all engine-certified LHD2b3 vehicles, which are estimated to be a small fraction of the diesel LHD2b3 vehicles and are discussed in Chapter 5.2.2.6. All Class 2b and 3 gasoline-fueled vehicles are chassis-certified and would not be affected by the proposed rule.

A glider vehicle is a new motor vehicle produced with a used or remanufactured engine, and typically does not include the aftertreatment systems needed to meet the 2007 or 2010 heavy-duty emission standards.^{ooo} In MOVES, glider vehicles are modeled as heavy heavy-duty diesel vehicles (Class 8 Trucks) that are assumed to emit at a level equivalent to the model year 2000 HHD vehicles³¹⁰. Annual glider sales are fixed at 1,500 units per year for 2018 and later based on the 2018 and later sales volume cap for glider vehicles set forth in the Heavy-duty Greenhouse Gas Phase 2 Rulemaking³¹⁵, as well as the number of glider manufacturers and their historic production levels, as documented in the population and activity report.³⁰⁹ For the proposed rule analysis, we assumed there is no change to the sales of glider vehicles and no change to glider vehicle emission rates from the baseline scenario.

^{NNN} Urban Bus vehicles are also considered HHD vehicles. They are modeled as a separate regulatory class in MOVES because they had stricter PM emission standards for 1994 through 2006 model years. For the control scenarios, the Urban Bus emission rates were assumed to be equivalent to HHD except for the age effects discussed in Section 5.2.2.1.2.

^{ooo} See the definition of "glider vehicle" in 40 CFR 1037.801 and our discussion in the preamble of the heavy-duty GHG Phase 2 rulemaking (81 FR 73941, October 25, 2016).

Table 5-2: MOVES Heavy-duty Regulatory Classes and Relevant MOVES Fuel Types

MOVES Regulatory Class Description	regClassName	regClassID	Gross Vehicle Weight Rating (GVWR) [lb.]	MOVES Fuel Types
Light Heavy-Duty Class 2b and 3 trucks	LHD2b3	41	8,501 – 14,000	Gasoline, Diesel
Light Heavy-Duty Class 4 and 5 Trucks	LHD45	42	14,001 – 19,500	Gasoline, Diesel
Medium Heavy-Duty (Class 6 and 7 Trucks)	MHD	46	19,501 – 33,000	Gasoline, Diesel
Heavy Heavy-Duty (Class 8 Trucks)	HHD	47	> 33,000	Diesel, NG
Urban Bus	Urban Bus	48	> 33,000	Diesel, NG
Gliders (Class 8 Trucks)	Glider Vehicles	49	> 33,000	Diesel

For heavy-duty diesel vehicles, we developed nitrogen oxide (NO_x) emission rates for running, start, and extended idle processes, as discussed in Chapters 5.2.2.1, 5.2.2.2, and 5.2.2.3, respectively, in response to the proposed duty-cycle and off-cycle standards and the alternatives. The lower control case NO_x emission rates are anticipated to be achieved using the technologies discussed in Chapter 3.1.3, including cylinder deactivation (CDA) and dual selective catalytic reduction exhaust aftertreatment system. We also revised heavy-duty diesel emission running rates for NO_x, total hydrocarbons (THC), carbon monoxide (CO), and particulate matter below 2.5 microns (PM_{2.5}), due to the proposed changes to the regulatory useful life and warranty, by modifying MOVES' tampering and mal-maintenance (T&M) calculations, as discussed in Chapter 5.2.2.1.2. We also eliminated the PM_{2.5} crankcase emissions from heavy-duty diesel vehicles due to the proposed closed crankcase design requirement for heavy-duty diesel engines as discussed in Section 5.2.2.4.

For heavy-duty gasoline vehicles, we developed revised NO_x, THC, CO, and PM_{2.5} emission rates for running exhaust in response to the proposed duty-cycle standards, as discussed in Chapter 5.2.2.6. We also developed revised THC refueling emission rates in response to the proposed refueling standard discussed in Chapter 5.2.2.7. MOVES does not model extended idle emissions for heavy-duty gasoline vehicles. We also did not revise the start emission rates for heavy-duty gasoline vehicles even though we expect reductions in the start emissions due to the proposed standards. We plan to revisit these assumptions in the final rulemaking analysis.

For heavy-duty NG vehicles, we did not estimate reductions in the NO_x or other emission rates due to the proposed heavy-duty spark-ignition duty-cycle standards (discussed in Section III of the Preamble). As shown in the MOVES heavy-duty exhaust report^{PPP}, the average FTP emissions for MY 2010-2017 CNG engine families is close to 0.1 g/hp-hr. We expect reductions in NO_x emissions from heavy-duty NG engines with the proposed and alternative scenarios, however, in part due to the small contribution of NG emissions to total emissions, we did not estimate the reductions in NG engines in this analysis. We can revisit these assumptions in the final rulemaking analysis.

^{PPP} See Table 4-2 in Exhaust Emission Rates for Heavy-Duty Onroad Vehicles in MOVES_CTL_NPRM³¹⁰

Similarly, we did not estimate emission reductions from the proposed and alternative useful life and warranty requirements for gasoline and NG vehicles. This is because, in MOVES, we do not tie emission estimates to heavy-duty gasoline or NG vehicle warranty and useful life periods, but rather estimate age effects from emissions data, or adapt light-duty gasoline or heavy-duty diesel age effects. Gasoline and NG-fueled vehicles' contributions to the heavy-duty vehicle NO_x emissions inventory are small (see Figure 5-16), and thus we expect minimal impacts on our emission inventory estimates from our conservative approach of estimating reductions solely from running emissions for these vehicles.^{QQQ} Depending on the availability of emissions data from gasoline and NG-fueled vehicles that are operated past their regulatory useful life, as well as data on heavy-duty gasoline start emissions, we will consider accounting for emission reductions from the lengthened warranty and useful life requirements, as well as reductions from the start emissions from these vehicles, in the final rulemaking analysis.

While we estimated different emission rates for the control scenarios, we did not estimate differences in the speciation of the total organic gases and particulate matter emissions between the baseline and control scenarios. Emissions speciation refers to the calculation of individual compounds or classes of compounds within a broader pollutant. For example, MOVES conducts speciation to estimate benzene from volatile organic compound (VOC) emissions and particle-phase naphthalene from particulate matter (PM) emissions. Speciation is important to estimate individual toxics and necessary for air quality modeling. We do not have data to support differences in the emissions speciation between the control case and baseline scenarios. Heavy-duty diesel vehicles in the control case scenarios apply the same speciation values as the baseline scenario for heavy-duty diesel vehicles model year 2010 and later. Similarly, emissions from heavy-duty gasoline vehicles in the control scenarios use the same speciation as heavy-duty gasoline vehicles in the baseline scenario. Changes in emissions for individual compounds presented in Section 5.3 (acetaldehyde, benzene, formaldehyde, methane, and naphthalene) are due to changes in the hydrocarbon and particulate matter emission rates for the control scenarios presented in this section.

5.2.2.1 Heavy-Duty Diesel Running Emission Rates

This section documents the approach used to develop the heavy-duty diesel emission running rates for the control scenarios. We first estimated new zero-mile NO_x emission rates in response to the proposed Option 1, Option 2 and the Alternative duty-cycle and off-cycle standards as discussed in Chapter 5.2.2.1.1. The zero-mile emission rate in MOVES is defined as the emission rate of a new vehicle without any tampering and mal-maintenance effects. We then estimated the effects of lengthened regulatory useful life and warranty periods and applied them to the aged NO_x, THC, CO and PM_{2.5} emission rates for the proposed and alternative standards in Chapter 5.2.2.1.2.

Emission rates in MOVES are defined by the operating mode, regulatory class, model year, and fuel type. The running operating modes are defined in Table 5-3.

^{QQQ} Based on the MOVES national run, the percentages of the NG vehicle contributions to HD NO_x inventory in calendar year 2045 are: 0.59% (baseline), 1.43% (proposed Option 1), 1.24% (proposed Option 2), and 1.53% (Alternative). These contributions are dependent on the current projections of NG in the future heavy-duty fleet and the emission rates of NG vehicles, many of which are already meeting the 0.02 g/hp-hr NO_x standard.

Table 5-3: MOVES Running Operating Mode Definitions

OpModeID	Operating Mode	Vehicle Speed (v, mph)	Scaled Tractive Power (STP, skW)
0	Deceleration/Braking	All speeds	
1	Idle	$v < 1.0$	
11	Coast	$1 \leq v < 25$	$STP < 0$
12	Cruise/Acceleration		$0 \leq STP < 3$
13	Cruise/Acceleration		$3 \leq STP < 6$
14	Cruise/Acceleration		$6 \leq STP < 9$
15	Cruise/Acceleration		$9 \leq STP < 12$
16	Cruise/Acceleration		$12 \leq STP$
21	Coast	$25 \leq v < 50$	$STP < 0$
22	Cruise/Acceleration		$0 \leq STP < 3$
23	Cruise/Acceleration		$3 \leq STP < 6$
24	Cruise/Acceleration		$6 \leq STP < 9$
25	Cruise/Acceleration		$9 \leq STP < 12$
27	Cruise/Acceleration		$12 \leq STP < 18$
28	Cruise/Acceleration		$18 \leq STP < 24$
29	Cruise/Acceleration		$24 \leq STP < 30$
30	Cruise/Acceleration		$30 \leq STP$
33	Cruise/Acceleration	$50 \leq v$	$STP < 6$
35	Cruise/Acceleration		$6 \leq STP < 12$
37	Cruise/Acceleration		$12 \leq STP < 18$
38	Cruise/Acceleration		$18 \leq STP < 24$
39	Cruise/Acceleration		$24 \leq STP < 30$
40	Cruise/Acceleration		$30 \leq STP$

Note: The braking mode is defined by deceleration events. The other running operating modes are defined by vehicle speed (v) and scaled tractive power (STP), which is the vehicle power scaled by a constant f_{scale} factor (in units of metric tons). The f_{scale} factors were updated in MOVES CTI NPRM for 2010 and later model years to be more comparable to the average weight of vehicles within each heavy-duty MOVES regulatory class. Further details on the heavy-duty operating modes and definitions are included in the MOVES CTI NPRM technical report.³¹⁰

5.2.2.1.1 Emission Rates Based on Duty-Cycle and Off-Cycle Standards

We developed zero-mile heavy-duty diesel NO_x emission rates that reflect the proposed and alternative duty-cycle standards and the off-cycle standards. To do so, we first estimated the effects of the duty-cycle standards and the off-cycle standards separately, as discussed in Chapters 5.2.2.1.1.1 and 5.2.2.1.1.2, respectively. Then, we estimated the combined effect of both the duty-cycle standards and off-cycle standards on the zero-mile emission rates used in MOVES (see Chapter 5.2.2.1.1.3).

5.2.2.1.1.1 *Emission Rates Based on Duty-Cycle Standards*

In this section, we document the methods used to develop revised NO_x running emission rates for heavy-duty diesel vehicles based on the proposed and alternative duty-cycle standards. The baseline, proposed, and alternative NO_x heavy-duty compression ignition duty-cycle exhaust emission standards are shown in Table 5-4. The duty-cycle standards include three separate tests: low load cycle (LLC), Federal Test Procedure (FTP), and Supplemental Emission

Test - Ramped Modal Cycle (SET-RMC). The proposed Option 1 standards have two steps, with initial standards starting in Model Year (MY) 2027 vehicles and more stringent standards starting with MY 2030 vehicles. The proposed Option 2 and the Alternative do not include any phase-in and start in MY 2027. For the proposed Option 1, HHD vehicles have two separate FTP duty-cycle test standards for MY 2031 and later vehicles; one standard that applies through an intermediate useful life of 435,000 miles and another standard through the extended full useful life of 800,000 miles.

Table 5-4: Heavy-duty Compression Ignition Duty-Cycle Cycle NO_x Standards for the Proposed Options and Alternative Scenarios

Scenario	Applicable Model Years	Regulatory Classes	LLC (g/hp-hr)	FTP (g/hp-hr)	SET-RMC (g/hp-hr)
Baseline	Model Year 2010+	LHD, MHD, HHD	-	0.2	0.2
Proposed Option 1	Model Year 2027-2030	LHD, MHD, HHD	0.09	0.035	0.035
	Model Year 2031+	LHD, MHD	0.05	0.02	0.02
		HHD ^A (435,000/800,000)	0.05/0.1	0.02/0.04	0.02/0.04
Proposed Option 2	Model Year 2027+	LHD, MHD, HHD	0.1	0.05	0.05
Alternative	Model Year 2027+	LHD, MHD, HHD	0.1	0.02	0.02

^A In the proposed Option 1, HHD engines have a standard at the intermediate useful life of 435,000 miles, and at the extended useful life of 800,000 miles. LHD and MHD only have standards at the extended useful life.

The proposed and alternative scenarios also include revised standards for PM emissions as discussed in Section III of the draft preamble. We did not model the revised PM standards for heavy-duty diesel vehicles in MOVES because the revised PM standards are intended to prevent backsliding of PM reductions already achieved with current heavy-duty diesel emission control systems. As discussed in Chapter 5.2.2.1.2, we estimate reductions in heavy-duty diesel PM emissions would occur due to the proposed lengthened warranty and useful life periods and due to the proposed crankcase emissions control, as discussed in Chapter 5.2.2.4.

To develop running exhaust emission rates for the HHD MY 2031 and later vehicles in the proposed Option 1, we calculated the average emission rate from duty-cycle test standards during the useful life of the vehicles by weighting each standard by the miles they apply to during the useful life period using Equation 5-1.

Equation 5-1

$$\begin{aligned} &\text{HHD Weighted Average Engine Certification Standards} \\ &= \left(\frac{435K}{\text{Extended Useful Life}} \right) \times (\text{Standard at } 435K) \\ &+ \left(1 - \frac{435K}{\text{Extended Useful Life}} \right) \times (\text{Standard at Extended Useful Life}) \end{aligned}$$

For the FTP and SET-RMC standard, this equation yields:

$$\begin{aligned} &\text{HHD MY 2031 Weighted Average Engine Certification Standards} \\ &= \left(\frac{435K}{800K} \right) \times 0.02 \left(\frac{g}{hp \cdot hr} \right) + \left(1 - \frac{435K}{800K} \right) \times 0.04 \left(\frac{g}{hp \cdot hr} \right) \\ &= 0.029 \left(\frac{g}{hp \cdot hr} \right) \end{aligned}$$

The weighted average LLC, FTP and SET-RMC emission standards for HHD MY 2031 and later model years in the proposed Option 1 are shown in Table 5-5.

Table 5-5: Proposed Option 1 Weighted Average Heavy Heavy-duty Compression Ignition Duty-Cycle Test NO_x Standards

Applicable Model Years	LLC (g/hp-hr)	FTP (g/hp-hr)	SET-RMC (g/hp-hr)
2031+	0.073	0.029	0.029

We used the proposed and alternative standards for the FTP and (SET-RMC) to estimate the effect of the duty-cycle standards on MOVES NO_x emission rates. Because we do not have sufficient (LLC) test data on existing heavy-duty diesel vehicles to develop the modeling inputs specific for the proposed LLC standard in MOVES, we used the FTP standard to model the impact of the standards on low-power operation.

Equation 5-2 through Equation 5-7 were used to incorporate the effects of more stringent FTP and SET-RMC engine duty-cycle emission standards on MOVES running exhaust NO_x emission rates for model years subject to the proposed and alternative standards. The term R_{duty} is the ratio between the proposed or alternative emission standard and the current FTP and SET-RMC duty-cycle standards (0.2 g/hp-hr).

Equation 5-2

$$R_{duty} = \frac{\text{Proposed or Alternative FTP or SET RMC standard}}{\text{Current standard}}$$

R_{duty} ranges between 10 and 25 percent for the control scenarios considered, as shown in Table 5-6.

Table 5-6: R_{duty} Ratios Calculated for Each Scenario

Scenario	Applicable Model Years	Regulatory Classes	FTP and SET standard (g/hp-hr)	R_{duty}
Proposed Option 1	2027-2030	LHD, MHD, HHD	0.035	18%
	2031+	LHD, MHD	0.02	10%
		HHD	0.029	15%
Proposed Option 2	2027+	LHD, MHD, HHD	0.05	25%
Alternative	2027+	LHD, MHD, HHD	0.02	10%

To estimate the effect of proposed and alternative engine dynamometer duty-cycle standards on in-use emissions, we used the relationship between reductions in the most recent duty-cycle standard compared to reductions in in-use emissions. The 2010 0.2 g/hp-hr NO_x emission standard³¹⁶ is the most recent heavy-duty NO_x emission standard. To evaluate the in-use effectiveness of the 2010 standard, we compared the in-use NO_x emission rates from vehicles that were certified to the previous heavy-duty NO_x standard and the 2010 standard. Equation 5-3 defines R_{in_use} as the ratio between the percent change observed in-use from vehicles compliant with the 2010 NO_x standard relative to vehicles compliant with the previous standard, and the percent change in the 2010 standard FTP standards relative to the previous standard.^{RRR} In other words, R_{in_use} is the ratio between the relative effectiveness of reducing in-use emissions compared to the relative reduction in the FTP duty-cycle emission standard.

Equation 5-3

$$R_{in_use} = \frac{\% \text{ Change in the inuse emission rates from 2010 compliant vehicles}}{\% \text{ Change in the 2010 FTP standard}}$$

The percent change in in-use emission rates from vehicles certified to the 2010 standard (the numerator in Equation 5-3) was estimated using Equation 5-4. The MOVES emission rates for HHD vehicles certified to the 2010 0.2 g/hp-hr standard (the numerator) are calculated from 93 MY 2010-2015 HHD vehicles with engine family emission limit (FEL) certified below the 0.2 g/hp-hr NO_x emissions level and tested as part of the Heavy-Duty In-Use Testing program.³¹⁰ The MOVES emission rates for HHD vehicles certified to the 2004-2006 standard (the denominator) are based on 91 MY 2003-2006 trucks from two in-use datasets: ROVER data collected by the US EPA and the Heavy-Duty Diesel Consent Decree data collected by West Virginia University. The in-use datasets and analysis used to derive the emission rates in MOVES CTI NPRM are documented in the MOVES CTI NPRM heavy-duty exhaust technical report.³¹⁰

^{RRR} In 2004-2006, the NMHC+NO_x emission standard was 2.4 g/hp-hr; the 0.2 g/hp-hr NO_x standard began to be phased-in starting in 2007, with a full-phase in 2010.

Equation 5-4

$$\begin{aligned} & \% \text{ Change in the in_use emission rates from 2010 compliant vehicles} \\ & = \frac{\text{Emission rate from HHD 2010 compliant vehicles}}{\text{HHD MY 2006 MOVES emission rate}} - 1 \end{aligned}$$

The percent change from Equation 5-4 was applied to each MOVES operating mode to evaluate the effectiveness of the 2010 standard across different ranges of in-use operating conditions, as shown in Figure 5-1 and Table 5-7. The emission reduction is larger for the higher speed and higher load MOVES operating modes, with the largest decrease observed for speeds above 50 mph (operating modes 33 through 35). The lowest effectiveness of the standards is observed for low speed and several low power operating modes (operating mode 1, 11, and 21), with an exception of the deceleration bin (operating mode 0).

Equation 5-5 was used to estimate the percent reduction between the 2010 standard and the 2004-2006 emission standard. This term is also the denominator of Equation 5-3. The percent reduction in the NO_x emission standard was estimated assuming that NO_x emissions consist of 70 percent of the combined NMHC + NO_x 2004-2006 emission standard (2.4 g/hp-hr), consistent with the assumption used in MOVES2014b.³¹⁷ This value is also plotted as a line in Figure 5-1 to compare to the in-use emission rate reductions.

Equation 5-5

$$\% \text{ Change in the 2010 FTP standard} = \frac{0.2}{(70\% \times 2.4)} - 1 = -88.1\%$$

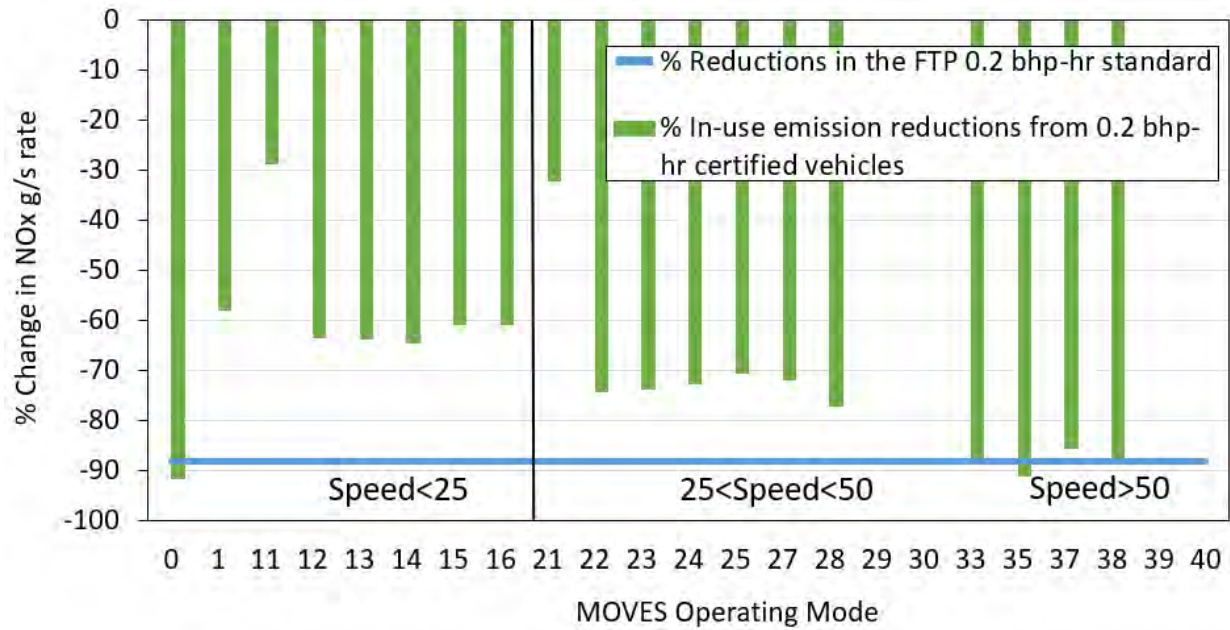


Figure 5-1: Percent change in in-use emission rates for 2010 standard (0.2 g/hp-hr) compliant HHD vehicles, compared to the percent change in the 2010 duty-cycle standard across MOVES operating modes

Table 5-7 displays the R_{in_use} as calculated by Equation 5-3. For operating modes with R_{in_use} values greater than one, the observed in-use emission reductions are greater than would be expected due to the change in FTP emission standard. R_{in_use} values less than one suggest that in-use emissions are less impacted than the change in the FTP emissions standard.

Table 5-7: Calculation of R_{in_use} by MOVES Operation Mode

MOVES OpMode	HHD MOVES MY 2006 NO _x emission rates (g/hr)	NO _x Emission rate from 2010 compliant HHD vehicles (g/hr) ^a	Percent change in in-use NO _x emission rates from 2010 compliant vehicles (%)	R_{in_use}
0	0.038	0.0031	-91.8	1.04
1	0.015	0.0063	-57.9	0.66
11	0.015	0.0106	-28.8	0.33
12	0.058	0.0210	-63.5	0.72
13	0.093	0.0339	-63.7	0.72
14	0.127	0.0453	-64.4	0.73
15	0.145	0.0565	-60.9	0.69
16	0.188	0.0734	-60.9	0.69
21	0.010	0.0066	-32.1	0.36
22	0.064	0.0163	-74.4	0.84
23	0.093	0.0243	-73.9	0.84
24	0.132	0.0359	-72.7	0.83
25	0.165	0.0485	-70.6	0.80
27	0.225	0.0633	-71.8	0.82
28	0.244	0.0558	-77.2	0.88
29	0.314			0.88 ^b
30	0.384			0.88
33	0.051	0.0062	-87.8	1.00
35	0.148	0.0130	-91.2	1.04
37	0.226	0.0323	-85.7	0.97
38	0.268	0.0306	-88.6	1.01
39	0.345			1.01
40	0.422			1.01

Notes:

^a The HHD rates in this table are based on f_{scale} of 17.1 metric tons to be consistent with the f_{scale} of the HHD MOVES CTI NPRM MY 2006 emission rates. Note that the f_{scale} for model year 2010 and later in MOVES CTI NPRM is 10 for HHD, 7 for MHD, and 5 for LHD45 and LHD2b3.³¹⁰

^b For operating modes lacking data, we used the same R_{in_use} for the closest operating mode.

Equation 5-6 is used to estimate the percentage reduction to NO_x running emissions from the change in the duty-cycle standard for each operating mode.^{SSS}

^{SSS} We assumed that the R_{in_use} values calculated by MOVES operating mode can be applied to the MOVES rates that are derived using a different f_{scale} . The change in f_{scale} does not change the definition of operating modes that are not defined by Scaled Tractive Power, STP (deceleration operating mode 0, and idle operating mode 1), or operating modes with negative STP values (operating mode 11 and 21), defined in Table 5-3. Changing the f_{scale} values does change the definition of vehicle operation in the other operating modes. However, because the R_{in_use} values are relatively constant for the positive power operating modes within each speed range as observed in Table 5-7Figure 5-1, we deemed it was not necessary to attempt to account for the f_{scale} differences when applying the R_{in_use} values.

Equation 5-6

$$R_{\text{duty_in_use}} = (1 - R_{\text{duty}}) \times R_{\text{in_use}}$$

Where:

$R_{\text{duty_in_use}}$ = the percent emission reductions in the in-use running NO_x emissions estimated from changing the FTP duty-cycle standard.

Equation 5-7 is used to estimate the heavy heavy-duty diesel NO_x running emission rates from the changes in the duty-cycle standard. The same calculations were applied to estimate the other heavy-duty diesel regulatory classes.^{TTT}

Equation 5-7

$$ER_{\text{duty_in_use}} = (1 - R_{\text{duty_in_use}}) \times ER_{\text{MOVES_baseline}}$$

Where:

$ER_{\text{duty_in_use}}$ = the MOVES running NO_x emission rates for the control scenarios based on reduction in the duty-cycle standard

$R_{\text{duty_in_use}}$ = the percent emission reductions in running NO_x emissions estimated from changing to FTP duty-cycle standard

$ER_{\text{MOVES_baseline}}$ = the MOVES baseline running NO_x emission rates for each regulatory class

The estimated HHD MOVES running NO_x emission rates for the control scenarios are shown in Figure 5-2.

^{TTT} We applied the $R_{\text{in_use}}$ developed on HHD data to both the LHD45 and MHD regulatory classes, which have different f_{scale} values in MOVES CTI NPRM for the 2010 and later model years. We believe this approximation is defensible for the similar reason provided in footnote SSS.

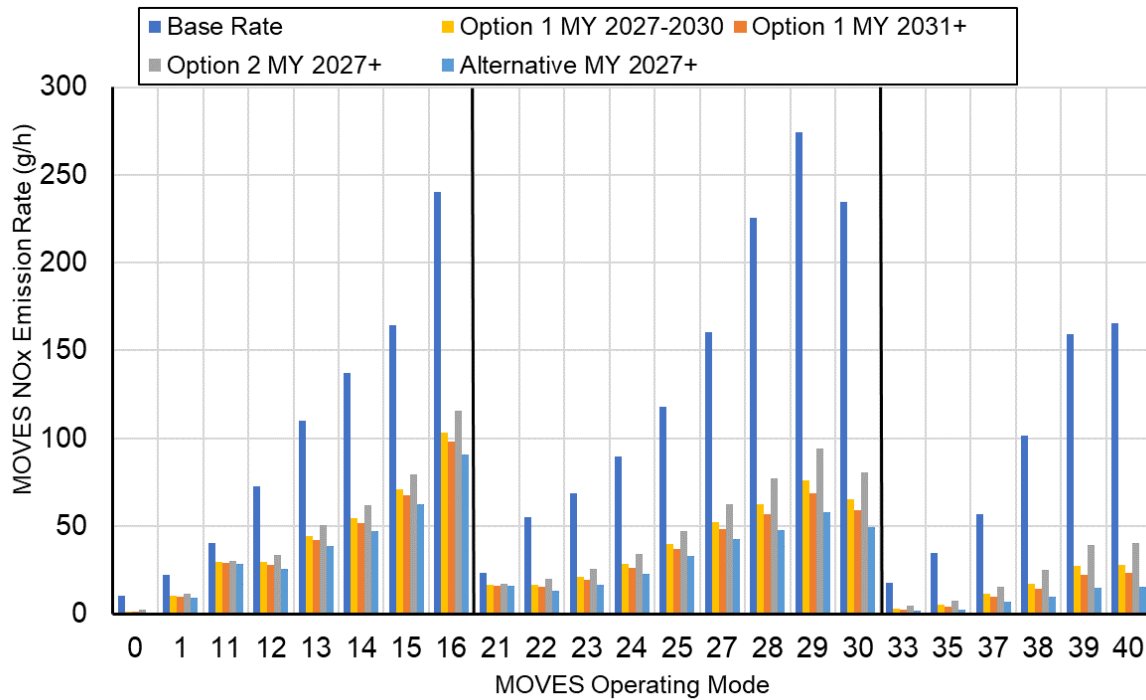


Figure 5-2: Duty-cycle-based running NO_x emissions, $ER_{duty_in_use}$, for HHD diesel for the control scenarios

5.2.2.1.1.2 Emission Rates Based on Off-cycle Standards

In this section, we document the methods used to estimate MOVES NO_x running emission rates based on the proposed and alternative off-cycle standards for heavy-duty diesel vehicles. Table 5-8 presents the calculated off-cycle standards used to develop MOVES inputs for the control scenarios. The proposed and alternative off-cycle standards all include requirements for operating conditions in three bins: idle, low-load, and medium-to-high load. The off-cycle operation is defined as follows: idle is less than 6 percent of maximum power; low-load is 6 to 20 percent of maximum power; and medium-to-high load is above 20 percent of maximum power. The off-cycle standards for the proposed Option 1 are set to be twice the engine-cycle standards for model year 2027-2030, and 1.5 times the engine-cycle standards for 2031+ that correspond to similar engine loads. For the proposed Option 2 and Alternative scenarios, the off-cycle standards are 1.5 times the engine-cycle standards for 2027+. In developing inputs to MOVES, we did not apply a scaling factor to the off-cycle idling operation, and assumed manufacturers would comply with the voluntary idle standard in all off-cycle idle operation. For developing inputs to MOVES, we multiplied the duty-cycle standards, including the proposed Option 1 weighted average HHD 2031+ NO_x standards from Table 5-5, by the corresponding off-cycle scaling factors shown in Table 5-8.

Table 5-8. Calculated Off-Cycle NO_x Standards used for the Control Scenarios

Scenario	Model Year	Regulatory Class	Engine Cycle	Reference Off-cycle NO _x Standard	Off-cycle Bin	Off-cycle scaling factor	Off-Cycle NO _x Standards (g/hr for idling, g/hp-hr for low-load and medium to high-load)
Proposed Option 1	2027-2030	LHD, MHD, HHD	Idle (g/hr)	5 ^A	Idle, < 6% power	1	5
			LLC (g/hp-hr)	0.09	Low-load, 6-20% power	2	0.18
			FTP & SET (g/hp-hr)	0.035	Medium to High Load, >20% power	2	0.07
	2031+	LHD, MHD	Idle (g/hr)	5	Idle, < 6% power	1	5
			LLC (g/hp-hr)	0.05	Low-load, 6-20% power	1.5	0.075
			FTP & SET (g/hp-hr)	0.02	Medium to High Load, >20% power	1.5	0.03
		HHD	Idle (g/hr)	5	Idle, < 6% power	1	5
			LLC (g/hp-hr)	0.073 ^B	Low-load, 6-20% power	1.5	0.110
			FTP & SET (g/hp-hr)	0.029 ^B	Medium to High Load, >20% power	1.5	0.044
Proposed Option 2	2027+	LHD, MHD, HHD	Idle (g/hr)	10	Idle, < 6% power	1	10
			LLC (g/hp-hr)	0.1	Low-load, 6-20% power	1.5	0.15
			FTP & SET (g/hp-hr)	0.05	Medium to High Load, >20% power	1.5	0.075
Alternative	2027+	LHD, MHD, HHD	Idle (g/hr)	10	Idle, < 6% power	1	10
			LLC (g/hp-hr)	0.1	Low-load, 6-20% power	1.5	0.15
			FTP & SET (g/hp-hr)	0.02	Medium to High Load, >20% power	1.5	0.03

^A As discussed in the Preamble Section III.C, the proposed Option 1 idle off-cycle bin standards are 10 g/hr for MY 2027-2030 and 7.5 g/hr for MY 2031+ However, we assumed vehicles comply with the voluntary idle standard presented in Preamble Section III. B.2.iv rather than the off-cycle idle bin standard. The voluntary idle standard is 5 g/hr for both steps of the proposed Option 1 and 10 g/hr for the proposed Option 2 and the Alternative.

^B For HHD vehicles we used the calculated average standard from the intermediate and full useful life standard presented in Table 5-5.

We calculated the voluntary idle NO_x g/hr standard in units of NO_x g/CO₂ kg using Equation 5-8, and the resulting values are displayed in Table 5-9.

Equation 5-8

$$\text{Voluntary Idle } \frac{\text{NO}_x}{\text{CO}_2} \text{ standard } \left(\frac{\text{g}}{\text{kg}} \right) = \left[\text{Voluntary Idle NO}_x \text{ standard } \left(\frac{\text{g}}{\text{hr}} \right) \right] / \left[\text{Idle CO}_2 \left(\frac{\text{kg}}{\text{hr}} \right) \right]$$

Where $\text{Idle CO}_2 \left(\frac{\text{kg}}{\text{hr}} \right)$ = the MOVES average CO₂ (kg/hr) emission rate for HHD diesel vehicles for MOVES idle (operating mode 1 defined in Table 5-3).

Table 5-9: Calculation of Voluntary Idle NO_x/CO₂ Standard (g/kg)

Scenario	Applicable Model Years	Voluntary Idle NO _x standard (g/hr)	Average HHD Idle (Operating Mode=1) CO ₂ emission rate (kg/hr)	Voluntary Idle NO _x /CO ₂ standard (g/kg)
Proposed Option 1	2027-2030	5	8.024	0.62
	2031+	5	8.024	0.62
Proposed Option 2	2027+	10	8.024	1.25
Alternative	2027+	10	8.024	1.25

Next, we converted the reference off-cycle NO_x standards into units of gram per hour (g/hr) for each MOVES operating mode. We refer to g/hr rates as the off-cycle standard compliant emission rates, which are shown in Table 5-10 in Columns (F) and (G) for HHD vehicles for proposed Option 1.

Table 5-10: Calculation of the Off-cycle NO_x Standard Compliant Emission Rate for HHD Diesel Vehicles for the Proposed Option 1

A	B	C	D	E	F	G
MOVES operating mode	MOVES MY 2027 HHD CO ₂ emission rate (kg/hr)	Mean power (hp)	Percent load	Power classification	MY 2027-2030 off-cycle compliant emission rate (g/hr)	MY 2031+ off-cycle compliant emission rate (g/hr)
0	5	4	0.90%	Idle	3.33	3.33
1	8	6	1.30%	Idle	5.00	5.00
11	13	0	-0.10%	Idle	8.04	8.04
12	23	29	6.10%	Idle	14.51	14.51
13	39	75	16.10%	Low-Load	13.58	8.22
14	53	122	25.90%	Medium to High Load	8.51	5.29
15	67	167	35.60%	Medium to High Load	11.70	7.27
16	109	285	60.60%	Medium to High Load	19.92	12.38
21	12	-5	-1.00%	Idle	7.24	7.24
22	32	34	7.20%	Idle	20.24	20.24
23	45	78	16.50%	Low-Load	13.96	8.46
24	60	122	26.00%	Medium to High Load	8.54	5.31
25	76	167	35.60%	Medium to High Load	11.72	7.29
27	99	231	49.10%	Medium to High Load	16.16	10.04
28	137	327	69.60%	Medium to High Load	22.90	14.23
29	174	408	86.90%	Medium to High Load	28.56	17.75
30	200	473	100.70%	Medium to High Load	33.10	20.57
33	29	34	7.30%	Idle	17.55	17.55
35	72	147	31.20%	Medium to High Load	10.28	6.39
37	104	228	48.60%	Medium to High Load	15.99	9.94
38	141	321	68.40%	Medium to High Load	22.50	13.98
39	175	402	85.60%	Medium to High Load	28.16	17.50
40	197	470	100.00%	Medium to High Load	32.89	20.44

In Table 5-10, Column (B) contains the MOVES CO₂ emission rate for Model Year 2027 HHD diesel vehicles for each MOVES operating mode. Column (C) includes the mean power for each operating mode bin calculated from the Heavy-Duty In-Use Testing data, which is the same data set that was used to derive the MOVES CO₂ emission rates.³¹⁰ The percent load, Column (D), is calculated for each operating mode bin using Equation 5-9.

Equation 5-9

$$\text{Percent Load}_{\text{OpMode}=i} = \frac{\text{Mean Power}_{\text{OpMode}=i}}{\text{Mean Power}_{\text{OpMode}=40}}$$

Where i = one of the 23 MOVES running exhaust operating modes from 0 to 40

$\text{Mean Power}_{\text{OpMode}=i}$ = the mean power for each of the MOVES operating modes shown in Column C.

$\text{Mean Power}_{\text{OpMode}=40}$ = assumed maximum power bin = 470 hp for HHD diesel vehicles.

We then assigned each MOVES operating mode into a power classification (Column (E)) based on the percent load (Column (D)), where percent load less than 8 percent of maximum power is idle, 8 to 25 percent of maximum power is low-load, and above 25 percent of maximum power is medium-to-high load.^{UUU}

The off-cycle NO_x standard compliant emission rate in Column (F) and (G) is then calculated based on the power classification and the stringency of the off-cycle standard. For operating modes classified as idle, we multiplied the MOVES CO₂ emission rate in Column (B) with the NO_x/CO₂ off-cycle idle standard calculated in Table 5-9 for the corresponding control scenario using Equation 5-10.

Equation 5-10

Idle Emission Rate

$$\begin{aligned} &= \text{MOVES MY 2027 HHD CO}_2 \text{ Emission Rate } \left(\frac{\text{g}}{\text{hr}} \right) \\ &\times \text{Idle } \frac{\text{NO}_x}{\text{CO}_2} \text{ in_use standard } \left(\frac{\text{g}}{\text{kg}} \right) \end{aligned}$$

For the operating modes classified as low-load and medium- to high-load, we multiplied the off-cycle (g/hp-hr) standard in Equation 5-11 for the corresponding control scenario and power classification by the mean power (Column C), as shown in Equation 5-11.

Equation 5-11

Low Load and Medium to High Load Emission Rate

$$= \text{Mean Power (hp)} \times \text{In_use standard } \left(\frac{\text{g}}{\text{hp} \cdot \text{hr}} \right)$$

The estimated off-cycle NO_x standard compliant emission rates for heavy heavy-duty diesel vehicles are shown in Figure 5-3. Similarly, we applied Equation 5-9 through Equation 5-11 to

^{UUU} At the time of our emission inventory analysis, we used a definition of less than 8% maximum power to define idle operation in-use (Bin 1), and 8% to 25% of maximum power for low-load (Bin 2), and greater than 25% maximum power as medium-to-high power (Bin 3). This definition of idle places more operation into low-load bins with more stringent emission standards than the idle bin (Bin 2 is more stringent than Bin 1). In the case of HHD, three operating modes (operating mode 12, 22 and 33) should be classified in the low-load bin rather than the idle bin. Due to the coarseness of the MOVES operating mode bins, no operating mode would be changed from low-load to medium-to-high-power and this change in definitions is expected to have a minor impact on the final emission rates. As shown in Figure 5-4 for two of the three HHD low-load operating modes affected by this change (operating mode 22 and 33), the final emission rate is determined by the certification standard, not the in-use standard. Nevertheless, we plan to update our emission inventory analysis for the final rulemaking based on the definitions of in-use operations selected for the final rule, which will be informed by stakeholder feedback on the proposed rule.

estimate the off-cycle standard compliant emission rates for the other MOVES regulatory classes using corresponding CO₂ rates and the mean power for those vehicles.

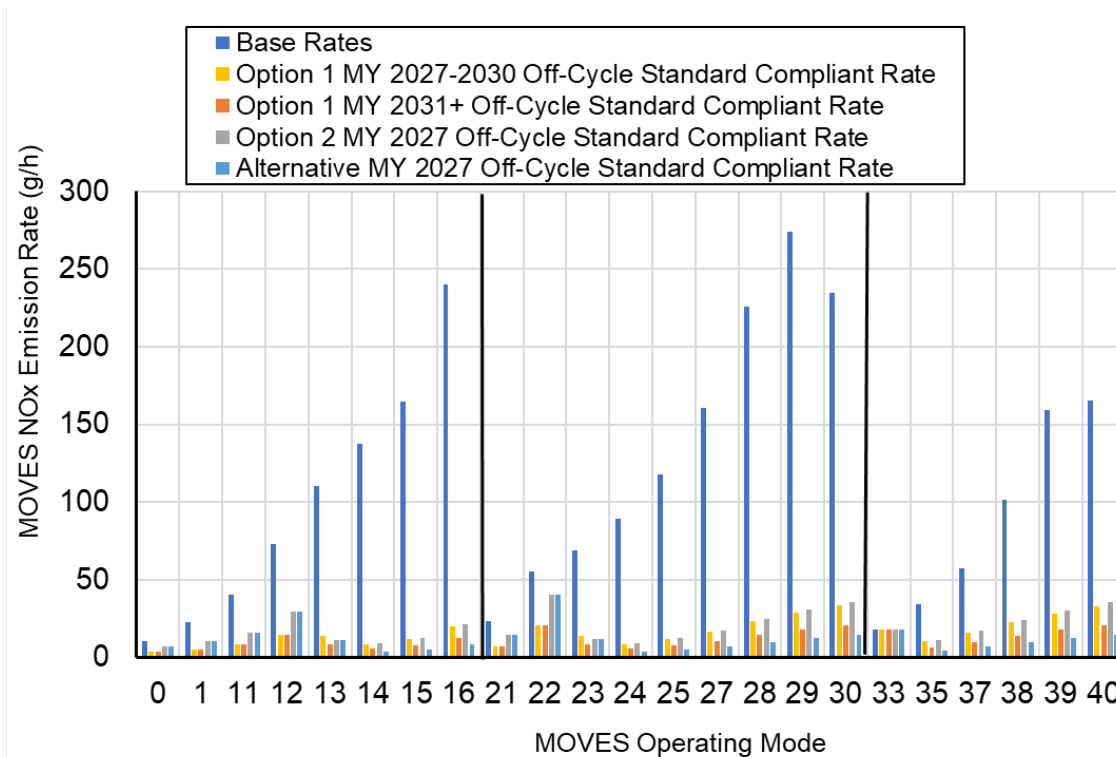


Figure 5-3: Base NO_x rates and off-cycle NO_x standard compliant emission rates for HHD diesel

5.2.2.1.1.3 Emission Rates Based on Combination of Duty-Cycle and Off-Cycle Standards

In this section, we document the methods used to develop MOVES NO_x emission rates for heavy-duty diesel vehicles that reflect the effects of both duty-cycle standards and off-cycle standards. As an example, Figure 5-4 shows that the proposed Option 1 HHD duty-cycle and off-cycle standards in MYs 2031 and later affect running emission rates differently across MOVES operating modes. The duty-cycle standard is estimated to have a larger impact than the off-cycle standard in five operating modes (operating modes 0, 22, 33, 35, and 37), while the off-cycle standard is estimated to have a larger impact in the remaining operating modes.

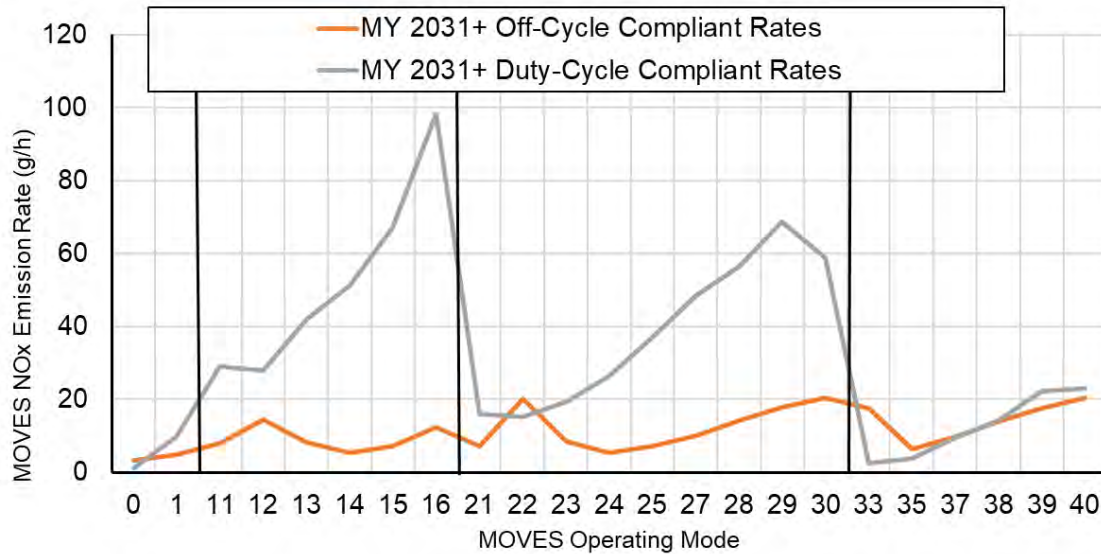


Figure 5-4: Comparison of Running NO_x emission rates for diesel-fueled HHD compliant with the MY2030 proposed Option 1 duty-cycle and off-cycle standards

Because manufacturers would need to comply with both the duty-cycle and off-cycle standards, we estimated the final MOVES NO_x emission rate for each operating mode as the lower of the two rates generated from the duty-cycle and the off-cycle standards (e.g., the emission rate based on the proposed Option 1 off-cycle standards is selected for operating mode 12, but the emission rate based on the proposed Option 1 duty-cycle standards is selected for operating mode 33). Figure 5-5 presents the estimated emission rates for HHD diesel vehicles that meet both the proposed Option 1 duty-cycle and off-cycle standards. The same approach was used to estimate the emission rates for proposed Option 2 and alternative scenarios. The proposed Option 1 emission rates for MHD, LHD45 regulatory classes are shown in Appendix 5.5.1.

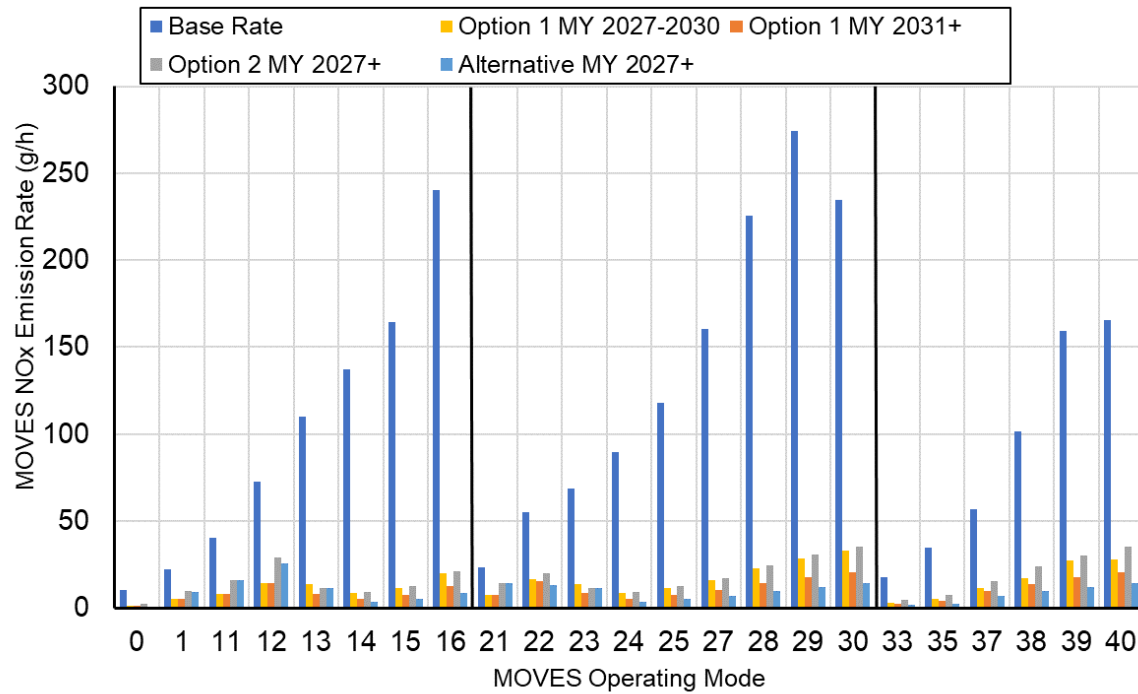


Figure 5-5: Estimated zero-mile NO_x emission rates for HHD diesel vehicles due to the proposed Option 1, Option 2 and Alternative duty-cycle and off-cycle standards

5.2.2.1.2 *Emission Rates Based on Proposed Changes in Warranty and Useful Life*

The MOVES NO_x, THC, CO, and PM_{2.5} emission rates for heavy-duty diesel engines in the control scenario are adjusted to reflect the useful life and warranty periods for the proposed and alternative scenarios shown in Table 5-11.

Table 5-11: Useful Life and Warranty Periods for Heavy-duty Diesel^A Engines and Aftertreatment Systems in the Control Scenarios

Scenario	Applicable Model Years	Warranty			Useful Life		
		LHD	MHD	HHD	LHD	MHD	HHD
Baseline	Model Year 2010+	5yr/ 50k	5yr/ 100k	5yr/ 100k	10yr/ 110k	10yr/ 185k	10yr/ 435k
Proposed Option 1	Model Year 2027-2030	7yr/ 150k	7yr/ 220k	7yr/ 450k	12yr/ 190k	11yr/ 270k	11yr/ 600k
	Model Year 2031+	10yr/ 210k	10yr/ 280k	10yr/ 600k	12yr/ 270k	12yr/ 350k	12yr/ 800k
Proposed Option 2	Model Year 2027+	5yr/ 110k	5yr/ 150k	5yr/ 350k	10yr/ 250k	10yr/ 325k	10yr/ 650k
Alternative	Model Year 2027+	10yr/ 280k	10yr/ 360k	10yr/ 800k	10yr/ 350k	10yr/ 450k	10yr/ 850k

^A Age effects for heavy-duty gasoline vehicles in MOVES are estimated directly from emissions data or adapted from light-duty gasoline or heavy-duty diesel age effects, and are not tied to warranty and useful life periods; thus we have not adjusted heavy-duty gasoline or NG engine emission rates due to the proposed and alternative warranty and useful life periods.

^B The MOVES baseline emission rates for LHD diesel were incorrectly developed using a warranty period of 100K instead of 50K, and thus we underestimated the emissions impact of the longer warranty periods for LHD diesel vehicles in the proposal and alternative scenarios. We will update the baseline warranty period for LHD diesel in the FRM analysis.

We used the existing methodology^{vvv} in MOVES to estimate the impact of lengthened useful life and warranty periods on heavy-duty diesel engine emissions for each of the three control scenarios (proposed Options 1 and 2 and Alternative).^{www} In that methodology, new vehicles/engines have zero-mile emission rates for each operating mode and maintain that rate until the age of the vehicle/engine matches the warranty period (Figure 5-6). Once the warranty period ends, the emission rate increases linearly until the vehicle/engine reaches its useful life age. At the end of the useful life, the emissions rates remain constant at a level calculated from the tampering and mal-maintenance (T&M) adjustment factor. In MOVES, we assume that tampering and mal-maintenance effects are the dominant source of emissions deterioration of fleet-wide heavy-duty diesel emissions. MOVES does not account for normal deterioration of heavy-duty diesel emissions, such as due to catalyst aging.

^{vvv} The existing methodology is documented in Appendix B "Tampering and Mal-maintenance" of the reference "Exhaust Emission Rates for Heavy-Duty Onroad Vehicles in MOVES CTI NPRM"³¹⁰

^{www} Emission rate inputs for the proposed Option 1 and 2 and Alternative scenarios without aging effects (zero-mile rates) are included with the other MOVES input tables in the docket.³⁰⁸ The zero-mile proposal emission rates are used to quantify the emission reductions due to the different control aspects of the proposed rulemaking as shown in Figure 5-24.

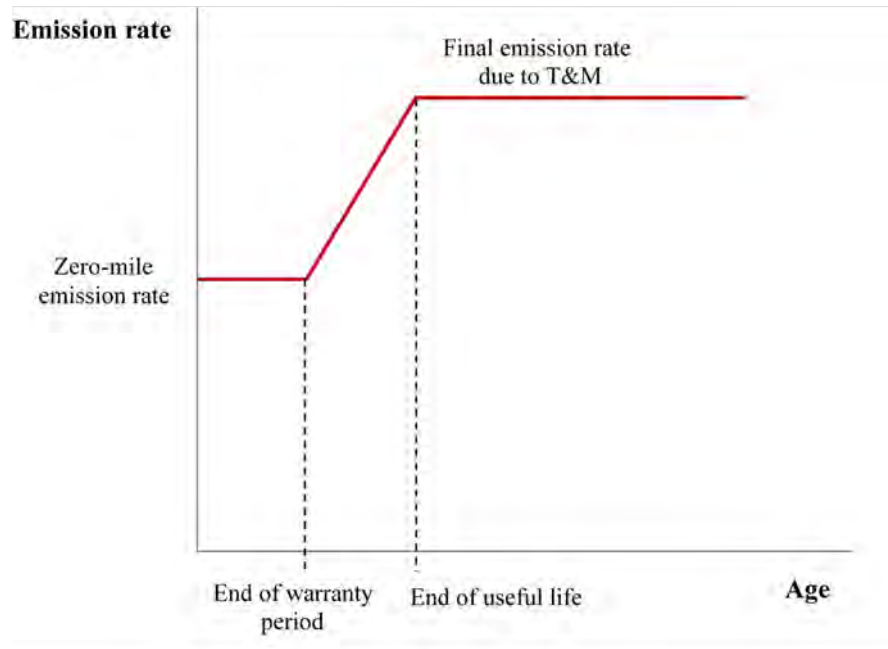


Figure 5-6: Methodology to model the effects of tampering and mal-maintenance (T&M) on emission rates according to warranty and useful life

For the baseline and control scenarios, we estimated the vehicle age at which heavy-duty diesel vehicles would reach the end of their warranty period and the end of their useful life period (Table 5-13). Table 5-12 shows example calculations for the proposed Option 1 MY 2027 standards. Row (A) shows the age limit of the standards: 5-year warranty period, 10-year useful life period. Row (B) shows the mileage limit of the standards. Row (C) shows the typical miles driven per year,^{xxx} which is used to calculate Row (D), the calculated age rounded to the nearest whole number when the mileage limit is reached. Row (E) is the smaller of the age at which the vehicle meets the end of its age limit, Row (A), or mileage limit, Row (D).

^{xxx} The typical miles per year used in Table 5-12 are the same values used in deriving the vehicle age at the end of the warranty period and baseline warranty and useful life assumed in MOVES CTI NPRM for the baseline case.³¹⁰

Table 5-12: Estimated Vehicle Age at the End of the Warranty Period and the Useful Life for Each Heavy-duty Diesel Regulatory Class for the Proposed Option 1 Model Year 2027 Scenario

Row		Warranty				Useful Life			
		LHD	MHD	HHD	Bus	LHD	MHD	HHD	Bus
(A)	Age limit	7	7	7	7	12	11	11	11
(B)	Mileage limit	150,000	220,000	450,000	450,000	190,000	270,000	600,000	600,000
(C)	Typical miles/year driven	26,000	41,000	105,000	44,000	26,000	41,000	105,000	44,000
(D)	Calculated age when the mileage limit is reached	6	5	4	10	7	7	6	14
(E)	Estimated age	6	5	4	7	7	7	6	11

Similar calculations were performed for other regulatory classes for the baseline and control scenarios using the same estimated mileage per year; the resulting estimates of vehicle age at the end of the warranty and useful life periods are shown in Table 5-13.

Table 5-13: Estimated Vehicle Age at the End of the Warranty Period and the Useful Life for Each Heavy-duty Diesel Regulatory Class in the Baseline and Control Scenarios

	Warranty				Useful Life			
	LHD	MHD	HHD	Bus	LHD	MHD	HHD	Bus
MOVES age								
Baseline	4	2	1	2	4	5	4	10
Proposed Option 1 Model Year 2027 - 2030	6	5	4	7	7	7	6	11
Proposed Option 1 Model Year 2031+	10	8	8	12	10	8	8	12
Proposed Option 2 Model Year 2027	4	4	4	4	4	10	8	8
Alternative Model Year 2027	10	9	8	10	10	10	8	10

The T&M adjustment factor is calculated as the sum of the product of the T&M frequency for each failure i , and the corresponding T&M emission effect, as shown in Equation 5-12.

Equation 5-12

$$f_{T\&M,p} = \sum_i (T\&M \text{ frequency}_i \times T\&M \text{ emission effect}_{p,i})$$

Where:

$f_{T\&M}$ = the tampering and mal-maintenance adjustment factor for pollutant p

$T\&M \text{ frequency}_i$ = estimated fleet average frequency of a tampering & mal-maintenance failure i .

$T\&M \text{ emission effect}_i$ = estimated emission effect for pollutant p associated with tampering & mal-maintenance failure i .

The emission rate at the end of useful life is then calculated using Equation 5-13.

Equation 5-13

$$ER_{\text{End of useful life},p,r,o} = ER_{\text{zero mile},p,r,o} \times (1 + f_{T\&M,p})$$

Where:

$ER_{\text{useful life},p,r,o}$ = the heavy-duty diesel emission rate at the end of warranty for each pollutant p, regulatory class, r, and operating mode, o

$ER_{\text{zero mile}}$ = the zero-mile heavy-duty diesel emission rate for each pollutant p, regulatory class, r, and operating mode, o

$f_{T\&M}$ = the tampering and mal-maintenance adjustment factor for each pollutant p (Equation 5-12)

We used the existing T&M frequency values from MOVES CTI NPRM for the baseline and control scenarios.³¹⁰ For THC, CO, and PM_{2.5}, we used the existing T&M emission effects from MOVES CTI NPRM for both the baseline and control scenarios.³¹⁰

For the NO_x T&M emissions effects, the baseline scenario is estimated using the existing MOVES CTI NPRM emission effects shown in Table 5-14. For the control scenarios, however, a different approach was taken. As NO_x emissions become more tightly controlled due to the application of advanced technologies, we anticipate the NO_x T&M emission effects will increase. To estimate the NO_x T&M emission effects for the control scenarios, we first calculated the average zero-mile NO_x emission rate $\overline{ER}_{\text{zero mile},NOx}$, the weighted average of the different operating modes o, and regulatory class r, using Equation 5-14.

Equation 5-14

$$\overline{ER}_{\text{zero mile},NOx} = \frac{\sum_{r,o} (ER_{\text{zero mile},NOx,r,o} \times t_{r,o})}{\sum_{r,o} t_{r,o}}$$

Where:

$\overline{ER}_{\text{zero mile},NOx}$ = the average heavy-duty diesel NO_x emission rate

$ER_{\text{zero mile},NOx,r,o}$ = the zero-mile heavy-duty diesel NO_x emission rate for regulatory class, r, and operating mode, o

$t_{r,o}$ = operation time by regulatory class and operating mode estimated by MOVES CTI NPRM for calendar year 2045

Next, we estimated the NO_x emission rate of vehicles with a tampering and mal-maintenance failure i, using Equation 5-15, which was derived from Equation 5-13 using the fleet average emission rate from Equation 5-14 and assuming the T&M frequency is 100 percent.

Equation 5-15

$$\overline{ER}_{T\&M\ i,NOx} = \overline{ER}_{\text{zero mile},NOx} \times (1 + \text{T\&M emission effect}_{i,NOx})$$

We then derived Equation 5-16, assuming that a NO_x aftertreatment equipment failure i, in the control scenario, would cause the average of the failed emission rates, $\overline{ER}_{T\&M\ i,NOx}$, to be the same as a NO_x aftertreatment failure in the baseline case, Baseline $\overline{ER}_{T\&M\ i,NOx}$.

Equation 5-16

$$\begin{aligned}\text{Baseline } \overline{\text{ER}}_{\text{T\&M } i, \text{NOX}} &= \text{Control } \overline{\text{ER}}_{\text{T\&M } i, \text{NOX}} \\ \text{Baseline } \overline{\text{ER}}_{\text{zero mile, NOX}} \times (1 + \text{Baseline T\&M emission effect}_{i, \text{NOX}}) \\ &= \text{Control } \overline{\text{ER}}_{\text{zero mile, NOX}} \times (1 + \text{Control T\&M emission effect}_{i, \text{NOX}})\end{aligned}$$

By rearranging Equation 5-16, we derived Equation 5-17 to estimate the control scenario NO_x T&M emissions effects.

Equation 5-17

$$\begin{aligned}\text{Control T\&M emission effect}_{i, \text{NOX}} \\ = \left[\frac{\text{Baseline } \overline{\text{ER}}_{\text{zero mile, NOX}} \times (1 + \text{Baseline T\&M emission effect}_{i, \text{NOX}})}{\text{Control } \overline{\text{ER}}_{\text{zero mile, NOX}}} \right] - 1\end{aligned}$$

Table 5-14 presents the T&M NO_x emission effects for the NO_x aftertreatment failures for the control scenarios calculated from Equation 5-17. The T&M NO_x emission effects for the NO_x aftertreatment failures are much larger than the baseline scenario, because the zero-mile NO_x emission rate in the control scenarios are lower than the baseline zero-mile NO_x emission rates. The NO_x T&M emission effects for the other T&M failures shown in Table 5-14 (e.g., Timing Advanced and EGR Disabled/Low-Flow) in the control scenarios use the same NO_x T&M emissions effects in the baseline and proposed and alternative control scenarios.

Table 5-14: NO_x Tampering & Mal-maintenance (T&M) Emission Effects

	Baseline	Proposed Option 1 MY 2027-2030	Proposed Option 1 MY 2031+	Proposed Option 2 MY 2027+	Alternative MY 2027+
Timing Advanced	6%	6%	6%	6%	6%
Timing Retarded	-20%	-20%	-20%	-20%	-20%
Injector Problem (all)	-1%	-1%	-1%	-1%	-1%
Puff Limiter Mis-set	0%	0%	0%	0%	0%
Puff Limited Disabled	0%	0%	0%	0%	0%
Max Fuel High	0%	0%	0%	0%	0%
Clogged Air Filter	0%	0%	0%	0%	0%
Wrong/Worn Turbo	0%	0%	0%	0%	0%
Intercooler Clogged	3%	3%	3%	3%	3%
Other Air Problem	0%	0%	0%	0%	0%
Engine Mechanical Failure	-10%	-10%	-10%	-10%	-10%
Excessive Oil Consumption	0%	0%	0%	0%	0%
Electronics Failed	0%	0%	0%	0%	0%
Electronics Tampered	8%	8%	8%	8%	8%
EGR Stuck Open	-20%	-20%	-20%	-20%	-20%
EGR Disabled/Low-Flow	5%	5%	5%	5%	5%
NO _x Aftertreatment Sensor	200%	1648%	2101%	1097%	1814%
Replacement NO _x Aftertreatment Sensor	200%	1648%	2101%	1097%	1814%
NO _x Aftertreatment Malfunction	500%	3395%	4303%	2294%	3728%
PM Filter Leak	0%	0%	0%	0%	0%
PM Filter Disabled	0%	0%	0%	0%	0%
Oxidation Catalyst Malfunction/Remove	0%	0%	0%	0%	0%

Using the NO_x T&M emission effects in Table 5-14, we then calculated T&M adjustment factors $f_{T\&M,NOX}$ for each scenario using Equation 5-12 and the baseline T&M frequency values. For THC, CO, and PM_{2.5}, we used the existing T&M adjustment factors $f_{T\&M,p}$ in MOVES CTI NPRM. Then, we calculated the heavy-duty diesel emission rate for each pollutant p , age a , regulatory class r , and operating mode o , using Equation 5-18.

Equation 5-18

$$ER_{p,r,a,o} = ER_{zero\ mile,p,r,o} \times (1 + s_a \times f_{T\&M})$$

Where:

$ER_{p,r,o,a}$ = the heavy-duty diesel emission rate for each pollutant p , regulatory class r , age a , operating mode o ,

$ER_{zero\ mile}$ = the zero-mile heavy-duty diesel emission rate for each pollutant p , regulatory class r , operating mode o

s_a = scaled age effect at age a

$f_{T\&M}$ = the tampering and mal-maintenance adjustment factor (Equation 5-12)

The scaled age effect, s_a , is calculated using the age of the vehicle in comparison to the warranty and useful life requirements, as shown in Table 5-15. When the vehicle age is between the end of the warranty and the useful life, s_a is interpolated between 0 and 1.

Table 5-15: Calculation of s_a

s_a	Where:
0	$\text{age} \leq \text{end of warranty age}$
$\frac{(\text{age} - \text{end of warranty age})}{(\text{Useful life age} - \text{end of warranty age})}$	$\text{end of warranty age} < \text{age} < \text{useful life}$
1	$\text{age} \geq \text{useful life}$

As the final step, the age-adjusted emission rates calculated in Equation 5-18 were averaged according to the age ranges shown in Table 5-16 that are used to define emission rates in MOVES for LHD45, MHD, HHD, and Urban Bus regulatory classes. The resulting age-adjusted running emissions have a relationship with vehicle age as shown in Figure 5-7 and Figure 5-8 for HHD NO_x emissions.^{YYY}

Table 5-16: MOVES ageGroupID Which Are Used to Define Running and Start Emission Rates

ageGroupID	Lower bound (years)	Upper bound (years)
3	0	3
405	4	5
607	6	7
809	8	9
1014	10	14
1519	15	19
2099	20	30

5.2.2.1.3 *Summary of Diesel NO_x Running Emission Rates*

Figure 5-7 and Figure 5-8 show average running NO_x emission rates (g/mile) in MOVES CTI NPRM for the model year 2027 and 2031 fleets across vehicle age for the baseline and control scenarios.^{ZZZ} The MOVES running emission rates for the control scenarios reflect the adjustments to the duty-cycle and off-cycle standards, and the extended warranty and useful life as discussed above in Chapter 5.2.2.1.1 and Chapter 5.2.2.1.2, respectively. The gram per mile average running emissions are also a function of the default activity assumptions in MOVES CTI NPRM.³⁰⁹

Figure 5-7 and Figure 5-8 show that the average zero-mile^{AAAA} NO_x emission rates for the control scenarios are significantly lower than the baseline scenario. The figures also demonstrate

^{YYY} The average emission rate accounts for the frequency of different operating modes according to MOVES estimate of in-use vehicle activity. The trend in individual operating modes will be slightly different than the average trend shown in Figure 5-7 and Figure 5-8. For example, the zero-mile idle operating mode is not reduced as much as the average emission rates in the control scenarios. Because the control case T&M emission effects were calculated using the average emission rates in Equation 5-17, individual emission rates in the control case, such as for idle, can be higher than the baseline scenario when fully aged. This is a feature of the method used to derive the aging effects, but the effect is averaged out when conducting emission inventory analysis.

^{ZZZ} The average emission rates are estimated from the national MOVES runs described in Section 0.

^{AAAA} The age 0-3 emission rates shown in Figure 5-7 for the proposed Option 1 and Option 2 do not represent the true zero-mile rates because the warranty period for HHD vehicles ends at age 3 (Table 5-13), and the MOVES

the larger T&M NO_x emission effect for the control scenarios than for the baseline scenario as explained in Chapter 5.2.2.1.2. Although not shown, the emission rate is constant from age 15 through age 30.. The impact of the longer emission warranty and useful life periods is reflected by the zero-mile NO_x emission rate extending for additional time periods, which corresponds to the emission warranty periods in the proposed Options 1 and 2 and Alternative.

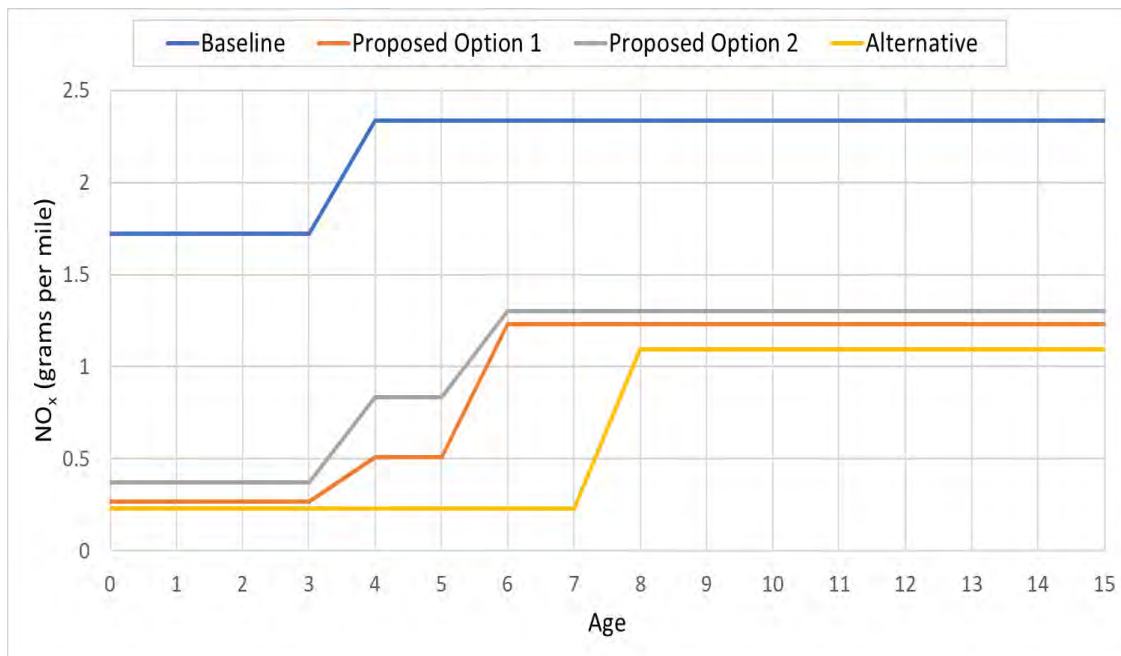


Figure 5-7: NO_x g/mile emission rates estimated from MOVES for HHD diesel long-haul combination trucks for the model year 2027 fleet across vehicle age for the baseline and control scenarios

emission rates are averaged according to the age groups shown in Table 5-16. In contrast, the emission rate for the proposed Option 1 scenario for the age 0-3 group in Figure 5-8 is equivalent to the zero-mile rate because the warranty period extends to age 6.

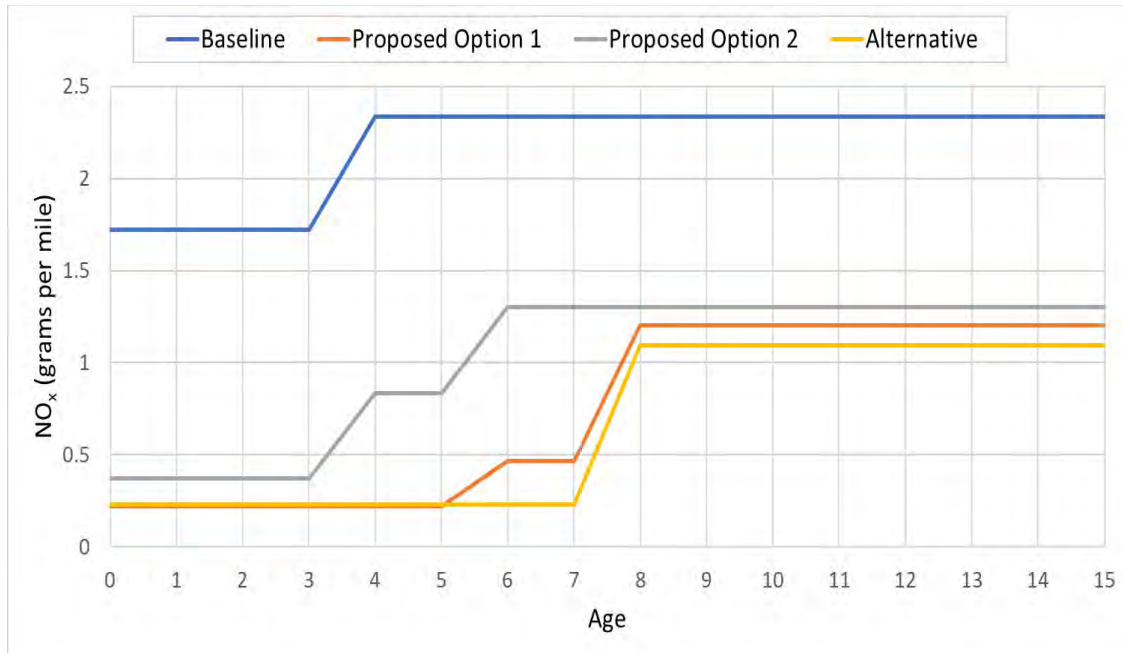


Figure 5-8: NO_x g/mile emission rates estimated from MOVES for HHD diesel long-haul combination trucks for the model year 2031 fleet across vehicle age for the baseline and control scenarios

5.2.2.2 Heavy-Duty Diesel Start Emission Rates

In this section, we describe the methods used to estimate lower start NO_x emission rates in MOVES CTI NPRM for the control scenarios due to the proposed and alternative duty-cycle standards. We did not estimate the impact of the off-cycle standard on start emissions, in part because the baseline MY 2010 and later start emission rates in MOVES CTI NPRM are not based on in-use data but are based on emissions data from the FTP duty-cycle.³¹⁰ Additionally, because the baseline heavy-duty diesel start emission rates estimated in MOVES CTI NPRM do not vary with age due to insufficient data³¹⁰, we did not estimate changes due to the proposed changes in warranty and useful life.

Start emission rates in MOVES are defined by regulatory class, fuel type, vehicle age and operating mode. Start operating modes in MOVES are also defined by different lengths of engine time (the time between the preceding engine off event and the engine start). The length of soak time for each MOVES operating mode bin is defined in Figure 5-10. Operating mode 108 represents a start with a soak longer than 720 minutes or 12 hours and is referred to as a 12-hour cold-start.

To estimate the start emissions under the control scenarios, we estimated the NO_x cold start emission rate (g/start) from the CARB Stage 1 HDD engine tested on the FTP duty-cycle cycle. Table 5-17 contains the NO_x Cold and Hot FTP measurements in Columns (B) and (C) for different aging lengths. Cold - Hot, Column (E), is calculated as the difference between the Columns (B) and (C). The cold start, Column (F), is then calculated by multiplying the difference in the Cold and Hot Start, Column (E), by the work performed on the FTP cycle, Column (D), as shown in Equation 5-19.

Equation 5-19

$$\text{NO}_x \text{ Cold Start } \left(\frac{\text{g}}{\text{start}} \right) = \left[\text{Cold } \left(\frac{\text{g}}{\text{hp} \cdot \text{hr}} \right) - \text{Hot } \left(\frac{\text{g}}{\text{hp} \cdot \text{hr}} \right) \right] \times \text{FTP work (hp} \cdot \text{hr)}$$

Table 5-17: Calculation of NO_x 12-hour Cold Starts from the CARB Stage 1 HHD Engine from the Cold and Hot FTP Cycle

	(A)	(B)	(C)	(E)	(D)	(F)
Aged hours	FTP composite (g/hp-hr)	Cold (g/hp-hr)	Hot (g/hp-hr)	Cold - Hot (g/hp-hr)	FTP Work (hp-hr)	Cold Start (g/start)
0	0.008	0.025	0.005	0.02	31.4	0.63
333	0.012	0.042	0.006	0.036	31.4	1.13
656	0.018	0.061	0.009	0.052	31.4	1.64
1000	0.024	0.092	0.01	0.082	31.4	2.58
1000 hr Post Ash Clean	0.026	0.109	0.009	0.1	31.4	3.14

The Stage 1 HHD engine is deemed representative of an engine-certified to a 0.02 g/hp-hr NO_x standard based on the FTP composite measurements in Column (A). Table 5-17 demonstrates that there was larger cold start measured with increase in aged hours, and after the ash clean out at 1000 hours. We used the 1000 hr, Post Ash Clean cold start emission rate (3.14 g/start shown in Table 5-17) to represent the 12-hour cold-start (operating mode 108) emission rate for the Alternative scenario.

To estimate the 12-hour cold-start NO_x emission rate HHD diesel vehicles for the control scenarios, we interpolated the HHD 12-hour cold-start between the Stage 1 cold start (3.14 g/start) and the MOVES baseline 12-hour cold-start (8.4 g/start), and their respective FTP duty-cycle standards using Equation 5-20 as shown in Figure 5-9 and Table 5-18 . For example, the interpolation yielded an estimated 12-hour cold start of 4.02 g/start for the 0.05 g/hp-hr FTP standard.

Equation 5-20

$$\begin{aligned} \text{Start ER}_{\text{FTP}_x, \text{HHD}, 12 \text{ hour}} &= \left(\frac{\text{MOVES start}_{\text{HHD}, 12 \text{ hour}} - \text{Stage1 start}}{\text{Baseline FTP} - \text{Stage1 FTP}} \right) \times (\text{FTP}_x - \text{Baseline FTP}) \\ &+ \text{MOVES start}_{\text{HHD}, 12 \text{ hour}} \end{aligned}$$

Where:

Start ER_{Duty-cycle standard x, HHD, 12 hour} = the estimated NO_x start emissions for an FTP duty-cycle standard, x, for heavy heavy-duty diesel emissions for a 12-hour cold-start (operating mode 108).

Stage1 start = 1000 Post Ash Clean start emission rate from the CARB Stage 1 HHD diesel engine = 3.14 g/start (Table 5-17)

Stage1 FTP = Composite FTP level of the CARB Stage 1 engine = 0.02 g/hp-hr

MOVES start_{HHD, 12 hour} = MOVES CTI NPRM baseline start emission rate for MY 2027 heavy heavy-duty diesel engine for a 12 hour soak (operating mode 108)

Baseline FTP = baseline FTP composite NO_x standard = 0.2 g/hp-hr

FTP_x = composite FTP standard in the control scenarios, either 0.035, 0.029, 0.05, or 0.02 g/hp-hr (Table 5-4 and Table 5-5)

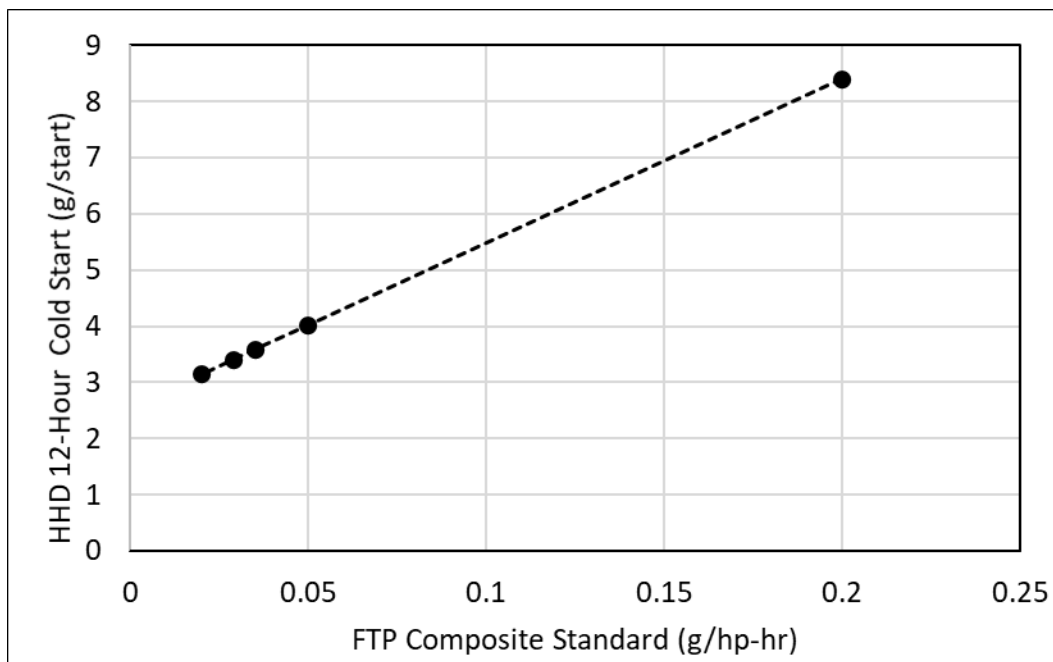


Figure 5-9: Estimated relationship between the HHD NO_x 12-hour cold-start and the composite FTP NO_x standards

Table 5-18: HHD Cold Start Emissions for Proposed and Alternative Scenarios

Scenario	Applicable Model Years	Weighted Average FTP standard (g/hp-hr)	Cold Start emissions (g/start)
Baseline	Model Year 2010+	0.2	8.40
Proposed Option 1	Model Year 2027-2030	0.035	3.58
	Model Year 2031+	0.029	3.41
Proposed Option 2	Model Year 2027+	0.05	4.02
Alternative	Model Year 2027+	0.02	3.14

We then used Equation 5-21 to estimate the MOVES NO_x emission rates for each MOVES heavy-duty regulatory class (LHD45, MHD, and HHD) and for each MOVES start operating mode classified by different soak times (Figure 5-10). We assumed that the relative difference in emission rates by regulatory class and by operating mode is the same in the baseline and control scenarios.

Equation 5-21

$$\text{Start ER}_{\text{FTP}=\text{x}, \text{reg class}=\text{y}, \text{soak}=\text{z}} = \text{Start ER}_{\text{Duty cycle standard x, HHD, 12}} \times \left(\frac{\text{MOVES start}_{\text{reg class}=\text{y}, \text{soak}=\text{z}}}{\text{MOVES start}_{\text{HHD, 12-hour}}} \right)$$

Where:

Start ER_{FTP} = the start NO_x emission rates for the control scenarios with FTP x (0.035, 0.029, 0.05, or 0.02) for regulatory class y (LHD45, MHD, and HHD), and soak length z

Start $ER_{Duty\ cycle\ standard\ x, HHD, 12-hour}$ = the estimated start emissions for an FTP duty-cycle standard, x, for heavy heavy-duty diesel emissions for a 12-hour soak (operating mode 108)

MOVES start_{reg class=y,soak=z} = MOVES CTI NPRM baseline start emission rate for MY 2027 for regulatory class y (LHD45, MHD, and HHD), and soak length z

MOVES start_{HHD,12-hour} = MOVES CTI NPRM baseline start emission rate for MY 2027 HHD diesel engine for a 12-hour soak (operating mode 108)

Figure 5-10 shows the estimated MOVES NO_x start emission rates for HHD diesel vehicles for the baseline scenario, as well as the proposed and alternative scenarios.

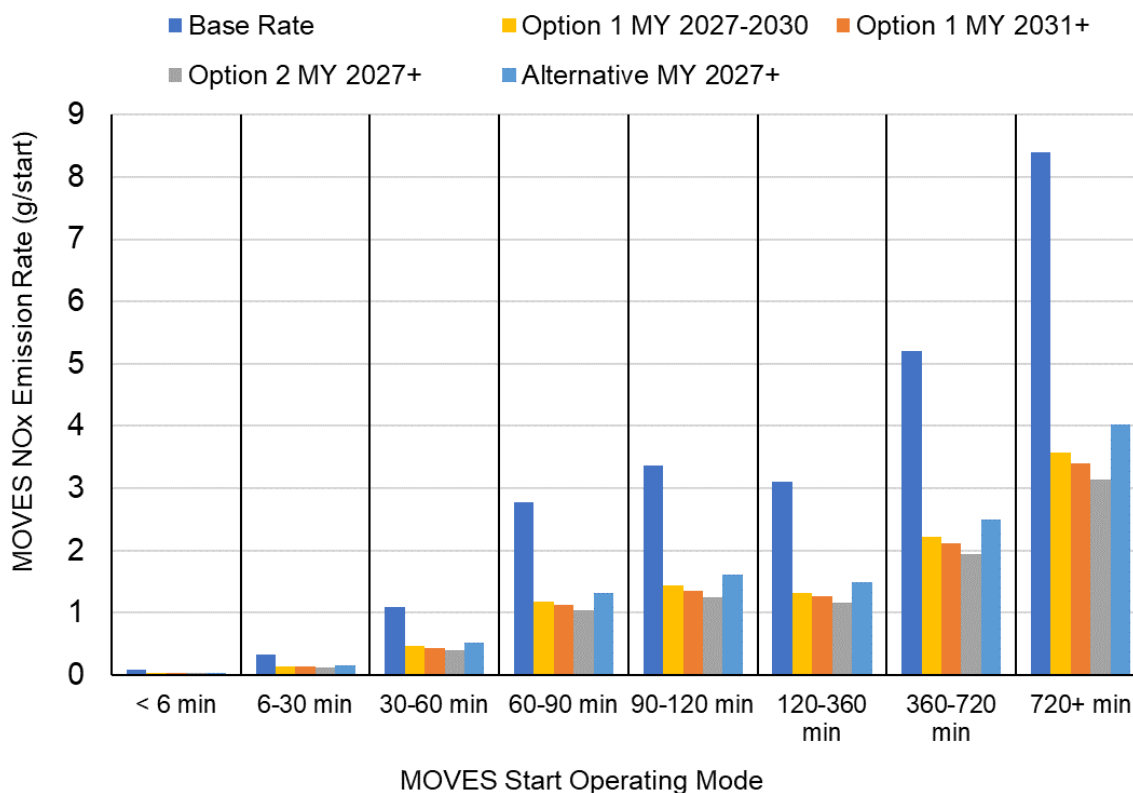


Figure 5-10: Duty-cycle-based NO_x start emissions for HHD Diesel for the baseline, proposed, and alternative control scenarios

5.2.2.3 Heavy-Duty Extended Idle Emission Rates

In MOVES, extended idling is defined as idling more than an hour, which occurs during hotelling activity when long-haul combination trucks idle during rest periods. MOVES has extended idle emission rates for long-haul combination trucks that include HHD, MHD,^{BBBB} and

^{BBBB} HHD and MHD have the same extended idle emission rates in MOVES.

glider vehicles^{CCCC}. All idling activity by other regulatory classes is modeled using the running idle emission rates (Table 5-3), which are different than extended idle emission rates. We anticipated that reductions in the HHD and MHD NO_x extended idle emissions rates would be driven by the proposed idle standard, rather than the proposed duty-cycle standards. The duty-cycle standards do not contain high duration extended idling (> 1 hour) that is representative of truck hotelling activity. In addition, we did not estimate lower extended idle emission rates due to the lengthened warranty or useful life periods.^{DDDD}

We estimated extended idle emission rates that would comply with the off-cycle NO_x/CO₂ g/kg standard calculated in Table 5-9. We then used Equation 5-10 to calculate the extended idle off-cycle NO_x g/hr emission rate based on the MOVES extended idle CO₂ g/hr emission rate, as shown in Table 5-19.

Table 5-19: Calculation of HHD and MHD Extended Idle NO_x g/hr Emission Rates

Control Scenario	Model Years	2027 MY Baseline Rates NO _x (g/hr)	2027 MY Baseline Rates CO ₂ (g/hr)	Idle Standard (g/hr)	Idle Standard NO _x /CO ₂ (g/kg)	Idle- standard compliant NO _x emission rate (g/hr)	% Change in NO _x emission rate
Proposed Option 1	Model Year 2027-2030	42.6	7191	5	0.6232	4.48	-89%
	Model Year 2031+	42.6	7191	5	0.6232	4.48	-89%
Proposed Option 2	Model Year 2027+	42.6	7191	10	1.25	8.99	-79%
Alternative	Model Year 2027+	42.6	7191	10	1.25	8.99	-79%

5.2.2.4 Heavy-duty Diesel Crankcase Emissions

MOVES CTI NPRM estimates that crankcase emissions contribute 38% of the PM_{2.5} exhaust emissions for MY 2007 and later heavy-duty diesel vehicles and assumes that all heavy-duty diesel vehicles have open crankcase systems in the baseline.³¹⁰ However, approximately one-third of heavy-duty diesel vehicles have closed crankcase systems, as described in Section III.B of the preamble and Chapter 1.1.4 of this draft RIA. Under the control scenarios, the PM_{2.5} crankcase emissions from the HHD, MHD, and LHD45 diesel vehicles are set to zero. For LHD2b3 diesel vehicles, we reduced the diesel emissions by 94.9%, because we assumed that 5.1% of the LHD2b3 diesel vehicles are engine-certified (Chapter 5.2.2.5). Because we are assuming that all heavy-duty diesel engines have open crankcase systems in the baseline, we anticipate that we are slightly over-estimating the PM_{2.5} benefits of the closed crankcase requirement in the control scenarios.

^{CCCC} We assumed there are no changes to glider emission rates due to the proposed rulemaking.

^{DDDD} Extended idle emission rates in MOVES are not differentiated by vehicle age.

MOVES CTI NPRM does not estimate the contribution of crankcase emissions to THC, NO_x, and CO exhaust emissions from heavy-duty diesel vehicles. Because of this, we did not estimate reductions in these gaseous pollutants from crankcase control.

For the final rulemaking, we anticipate updating MOVES baseline crankcase emission rates to account for the current fraction of closed crankcase systems; incorporate estimates of THC, NO_x, and CO crankcase emissions into the baseline; and incorporate newer crankcase emission estimates from a more recent test program. With these updates, we anticipate that compared to this analysis, estimated benefits from the closed crankcase requirement could potentially increase for THC, NO_x, and CO, and decrease for PM_{2.5}.

5.2.2.5 Light Heavy-Duty Class 2b and 3 Diesel Emission Rates

We assumed that in 2027 and later model years, 5.1 percent of the diesel-fueled LHD2b3 vehicles will be engine-certified and would be impacted by the proposed rule.^{EEEE,FFFF} To develop the emission rates for LHD2b3 vehicles, for the control scenarios, we assumed that 5.1 percent of the emissions from LHD2b3 are equivalent to the controlled emissions of LHD45 regulatory class vehicles. This is consistent with the analysis for model year 2010 and later diesel vehicles, where we used the same data from the HDIUT program to estimate emission rates for both LHD2b3 and LHD45 vehicles.³¹⁰ In addition, we assumed that the proposed duty-cycle, off-cycle, and warranty and useful life requirements are the same for all engine-certified LHD vehicles.

We did not estimate the contribution of engine-certified vehicles on the emission rates for diesel-fueled LHD2b3 in the baseline scenario.^{GGGG} Because the LHD2b3 diesel emission rates certified to engine standards are higher than the emission rates certified to chassis standards, the control scenarios generally increase NO_x emissions compared to the baseline scenario for diesel LHD2b3 vehicles for most calendar years, even though we anticipate the proposed rule would reduce NO_x emissions for engine-certified LHD2b3 vehicles. We included the emission contribution from engine-certified diesel-fueled LHD2b3 vehicles in the control scenarios to provide our most accurate estimation of future NO_x emissions, while acknowledging that we are underestimating the benefits of controlling these vehicles due to their absence from the baseline

^{EEEE} As noted in Section I, Class 2b and 3 vehicles with GVWR between 8,500 and 14,000 pounds are primarily commercial pickup trucks and vans and are sometimes referred to as "medium-duty vehicles". The majority of Class 2b and 3 vehicles are certified as complete vehicles and will be included in a future combined light-duty and medium-duty rulemaking action, per Executive Order 14037, Section 2a.

^{FFFF} In Appendix 5.5.1, we present the analysis suggesting that 4.2% of MY 2027 diesel-fueled LHD2b3 vehicles would be engine-certified. However, we mistakenly used 5.1% in the development of the MOVES rates for LHD2b3 vehicles and subsequent inventory analysis. Given the small contribution of engine-certified LHD2b3 to the total emissions inventory, we expect the difference between the intended and used values to have a negligible impact on the NPRM analysis. In addition, we deem that both values (4.2% and 5.1%) are within the range of feasible values for the fraction of engine-certified LHD2b3 vehicles in future years. Nonetheless, for the final rulemaking analysis, we may revisit our estimate of the fraction of engine-certified engines in 2027 and later model years, depending on available data and resources.

^{GGGG} In the baseline case created for MOVES CTI NPRM, we assumed, for simplicity, that 100% of diesel-fueled LHD2b3 vehicles are chassis-certified and are subject to the light-duty Tier 3 emission standard. The estimated NO_x emission rates for engine-certified diesel LHD2b3 vehicles (subject to the proposed rule) are higher than chassis-certified diesel LHD2b3 vehicles (subject to the light-duty Tier 3 standard).

scenario. We plan on revisiting our assumptions to exclude the contribution of engine-certified vehicles from baseline emission rates for diesel-fueled LHD2b3 vehicles in the final rulemaking analysis.

5.2.2.6 Heavy-Duty Gasoline Running Emission Rates

In this section, we describe the methods used to develop the running exhaust emission rates for NO_x, THC, CO, and PM_{2.5} from heavy-duty gasoline vehicles in MOVES for the control scenarios. In this rulemaking, we are not proposing off-cycle standards for vehicles fueled by gasoline or NG. Furthermore, even though we anticipate emission benefits from the lengthened warranty and useful life periods from gasoline and NG-fueled vehicles, they were not included in the current analysis.

The proposed FTP duty-cycle standards shown in Table 5-4 apply to both heavy-duty compression-ignition engines and heavy-duty spark-ignition engines.^{HHHH} For the control scenarios, we updated the NO_x exhaust emission rates for gasoline, assuming that emissions are reduced for all operating modes based on the reduction in the NO_x FTP standards from the current 0.2 g/hp-hr standard. Table 5-20 shows the estimated reduction in NO_x emission rates, which is consistent with the ratio of the current FTP emission standards and the proposed FTP standards shown in Table 5-6.

In addition to modeling the proposed standards for NO_x, we estimated emission rate reductions due to the proposed standards for HC, CO and PM_{2.5}. As discussed in the Preamble section III.D, the proposed emissions standards for HC, CO, and PM_{2.5} heavy-duty spark ignition are lower than the current MY 2010 standards. We estimated reduced THC and CO emission rates assuming that those emissions would be reduced due to improvements in the three-way catalyst emission controls. We used initial data from our baseline testing and from the heavy-duty gasoline technology demonstration program presented in Chapter 3.2 to estimate our modeled emissions levels. We assumed a 65 percent reduction in THC emissions would occur at a NO_x standard of 0.1 g/hp-hr.^{IIII} We assumed additional decreases in THC emissions to reflect tighter proposed NO_x standards in proposed Option 1 in MY 2031 and the Alternative in MY 2027. We derived Equation 5-22 assuming a linear decrease in THC emissions between the estimated THC emissions emitted at the 0.1 g/hp-hr NO_x FTP level, and zero THC emissions at a hypothetical 0 g/hp-hr NO_x FTP level. We then used Equation 5-22 to estimate the reductions in THC emissions using the NO_x levels for the Proposed Option 1 MY 2027-2030, Proposed Option 1 MY 2031+, Proposed Option 2, and the Alternative scenarios (Table 5-20).

^{HHHH} Our inventory analysis for HD SI engines only evaluated the impact of the proposed FTP duty-cycle standards. We did not analyze the impact of our proposed SET duty-cycle standards or idle provisions for HD SI engines, but will consider including them in the final rulemaking analysis.

^{IIII} The proposal analyzed for the air quality modeling assumed an FTP standard at 0.1 g/hp-hr (Table 5-27)

Equation 5-22

$$R_{gasoline,THC,NO_x FTP} = 1 - \left(\frac{NO_x FTP Standard}{0.1 \frac{g}{bhp \cdot hr}} \right) \times (1 - R_{gasoline,THC,0.1 NO_x FTP})$$

$$= 1 - \left(\frac{NO_x FTP Standard}{0.1 \frac{g}{bhp \cdot hr}} \right) \times (1 - 65\%)$$

Where:

$R_{gasoline,THC,NO_x FTP}$ = percent emission reductions in heavy-duty gasoline THC emissions for NO_x FTP standards more stringent than the 0.1 NO_x FTP standard, calculated values shown in Table 5-20

NO_x FTP Standard = NO_x FTP standards in the Proposed and Alternative scenarios

We are proposing a single CO standard for MY 2027 and later HD SI engines and we maintained a 60 percent reduction in CO for all scenarios (see Table 5-20). To meet the proposed PM standards, manufacturers are expected to improve fuel control and limit the need for catalyst protection. We assumed a 50 percent reduction in PM_{2.5}, consistent with the proposed 50 percent lower PM standard, for all scenarios. Table 5-20 contains the emission rate reductions, $R_{gasoline}$, applied in MOVES for the emission inventory analysis.

Table 5-20: Running Emission Rate Reductions From Heavy-duty Gasoline Vehicles Due to Proposed and Alternative Standards, $R_{gasoline}$, Across All Heavy-duty Gasoline Regulatory Classes and Operating Modes

Control Scenario	Model Years	Regulatory Class ^A	FTP/SET NO _x standard (g/hp-hr)	NO _x	THC	CO	PM _{2.5}
Proposed Option 1	2027-2030	LHD, MHD, HHD	0.035	82.5%	87.8%	60%	50%
	2031+	LHD, MHD, HHD	0.02	90.0%	93.0%	60%	50%
Proposed Option 2	2027+	LHD, MHD, HHD	0.05	75.0%	82.5%	60%	50%
Alternative	2027+	LHD, MHD, HHD	0.02	90.0%	93.0%	60%	50%

^A The proposed and alternative spark-ignition engine standards are the same for LHD, MHD, and HHD engines, unlike the proposed Option 1 standards for compression-ignition engines (Preamble Section III.2)

We used Equation 5-23 to estimate the MOVES NO_x emission rates for the control scenarios using the $R_{gasoline}$ values for heavy-duty gasoline vehicles. Since we are not proposing to require an in-use testing program for spark-ignition engines, we did not estimate operating mode-specific effectiveness of reductions of the in-use emissions compared to duty-cycle standard emissions, as was done for diesel running emissions. Instead, we assumed these reductions apply uniformly across all running exhaust operating modes. As such, we used Equation 5-23 to estimate the MOVES emission rates proportionally for all operating modes.

Equation 5-23

$$ER_{control} = (1 - R_{gasoline}) \times ER_{MOVES_baseline}$$

Where:

$ER_{control}$ = MOVES running exhaust emission rates for the control scenarios based on the reduction in the FTP duty-cycle standard

$R_{gasoline}$ = percent emission reductions in heavy-duty gasoline emissions from Table 5-20

$ER_{MOVES\ baseline}$ = MOVES running exhaust emission rates for the baseline

The estimated heavy-duty gasoline MOVES running emission rates for the Baseline, proposed Options 1 and 2, and the Alternative scenarios are shown for NO_x and THC emissions in Figure 5-11 and Figure 5-12, respectively. CO and PM_{2.5} were similarly estimated from the reductions shown in Table 5-20, but they have the same emission rates within each regulatory class for all the control scenarios and, therefore, are not plotted.

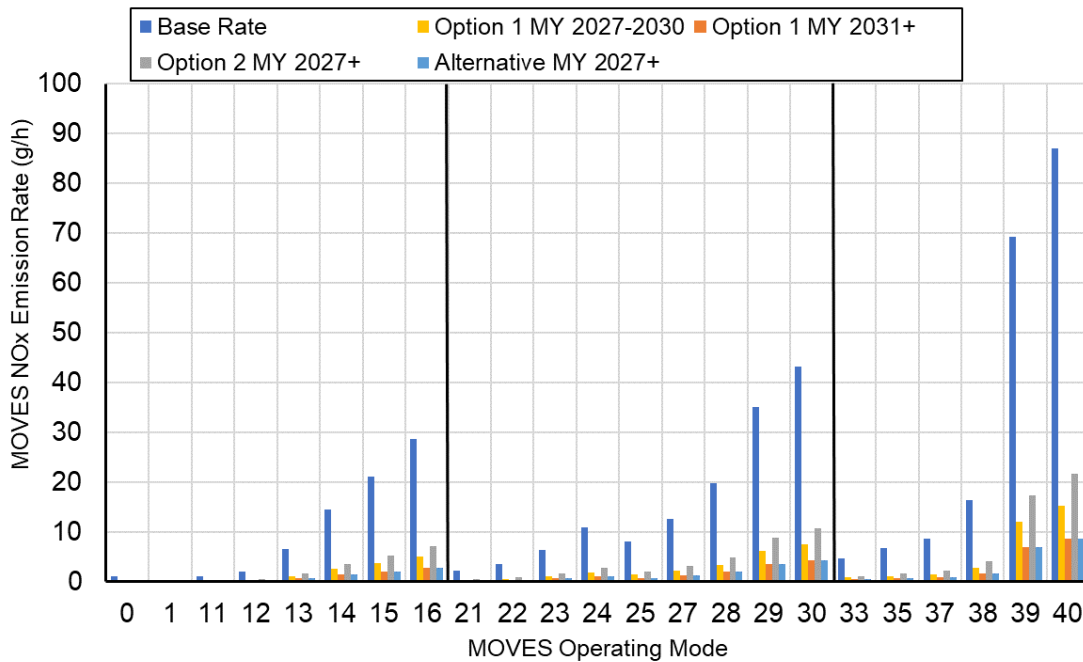


Figure 5-11: Duty-cycle-based running NO_x emission rates for LHD gasoline for the control scenarios

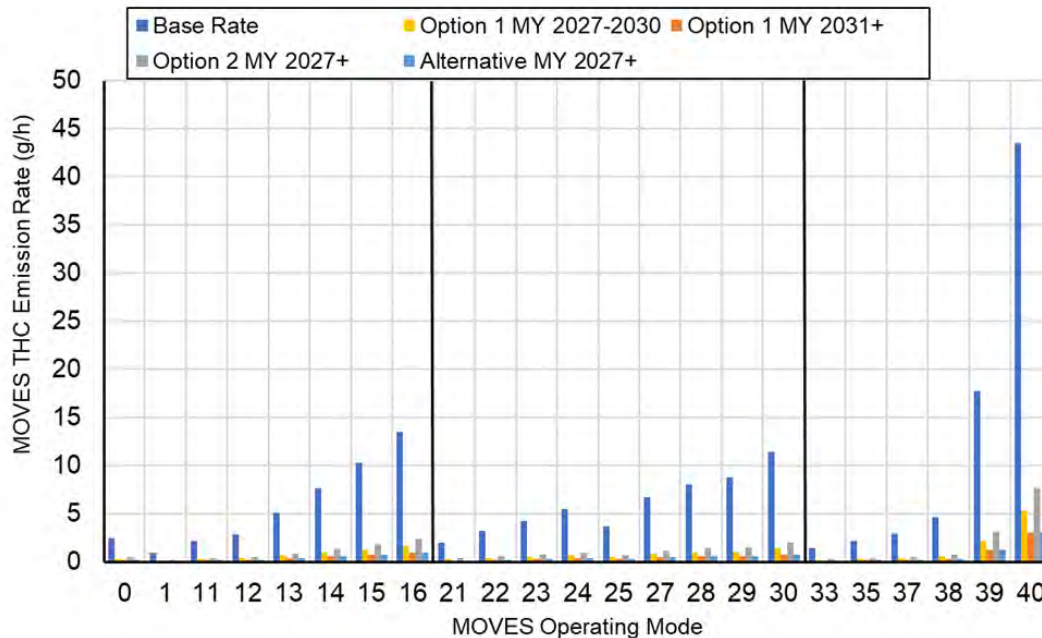


Figure 5-12: LHD gasoline Duty-cycle-based running THC emission rates for LHD gasoline for the control scenarios

5.2.2.7 Heavy-Duty Gasoline Refueling Emission Rates

In this section, we describe the methods used to estimate lower refueling emission rates in MOVES for the control scenarios due to the proposed Onboard Refueling Vapor Recovery (ORVR) requirements. Refueling emissions result when the pumped gasoline displaces the vapor in the vehicle tank. The THC emissions are a function of temperature and the gasoline Reid Vapor Pressure (RVP).^{JJJ} The emissions control technology which collects the vapor from the refueling events is the ORVR system. ORVR requirements for light-duty vehicles started phasing in as part of EPA's Refueling Emission Regulations for Light-Duty Vehicles and Light-Duty Trucks Final Rule³¹⁸ in 1998. Under the EPA's Tier 2 vehicle program, all complete vehicles with a gross vehicle weight rating (GVWR) of 8,500 lbs up to 14,000 lbs (MOVES regulatory class LHD2b3) were required to meet the ORVR requirements between 2004 and 2006 model years.³¹⁹ With the Tier 3 rulemaking, all heavy-duty trucks up to 14,000 lbs and all complete vehicles greater than 14,000 lbs are required to meet a refueling standard of 0.2 grams of HC per gallon of gasoline dispensed by 2022.³²⁰

Table 5-21 shows the ORVR adoption rates applied to all heavy-duty gasoline trucks in MOVES. For the baseline scenario, we estimated that all heavy-duty gasoline trucks up to 14,000 lbs will have ORVR control by 2018 (as shown in Table 5-21). No heavy-duty gasoline vehicles over 14,000 lb GVWR are being certified today^{KKKK} as complete vehicles, and our

^{JJJ} See additional discussion of refueling updates in the Updates to MOVES for Emissions Analysis of the HD 2027 NPRM³¹¹

^{KKKK} We expect that only one complete vehicle model will exist in 2022 and it is not yet certified.

baseline scenario reflects a population of 100 percent incomplete vehicles that have not adopted ORVR technologies and are not expected to adopt ORVR without a regulatory action, due to the costs and added complexities.

As part of this rulemaking, we are proposing that all heavy-duty gasoline vehicles, including those sold as incomplete vehicles, be required to have an ORVR system and be certified to the same standard as light-duty by model year 2027. For all three control scenarios modeled for the proposed rule, we assumed manufacturers would fully implement ORVR technologies in 2027 in the over 14,000 GVWR vehicle categories as shown in Table 5-21. For a 100 percent phase-in of ORVR, we estimated a 98 percent reduction in refueling emissions, because we assume that some ORVR systems would fail or may not be fully effective, similar to our assumptions made for current ORVR systems in light-duty vehicles.³¹¹ The emissions inventory impact of the proposed ORVR control is summarized in Chapter 5.3.3.

Table 5-21: Phase-In of Onboard Refueling Vapor Recovery (ORVR) for Heavy-duty Trucks

Model Year	Light Heavy-Duty Trucks 8,500-10,000 lbs GVWR (Class 2b)	Heavy-Duty Trucks 10,000-14,000 lbs GVWR (Class 3)	Heavy-Duty Trucks > 14,000 lbs GVWR (LHD45 and MHD) including incompletes	
			Baseline	Control
2003 and earlier	0%	0%	0%	0%
2004	40%	0%	0%	0%
2005	80%	0%	0%	0%
2006-2017	100%	0%	0%	0%
2018-2026	100%	100%	0%	0%
2027 and newer	100%	100%	0%	100%

5.3 National Emissions Inventory Results

In the following sections, we present the emissions impacts of the control scenarios (proposed options and alternative) in three select calendar years.^{LLLL} The national (50 states and Washington DC, excluding Puerto Rico and the Virgin Islands) highway heavy-duty vehicle emission inventory was generated using the national-scale option in MOVES CTI NPRM with the methodology and the model inputs as described in Chapter 5.2.

^{LLLL} The proposed criteria pollutant program is expected to have minimal impacts on CO₂ emissions. We estimated a small fuel savings for heavy-duty gasoline vehicles in Section 7.2.2 due to ORVR control (Chapter 5.2.2.7). However, for MOVES emissions inventories, we estimated no differences in the CO₂ emission rates for the baseline and control scenarios. See draft RIA Chapter 1 for more discussion of the technologies evaluated to control NO_x emissions without impacting CO₂ emissions. See Section XI for our analysis of CO₂ emission impacts of the proposed revisions to the Heavy Duty GHG Phase 2 program.

5.3.1 Proposed Options

Table 5-22 summarizes the emission impacts of the proposed Option 1 for three select calendar years. Chapter 5.5.5 shows NO_x, VOC, PM_{2.5}, and CO inventories for calendar years between 2027 and 2045.

**Table 5-22: National Emission Reductions from Heavy-duty Vehicles in Calendar Years 2030, 2040, and 2045
— Proposed Option 1 Program Emissions Relative to Heavy-Duty Vehicle Emissions Baseline**

Pollutant	2030		2040		2045	
	US Short Tons	% Reduction	US Short Tons	% Reduction	US Short Tons	% Reduction
NO _x	153,608	16.4%	491,318	55.9%	558,780	60.5%
VOC	4,681	5.0%	15,199	18.7%	17,975	21.0%
Primary Exhaust PM _{2.5} - Total	408	3.4%	1,741	23.7%	2,005	26.4%
Carbon Monoxide (CO)	51,154	3.2%	241,974	15.2%	289,835	17.2%
1,3-Butadiene*	0	0.0%	0	0.0%	0	0.0%
Acetaldehyde	8	0.4%	46	2.5%	52	2.7%
Benzene	42	4.1%	181	23.1%	221	26.8%
Formaldehyde	12	0.5%	63	4.1%	75	4.6%
Methane (CH ₄)	166	0.2%	881	0.7%	1,025	0.7%
Naphthalene	1.3	0.9%	6.5	14.3%	8	16.7%

* No change is observed in 1,3-butadiene emissions in the control scenarios, because, in MOVES CTI NPRM, 1,3-butadiene emissions do not contribute to VOC emissions from 2027 and later diesel running and start, heavy-duty gasoline running, and gasoline refueling^{311,321}

More details about the impacts of the proposed Option 1 can be found in Chapter 5.5.3 where the emission reductions are categorized by vehicle fuel type with further splits by emission process and by heavy-duty regulatory class. Additional details are also provided in Chapter 5.5.4 regarding the NO_x emissions in calendar year 2045 from different engine operational processes with and without the proposed Option 1 or 2 standards. Table 5-23 summarizes the emissions impacts in three selected calendar years for proposed Option 2.

**Table 5-23: National Emission Reductions from Heavy-duty Vehicles in Calendar Years 2030, 2040, and 2045
— Proposed Option 2 Program Emissions Relative to Heavy-Duty Vehicle Emissions Baseline**

Pollutant	2030		2040		2045	
	US Short Tons	% Reduction	US Short Tons	% Reduction	US Short Tons	% Reduction
NOX	140,691	15.0%	383,350	43.6%	437,869	47.4%
VOC	4,645	5.0%	14,623	18.0%	17,283	20.2%
Primary Exhaust PM _{2.5} - Total	408	3.4%	1,600	21.8%	1,856	24.4%
Carbon Monoxide (CO)	51,154	3.2%	216,413	13.6%	262,574	15.6%
1,3-Butadiene	0	0.0%	0	0.0%	0	0.0%
Acetaldehyde	8	0.4%	32	1.8%	37	1.9%
Benzene	41	4.0%	167	21.3%	202	24.5%
Formaldehyde	12	0.5%	51	3.3%	61	3.7%
Methane (CH ₄)	160	0.1%	654	0.5%	770	0.6%
Naphthalene	1.2	0.8%	5.7	12.6%	7	14.6%

5.3.2 Alternative

Table 5-24 summarizes the emissions impacts in three selected calendar years for the Alternative scenario.

**Table 5-24: National Emission Reductions from Heavy-duty Vehicles in Calendar Years 2030, 2040, and 2045
— Alternative Program Emissions Relative to Heavy-Duty Vehicle Emissions Baseline**

Pollutant	CY2030		CY2040		CY2045	
	US Short Tons	% Reduction	US Short Tons	% Reduction	US Short Tons	% Reduction
NOX	155,954	16.7%	500,367	56.9%	566,100	61.3%
VOC	4,716	5.0%	15,312	18.9%	18,069	21.1%
Primary Exhaust PM _{2.5} - Total	408	3.4%	1,822	24.8%	2,090	27.5%
Carbon Monoxide (CO)	51,154	3.2%	247,475	15.5%	295,561	17.5%
1,3-Butadiene	0	0.0%	0	0.0%	0	0.0%
Acetaldehyde	9	0.4%	49	2.7%	56	2.9%
Benzene	44	4.3%	183	23.3%	222	26.9%
Formaldehyde	13	0.6%	66	4.3%	78	4.7%
Methane (CH ₄)	172	0.2%	934	0.7%	1,076	0.8%
Naphthalene	1.4	0.9%	6.6	14.6%	8	16.9%

5.3.3 Impacts of Heavy-Duty Gasoline Refueling Controls

Table 5-25 shows the estimated impact on refueling emissions from heavy-duty vehicles due to the proposed refueling emission standard. For heavy-duty vehicles, MOVES CTI NPRM only estimates refueling emissions from gasoline-fueled vehicles. Thus, the reductions reflect the control of the refueling emissions from only the heavy-duty gasoline vehicles above 14,000 lbs. Because benzene is calculated as a fraction of VOC emissions, the percent reductions are the same for both pollutants as shown in Table 5-25.

Table 5-25: Emission Reductions Due to Adoption of ORVR for Heavy-duty Vehicles Relative to Heavy-Duty Vehicle Emissions Baseline

Calendar Year	Pollutant	Reductions in US Short Tons	% Reduction
2027	Benzene	3	7.0%
	VOC	955	7.0%
2030	Benzene	14	29.2%
	VOC	3980	29.2%
2040	Benzene	41	80.2%
	VOC	11637	80.2%
2045	Benzene	48	88.5%
	VOC	13678	88.5%

5.4 Emissions Inventories for Air Quality Modeling

The air quality modeling analysis completed for this proposal requires emission inventories with greater geographical and temporal resolution than the national-scale inventories described in Chapter 5.3. The approach for estimating emission inventories for an air quality modeling analysis is extremely complex and time and resource intensive since it involves modeling of each 12 km grid cell, for each hour of the day, for the entire year.

The methodology for developing emission inventories for air quality modeling, also referred to as SMOKE-MOVES emission inventories, is summarized here. Additional details, including information for sectors other than onroad vehicles, are available in the Air Quality Modeling Technical Support Document (AQM TSD).³²² Figure 5-13 illustrates the process involved in generating the onroad emissions inventories for use in air quality modeling. First, the meteorological preprocessor, Met4Moves, is used to generate the temperature ranges, relative humidity, and temperature profiles that are needed for MOVES CTI NPRM is used to generate county-level onroad emission factors (EF) by temperature and speed bins. As discussed below, the MOVES emission rates for the air quality modeling inventory differed from the emission rates discussed in Chapter 5.2.2. Additionally, other MOVES data inputs for the county-level runs sometimes differ from the inputs used for the national inventory. For example, the county-level MOVES runs include county-specific inputs including: fuel programs, inspection and maintenance programs, adoption of LEV standards, and the age distribution of the local vehicle fleet. The emission factors for each representative county were generated with multiple runs of the MOVES CTI NPRM version of the model.

The MOVES-generated onroad emission factors were then combined with activity data to produce emissions within the Sparse Matrix Operator Kernel Emissions (SMOKE) modeling system. The collection of tools that compute the onroad mobile source emissions (as one of the sectors included in the air quality modeling) are known as SMOKE-MOVES. SMOKE-MOVES uses a combination of vehicle activity data, emission factors from MOVES, meteorology data, and temporal allocation information to estimate hourly onroad emissions. Additional types of ancillary data are used for the emissions processing, such as spatial surrogates which spatially allocate emissions to the 12 km grid cells used for air quality modeling.

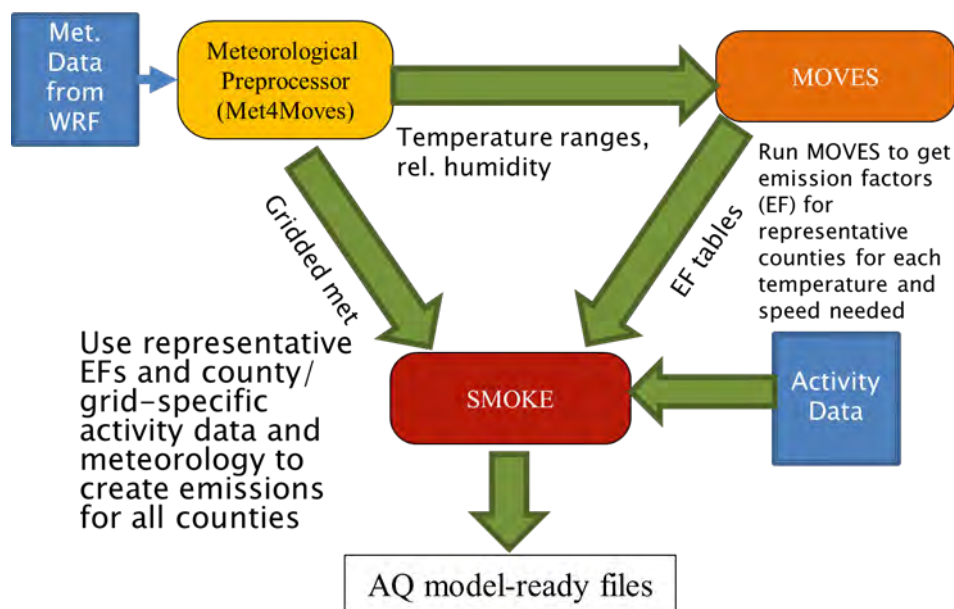


Figure 5-13: Modeling process of onroad emissions as part of the input for air quality modeling

5.4.1 Control Scenario Evaluated for the Air Quality Modeling Analysis

The control scenario evaluated for the air quality modeling analysis contains differences from the proposed Option 1 that is outlined in Preamble Sections III and IV and used to develop the national emissions inventories discussed in Chapter 5.2.2. Because the air quality modeling analysis is a time and resource intensive process, the work was conducted using a preliminary control case that differed from the proposal. We used the same methodology as documented in Chapter 5.2.2 to develop the running, start, and extended idle emission rates for the air quality modeling analysis, but different standards, emission warranty, useful life periods, and phase-in schedules. In addition, we did not account for the closed crankcase control in the air quality analysis. There are no differences in the refueling control in the proposed Option 1 and the scenario analyzed for air quality modeling. Table 5-26 summarizes the differences between the MOVES inputs and emission rates between proposed Option 1 and the air quality modeling scenario, including the directional impact for the air quality modeling scenario emissions as compared to proposed Option 1. The net impact of the differences in the control scenarios and the differences in the emission inventory methodology are presented in Chapter 5.4.3.

Table 5-26. Summary of Differences between Emissions in Proposed Option 1 and the Control Scenario Analyzed for Air Quality Modeling

Program Component	Fuel Types	Processes	Directional Impact for the Air Quality Modeling Scenario compared to Option 1
Duty cycle and off-cycle standards	Diesel	Running, Start, Extended Idle	Increase in NO _x emissions
	Gasoline	Running, Start	Increase in NO _x and THC emissions
Warranty Periods	Diesel	Running	Slight increase in NO _x , THC, CO, and PM _{2.5} emissions
Useful Life Periods	Diesel	Running	Slight decrease in NO _x , THC, CO, and PM _{2.5} emissions
Crankcase Control	Diesel	Crankcase	Increase in PM _{2.5} emissions
Delayed phase-in (2031 vs. 2030)	Diesel	Running, Start, Extended Idle	Decrease in NO _x , THC, CO, and PM _{2.5} emissions
	Gasoline	Running, Start	
Refueling Standard	Gasoline	Refueling	No change

Table 5-27 compares the differences in the duty-cycle standards used in developing the running, start, and extended idle emission rates in the proposed Option 1 and the scenario analyzed for the air quality modeling analysis.

Table 5-27: Duty-Cycle NO_x Standards for Proposed Option 1 and the Control Scenario Analyzed for Air Quality Modeling^A

Model Year	Engine	Duty Cycle	Duty-Cycle NO _x Standards (mg/hp-hr)	
			Scenario Analyzed for Air Quality Modeling	Option 1
2027	HHD, MHD, LHD	FTP	100	35
		SET	50	35
		LLC	200	90
		Idle ^C	18 g/hr	5 g/hr
	HD SI	FTP	100	35
		SET	50	35
2030 or 2031 ^A	HHD, MHD, LHD	FTP	50	20 [40 HHD] ^B
		SET	20	20 [40 HHD] ^B
		LLC	100	50 [100 HHD] ^B
		Idle ^C	10 g/hr	5 g/hr
	HD SI	FTP	50	20
		SET	20	20

^A The MY 2030 applies to the scenario for air quality modeling while MY 2031 applies to proposed Option 1.

^B Values in brackets [] denote standards that only apply to HHD engines.

^C In both scenarios, we assumed compliance with the Voluntary Idle standard which is more stringent than the off-cycle standard as discussed in Chapter 5.2.2.1.1.2 .

In the control scenario analyzed for air quality modeling, the FTP and SET standards are different from one another. The R_{duty} values calculated from the FTP are applied to MOVES

running operating modes for vehicle speeds below 50 miles per hour, which aligns with the transient behavior of the FTP cycle. The R_{duty} from the SET standard are applied to MOVES operating modes above 50 mph (operating mode 33 and above), which aligns with the high-speed activity that is targeted with the SET standard. In the proposed options and the alternative, the FTP and SET standards are equivalent, so we used the same R_{duty} values to calculate the emission rates for all running operating modes as discussed in Section 5.2.2.1.1.1.

Table 5-28. R_{duty} Ratios Calculated for the Control Scenario Analyzed for Air Quality Modeling

Scenario	Applicable Model Years	Emission standard		R _{duty}	
		(g/hp-hr)			
		FTP	SET-RMC	FTP	SET-RMC
Air Quality Modeling	Model Year 2027-2029	0.1	0.05	50%	25%
	Model Year 2030+	0.05	0.02	25%	10%

The differences in the warranty and useful life periods used in the control scenario analyzed for air quality modeling are shown in Table 5-29 and Table 5-30. Aside from the differences in the warranty and useful life periods, we used the same methodology to estimate the impact on diesel running emission rates. In general, the warranty periods are longer in proposed Option 1 compared to the scenario analyzed for air quality modeling. Furthermore, Option 1 has shorter useful life periods than in the control scenario analyzed for air quality modeling.

Table 5-29: Warranty Mileages and Years in Option 1 and the Control Scenario Analyzed for Air Quality Modeling

Model Year	Engine	Warranty Mileage		Warranty Years	
		Air Quality Modeling Control Scenario	Option 1	Air Quality Modeling Control Scenario	Option 1
2027	HHD	350k	450k	5 years	7 years
	MHD	150k	220k		
	LHD	110k	150k		
	HD SI	110k	200k	5 years	7 years
2030 or 2031 ^A	HHD	600k	600k	7 years	10 years
	MHD	260k	280k		
	LHD	200k	210k		
	HD SI	160k	160k	7 years	10 years

^A The MY 2030 applies to the air quality modeling control scenario while MY 2031 applies to Option 1.

Table 5-30: Useful Life Mileages and Years in Option 1 and the Control Scenario Analyzed for Air Quality Modeling

Model Year	Engine	Useful Life Mileage		Useful Life Years	
		Air Quality Modeling Control Scenario	Option 1	Air Quality Modeling Control Scenario	Option 1
2027	HHD	650k	600k	10 years	11 years
	MHD	325k	270k		12 years
	LHD	250k	190k		
	HD SI	200k	155k	10 years	12 years
2030 or 2031 ^A	HHD	850k	800k	10 years	12 years
	MHD	450k	350k		15 years
	LHD	350k	270k		
	HD SI	200k	200k	10 years	15 years

^A The MY 2030 applies to the air quality modeling control scenario while MY 2031 applies to Option 1.

5.4.2 Estimated Differences in the Emission Reductions between the SMOKE-MOVES and National-Scale Emission Inventories

Table 5-31 presents the emission reductions from all onroad vehicles (both light-duty and heavy-duty) estimated from the SMOKE-MOVES inventories; for comparison, the table also includes the estimated reductions from the national-scale inventories using the MOVES inputs developed for the air quality modeling control scenario. Comparison between the SMOKE-MOVES inventories and national-scale inventories shows that the percent emission reduction trends are generally similar, although the SMOKE-MOVES inventory reductions are smaller relative to the national-scale inventories. There are several factors that contribute to the differences between the SMOKE-MOVES inventories and the national inventories. The most important factor is the methodological differences — SMOKE-MOVES utilizes more localized input data (such as local vehicle age distributions), and local meteorology data — but there is also a domain difference (48 contiguous states for the SMOKE-MOVES inventories and 50 states for the national inventories). As a result, we also present the SMOKE-MOVES inventories for the 50 states to compare to the national emissions inventory in Table 5-31.

Table 5-31: Onroad Vehicle Emission Reductions from the Air Quality Modeling Control Scenario Using SMOKE-MOVES Inventories and National Inventories

Pollutant	CY2045 Reduction in SMOKE-MOVES Inventory (Contiguous US - 48 states; used in AQ modeling [^])		CY2045 Reduction in SMOKE-MOVES Inventory (50 states)		CY2045 Reduction in MOVES National Inventory (50 states)	
	US Short Tons	% Reduction	US Short Tons	% Reduction	US Short Tons	% Reduction
NO _x	447,436	48.1%	449,408	48.0%	539,468	52.7%
VOC	7,756	1.7%	7,854	1.7%	17,750	3.4%
PM _{2.5} - Primary	544	1.4%	548	1.4%	746	1.8%
Carbon Monoxide (CO)	165,973	3.6%	167,241	3.6%	289,756	5.9%
1,3-Butadiene*	0	0.0%	0	0.0%	0	0.0%
Acetaldehyde	35	0.9%	35	0.9%	51	1.1%
Benzene	112	1.6%	113	1.6%	210	2.8%
Formaldehyde	45	1.6%	46	1.6%	72	2.4%
Naphthalene	4	1.5%	4	1.5%	7	2.4%

Notes: The 48-state SMOKE-MOVES Emissions Inventory was used as emissions inputs to CMAQ, which currently has a domain that only covers the contiguous 48 states.

* No change is observed in 1,3-butadiene emissions in the control scenarios, because in MOVES CTI NPRM, 1,3-butadiene emissions do not contribute to VOC emissions from 2027 and later diesel running and start, heavy-duty gasoline running, and gasoline refueling.³¹¹

5.4.3 Estimated Differences in the Emission Reductions between Option 1 and the Control Scenario Analyzed for Air Quality Modeling

Table 5-32 contains a comparison of the national emissions inventory reduction for proposed Option 1 compared to the control scenario analyzed for air quality modeling, for all onroad vehicles (both light-duty and heavy-duty). As discussed in Chapter 5.4.1, we anticipate larger reduction in NO_x emissions from Option 1 compared to what was analyzed for air quality modeling, due to the lower NO_x duty-cycle emission standards. In addition, we anticipate larger reductions in PM_{2.5} emissions because Option 1 accounts for crankcase control. Slightly larger reductions are observed in VOC emissions, which is attributed to the lower gasoline tailpipe THC emissions with the more stringent NO_x emission standards. Small changes are observed for CO emissions due to the differences in the emissions warranty and useful life standards.

Table 5-32 Comparison of the Onroad Vehicle Emission Reductions from the Air Quality Modeling Control Scenario vs. Option 1

Pollutant	CY2045 Reduction in MOVES National Inventory (50 states) using the Air Quality Modeling Control Scenario		CY2045 Reduction in MOVES National Inventory (50 states) from Option 1	
	US Short Tons	% Reduction	US Short Tons	% Reduction
NO _x	539,468	52.7%	558,780	54.6%
VOC	17,750	3.4%	17,975	3.5%
PM _{2.5} - Primary [^]	746	1.8%	2,005	4.8%
Carbon Monoxide (CO)	289,756	5.9%	289,835	5.9%
1,3-Butadiene*	0	0.0%	0	0.0%
Acetaldehyde	51	1.1%	52	1.2%
Benzene	210	2.8%	221	3.0%
Formaldehyde	72	2.4%	75	2.5%
Naphthalene	7	2.4%	8.0	2.5%

Notes: ^ The PM_{2.5} reductions in the Option 1 include additional reductions from accounting for the closed crankcase requirement for HD diesel vehicles.

* No change is observed in 1,3-butadiene emissions in the control scenarios, because in MOVES CTI NPRM, 1,3-butadiene emissions do not contribute to VOC emissions from 2027 and later diesel running and start, heavy-duty gasoline running, and gasoline refueling.³¹¹

5.5 Chapter 5 Appendix

5.5.1 Estimation of Engine-Certified Fraction among Model Year 2027 Diesel-Fueled LHD2b3 Vehicles

We estimated the fraction of engine-certified diesel vehicles in MY 2027 using a combination of the vehicle activity data in MOVES CTI NPRM and national vehicle registration data. The vehicle population in MOVES CTI NPRM for current and future years, detailed by regulatory class, fuel type, vehicle age, and MOVES vehicle activity type, are derived from vehicle registration data and sales and fleet population projections as documented in a MOVES technical report.³⁰⁹ Table 5-33 contains the national sales volumes of LHD2b3 diesel-fueled vehicles estimated for MY 2027 among four MOVES vehicle activity types referred to as source types. All Class 3 vehicles are classified in the vocational source types (single-unit short-haul and single-unit long-haul trucks).

Table 5-33: Sales Volumes of Model Year 2027 LHD2b3 Diesel-Fueled Vehicles Estimated by MOVES CTI NPRM

Source Type	Sales Volume
Passenger Truck	95,308
Light-Commercial Truck	15,820
Single Unit Short-haul Truck	113,959
Single Unit Long-haul Truck	5,026
<i>Total</i>	<i>230,114</i>

Using the sales volume in Table 5-33, we estimated the fraction of Class 3 vocational diesel vehicles of the total diesel LHD2b3 sales with Equation 5-24. We first estimated the fraction of

Class 3 vocational vehicles, because we assume that most of the engine-certified vehicles exist within Class 3 vehicles.

Equation 5-24

$$\begin{aligned} & \frac{\text{MY 2027 Diesel Class 3 vocational}}{\text{MY 2027 Diesel Class 2b3}} \\ &= \frac{\text{Single Unit Shorthaul} + \text{Single Unit Longhaul (Table 5-33)}}{\text{Total}} \\ &= \frac{113,959 + 5,026}{230,114} = 51.7\% \end{aligned}$$

To estimate the fraction of Class 3 diesel vehicles in model year 2027 that are engine-certified, we estimated the current fraction of engine-certified Class 3 diesel vehicles in the national fleet using national vehicle registration data. Fiat Chrysler Automobiles (FCA) is currently the only vehicle manufacturer to assemble engine-certified 2b3 vehicles. FCA engine-certified vehicles are assembled with Cummins diesel engines. We did not estimate the fraction of engine-certified vehicles from the manufacturer-submitted production volumes to EPA, because the use of this data could compromise the sales data that was claimed to be confidential business information.^{MMMM} Using the 2014 national registration data that was used to develop the vehicle activity in MOVES CTI NPRM, we estimated that 16.1 percent of Class 3 diesel-fueled vocational vehicles were produced by FCA (across all model years). We then used Equation 5-25 to estimate the fraction of engine-certified vehicles among all diesel-fueled 2b3 vehicles in MY 2027. Because FCA manufacturers both chassis and engine-certified diesel 2b3 vehicles, we assumed 50 percent of them are engine-certified.

Equation 5-25

$$\begin{aligned} & \frac{\text{MY 2027 Engine certified Diesel Class 3 vehicles}}{\text{MY 2026 Diesel 2b3 vehicles}} \\ &= \left(\frac{\text{MY 2027 Diesel Class 3 diesel vocational}}{\text{MY 2026 Diesel 2b3}} \right) \\ &\times \left(\frac{\text{FCA Class 3 diesel vocational vehicles in CY 2014}}{\text{Class 3 diesel vocational vehicles in CY 2014}} \right) \\ &\times \left(\frac{\text{Engine certified FCA Class 3 diesel vocational vehicles}}{\text{FCA Class 3 diesel vocational vehicles}} \right) \\ &= 51.7\% \times 16.1\% \times 50\% \\ &= 4.2\% \end{aligned}$$

Equation 5-25 yields an estimate fraction of engine-certified vehicles of diesel 2b3 vehicles in MY 2027 as 4.2 percent. We also assume the fraction of engine-certified diesel 2b3 vehicles will remain constant across the model years analyzed for the proposed rule (2027-2045 model years).

^{MMMM} See Section XII.A.I of the preamble to this rulemaking for our proposed determinations for confidential business information.

5.5.2 Zero-Mile Emission Rates for the Control Scenarios

The zero-mile NO_x emission rates for HHD diesel vehicles in the proposed and alternative scenarios due to the duty-cycle and off-cycle standards are displayed in Figure 5-5.

Figure 5-14 and Figure 5-15 display the zero-mile NO_x emission rates for LHD45 and MHD diesel vehicles in the proposed and the alternative scenarios.

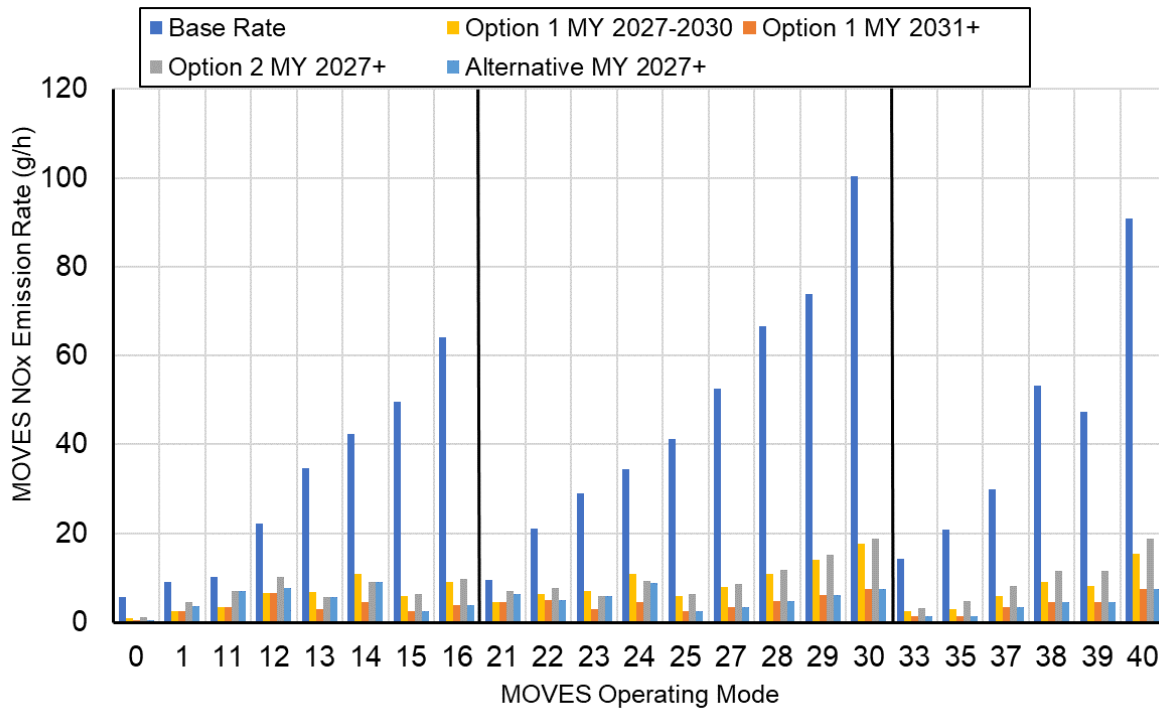


Figure 5-14: Estimated zero-mile emission rates for LHD45 diesel vehicles due to the proposed and alternative duty-cycle and off-cycle standards

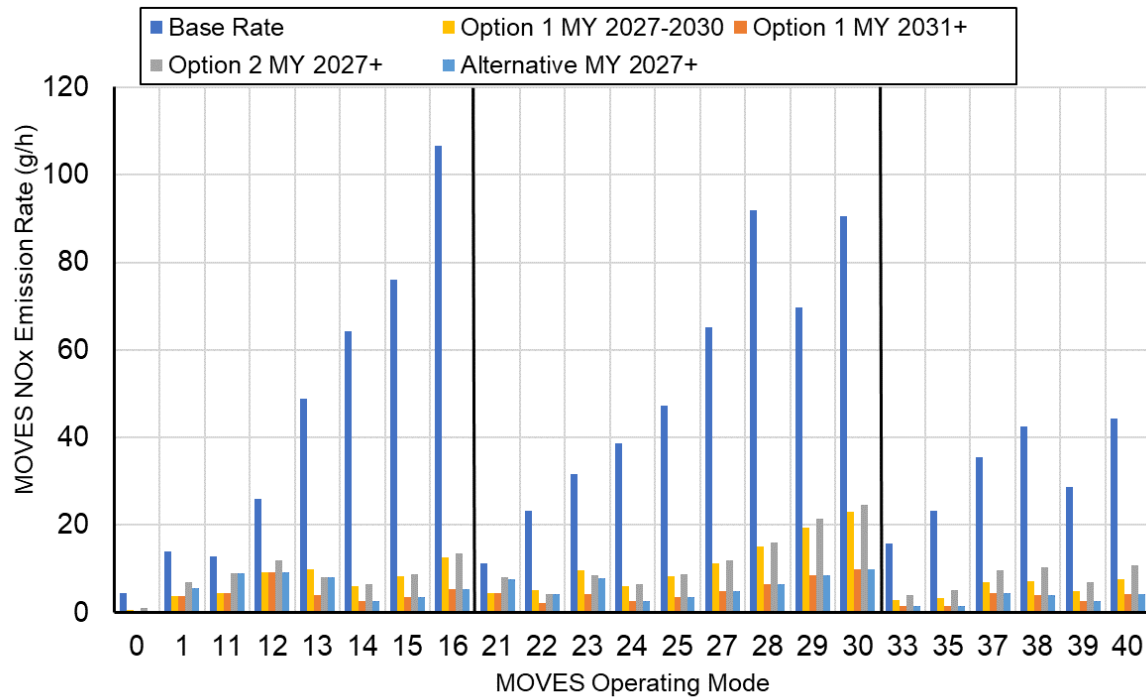


Figure 5-15: Estimated zero-mile emission rates for MHD diesel vehicles due to the proposed and alternative duty-cycle and off-cycle standards

5.5.3 Details of the Emission Impacts of the Proposed Option 1 Program

In this section, we provide details of the national emission reductions from the heavy-duty vehicles due to the proposed Option 1 program (previously summarized in Chapter 5.3.1).

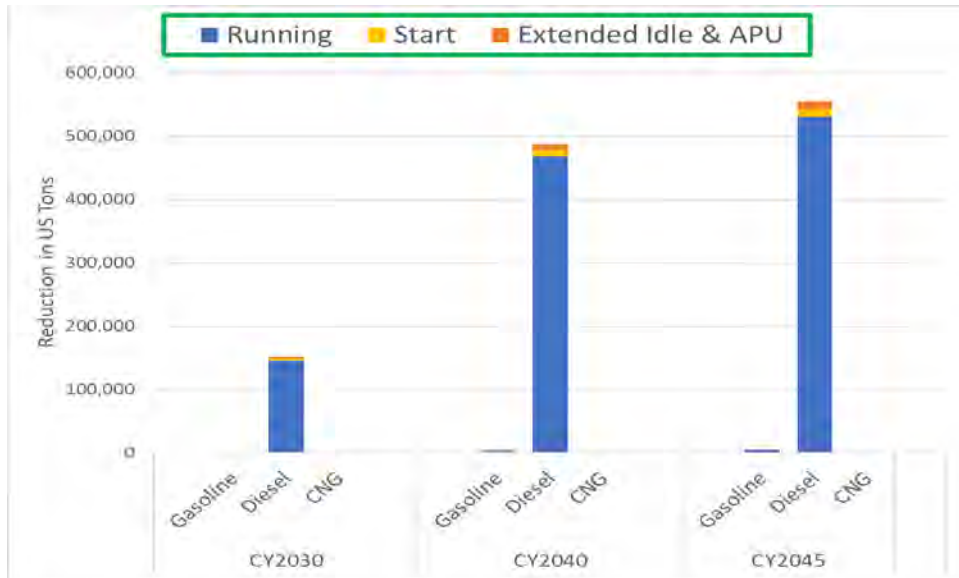


Figure 5-16: National NO_x Emission Reductions from Heavy-duty Vehicles in Calendar Years 2030, 2040, and 2045 — Proposed Option 1 Program Reductions from the Baseline for Each Fuel Type Category by Emission Process

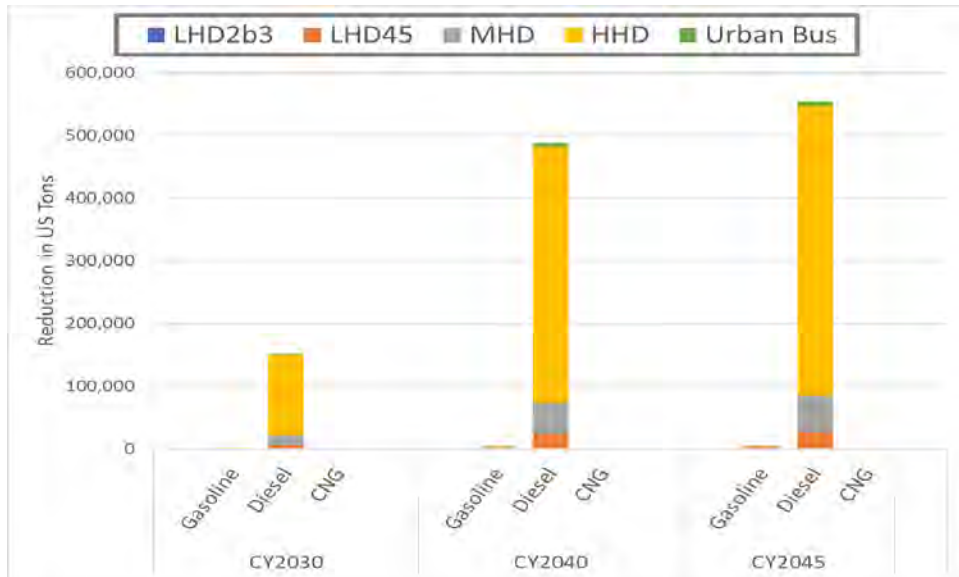


Figure 5-17: National NO_x Emission Reductions from Heavy-duty Vehicles in Calendar Years 2030, 2040, and 2045 — Proposed Option 1 Program Reductions from the Baseline for Each Fuel Type Category by HD Regulatory Class

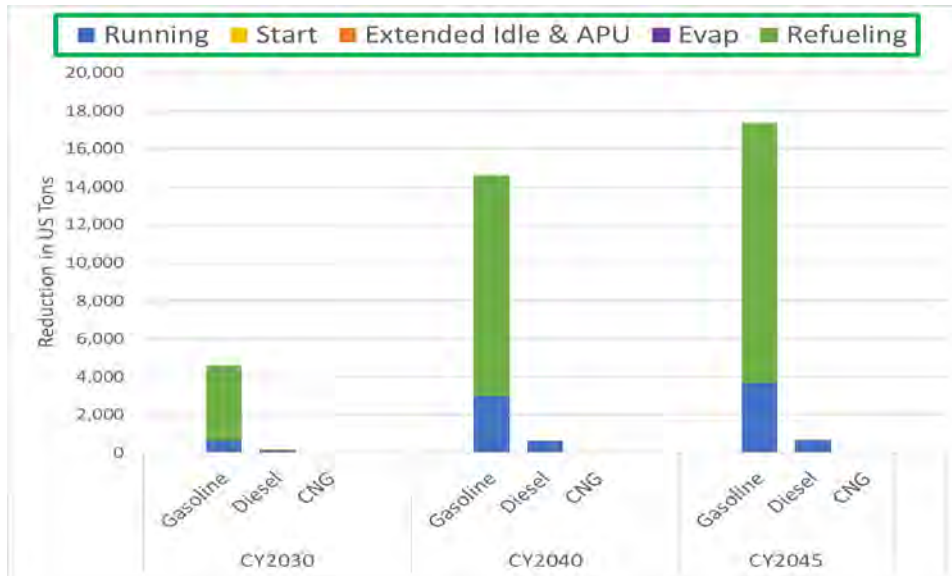


Figure 5-18: National VOC Emission Reductions from Heavy-duty Vehicles in Calendar Years 2030, 2040, and 2045 – Proposed Option 1 Program Reductions from the Baseline for Each Fuel Type Category by Emission Process

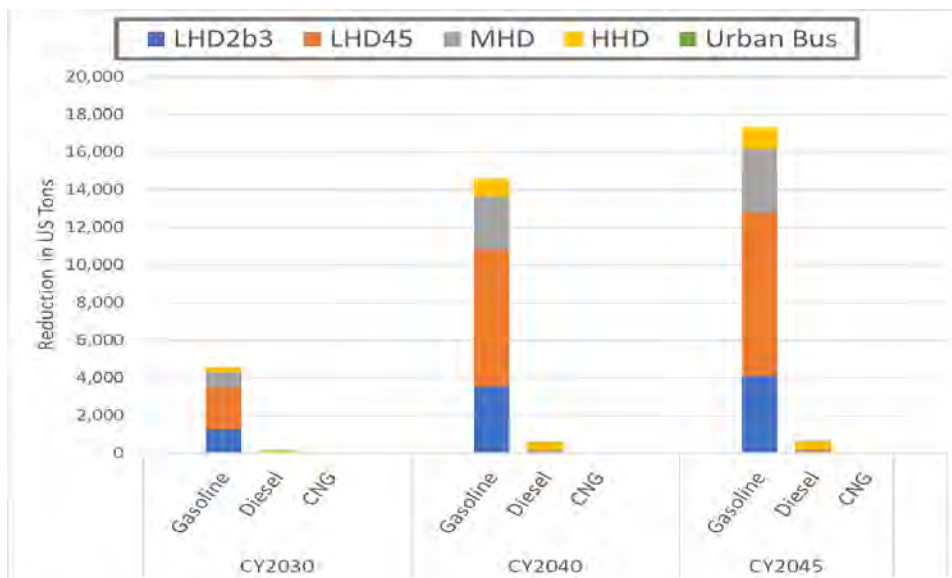


Figure 5-19: National VOC Emission Reductions from Heavy-duty Vehicles in Calendar Years 2030, 2040, and 2045 – Proposed Option 1 Program Reductions from the Baseline for Each Fuel Type Category by HD Regulatory Class

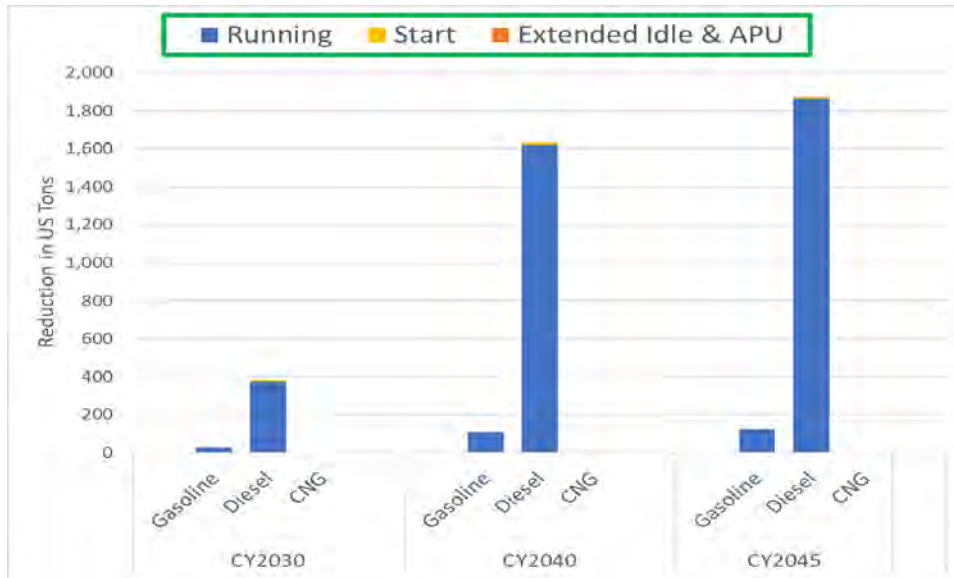


Figure 5-20: National Exhaust PM_{2.5} Emission Reductions from Heavy-duty Vehicles in Calendar Years 2030, 2040, and 2045 — Proposed Option 1 Program Reductions from the Baseline for Each Fuel Type Category by Emission Process

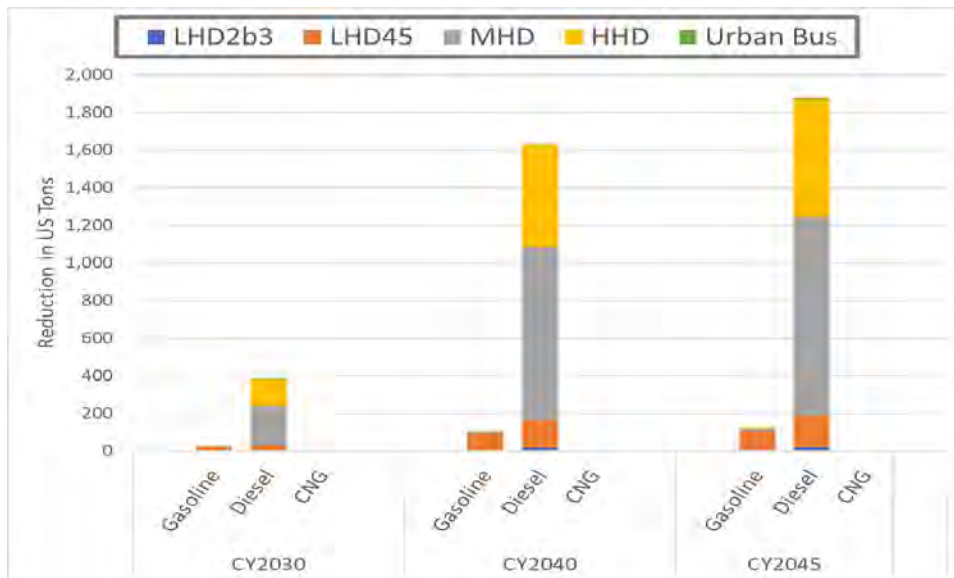


Figure 5-21: National Exhaust PM_{2.5} Emission Reductions from Heavy-duty Vehicles in Calendar Years 2030, 2040, and 2045 — Proposed Option 1 Program Reductions from the Baseline for Each Fuel Type Category by HD Regulatory Class

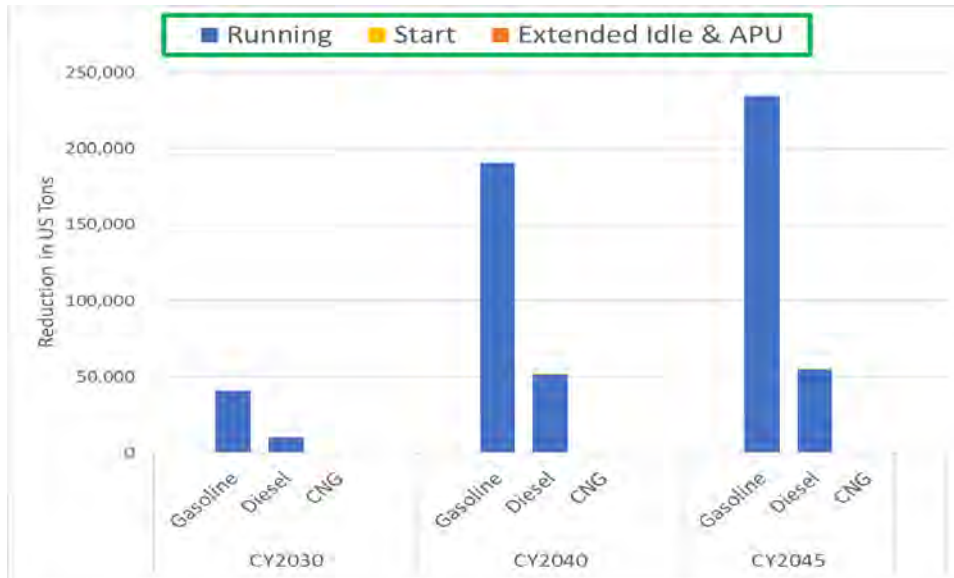


Figure 5-22: National CO Emission Reductions from Heavy-duty Vehicles in Calendar Years 2030, 2040, and 2045 – Proposed Option 1 Program Reductions from the Baseline for Each Fuel Type Category by Emission Process

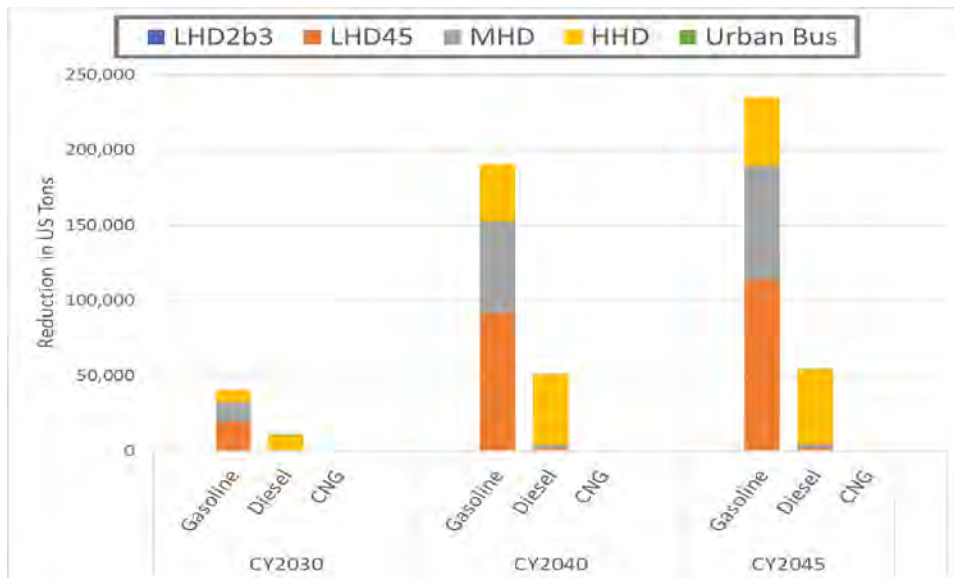


Figure 5-23: National CO Emission Reductions from Heavy-duty Vehicles in Calendar Years 2030, 2040, and 2045 – Proposed Option 1 Program Reductions from the Baseline for Each Fuel Type Category by HD Regulatory Class

5.5.4 Onroad Heavy-Duty NO_x Emissions by Engine Operational Process for the Baseline, Proposed Option 1, and Proposed Option 2 Standards

Figure 5-24 displays the estimated national onroad heavy-duty NO_x emissions in 2045 in the baseline and in the proposed Option 1 and 2 by engine operation process for the MY 2027 and later fleet impacted by the proposed rule. See Section VI of the preamble for more discussion on these comparisons.

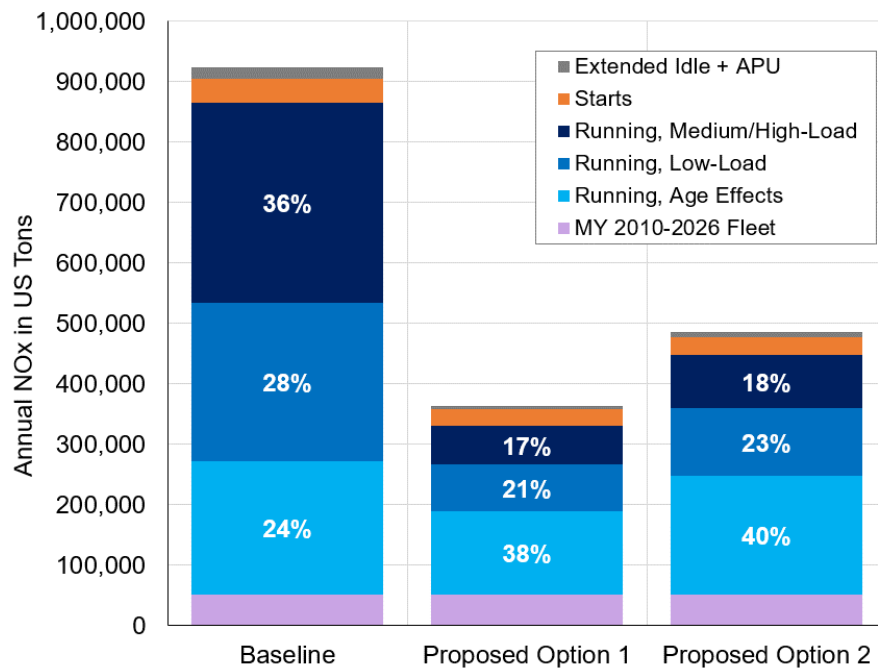


Figure 5-24: Comparison of Calendar Year 2045 Onroad Heavy-Duty NO_x Emissions from Different Engine Operational Process^{NNNN} for the Baseline, Proposed Option 1, and Proposed Option 2 Standards

5.5.5 Year-Over-Year Criteria Pollutant Emissions for Calendar Years Between 2027 and 2045

In this section, we present MOVES national inventory emissions (for selected criteria pollutants) across multiple calendar years (2027-2045) for baseline and control scenarios.

The national heavy-duty vehicle emissions inventories are summarized in Table 5-34 through Table 5-37 below for NO_x, VOC, PM_{2.5} (exhaust), and CO, respectively, for the baseline, proposed Options 1 and 2, and alternative scenarios. The same results are also displayed graphically in Figure 5-25 through Figure 5-28.

^{NNNN} In this graph, the "low-load running" emissions refer to the running exhaust emissions (for model year 2027 and later without age effects) from MOVES running operating mode 0, 1, 11-14, 21-24, 33, plus 50% of operating mode 35 (see Table 5-3 for MOVES operating mode definitions). The remainder are considered "medium/high-load running" emissions. The contribution of the "Running, Age Effects" was estimated by conducting a series of MOVES runs with and without running aging effects for the baseline and proposed Options 1 and 2. The MOVES inputs without the aging effects are available in the rulemaking docket.³⁰⁸

Table 5-34: National Heavy-duty Vehicle NO_x Emissions (Annual US Tons) For Calendar Years Between 2027 and 2045

Calendar Year	Baseline	Proposed Option 1	Proposed Option 2	Alternative
2027	1,043,853	1,008,012	1,011,033	1,007,470
2028	998,254	924,616	930,819	923,500
2029	964,637	851,723	861,225	850,004
2030	935,698	782,090	795,007	779,744
2031	913,916	709,061	732,174	702,657
2032	896,771	642,716	675,748	632,455
2033	879,841	594,289	631,471	564,540
2034	873,529	558,114	599,299	509,977
2035	869,923	522,722	573,172	475,752
2036	870,446	493,595	552,832	448,090
2037	867,129	450,951	531,055	422,827
2038	871,297	418,629	518,199	406,754
2039	875,406	403,131	506,957	392,702
2040	879,258	387,940	495,908	378,891
2041	887,603	379,711	490,737	371,129
2042	895,708	373,391	487,126	365,198
2043	904,248	369,393	485,498	361,553
2044	913,557	366,489	484,953	358,940
2045	923,026	364,245	485,157	356,926

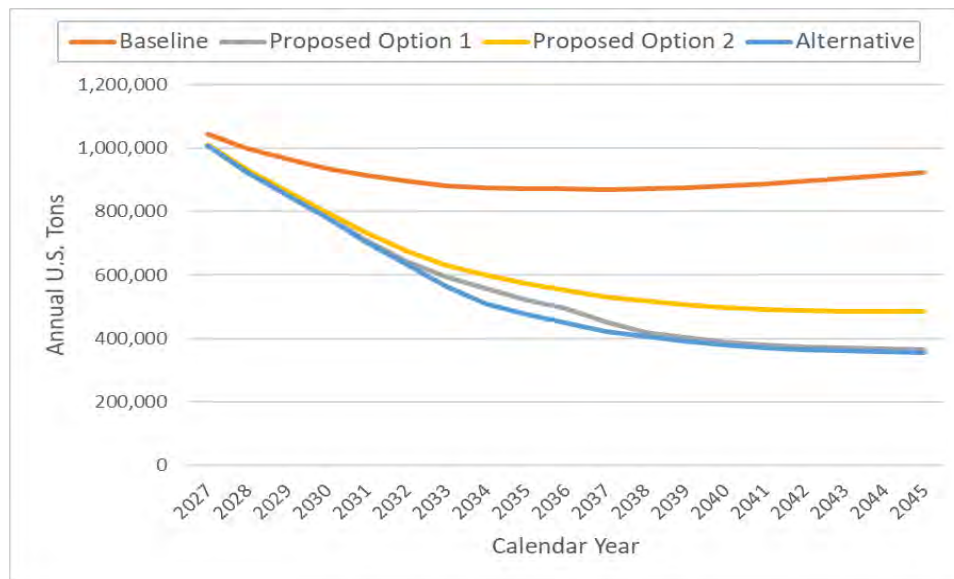


Figure 5-25: National Heavy-duty Vehicle NO_x Emissions (Annual US Tons) For Calendar Years Between 2027 and 2045

Table 5-35: National Heavy-Duty Vehicle VOC Emissions (Annual US Tons) For Calendar Years Between 2027 and 2045

Calendar Year	Baseline	Proposed Option 1	Proposed Option 2	Alternative
2027	109,222	108,099	108,107	108,090
2028	101,990	99,707	99,725	99,690
2029	98,801	95,335	95,362	95,309
2030	93,833	89,153	89,189	89,117
2031	90,551	84,635	84,714	84,577
2032	87,467	80,355	80,477	80,277
2033	85,156	76,812	76,961	76,630
2034	83,542	74,014	74,189	73,734
2035	81,916	71,275	71,498	70,982
2036	81,897	70,213	70,483	69,911
2037	79,966	67,269	67,656	67,050
2038	80,680	67,036	67,532	66,896
2039	81,242	66,803	67,340	66,677
2040	81,205	66,006	66,582	65,893
2041	82,137	66,267	66,871	66,159
2042	82,991	66,530	67,158	66,426
2043	83,770	66,780	67,431	66,680
2044	84,572	67,076	67,748	66,980
2045	85,520	67,545	68,237	67,451

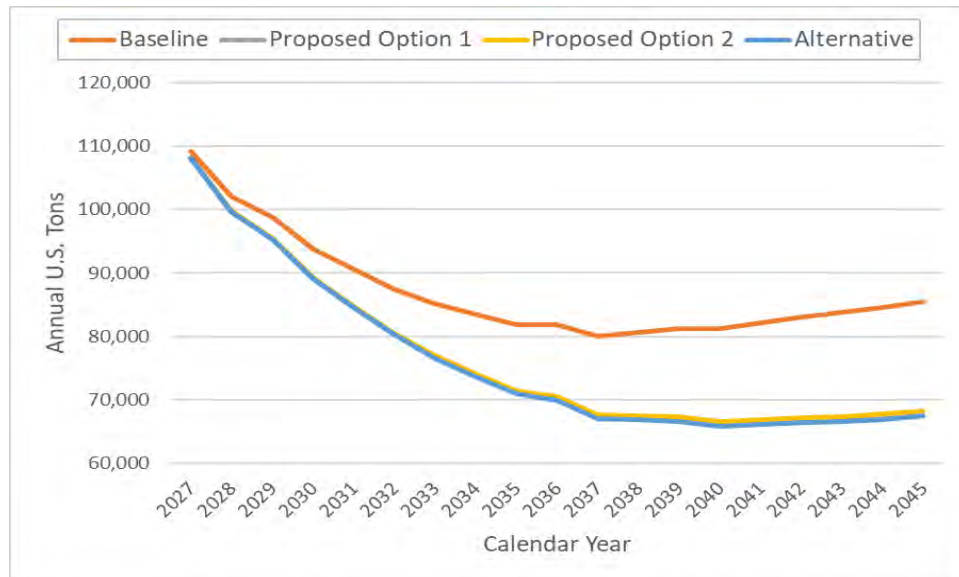


Figure 5-26: National Heavy-Duty Vehicle VOC Emissions (Annual US Tons) For Calendar Years Between 2027 and 2045

Table 5-36: National Heavy-duty Vehicle PM_{2.5} (Exhaust Only) Emissions (Annual US Tons) For Calendar Years Between 2027 and 2045

Calendar Year	Baseline	Proposed Option 1	Proposed Option 2	Alternative
2027	17,174	17,078	17,078	17,078
2028	14,747	14,550	14,550	14,550
2029	13,412	13,111	13,111	13,111
2030	11,997	11,590	11,590	11,590
2031	10,979	10,374	10,387	10,368
2032	10,078	9,284	9,308	9,272
2033	9,349	8,412	8,432	8,346
2034	8,833	7,763	7,778	7,646
2035	8,400	7,210	7,231	7,058
2036	8,119	6,818	6,844	6,635
2037	7,303	5,857	5,936	5,723
2038	7,332	5,750	5,879	5,663
2039	7,350	5,686	5,821	5,602
2040	7,335	5,593	5,734	5,512
2041	7,381	5,575	5,718	5,494
2042	7,427	5,565	5,709	5,483
2043	7,479	5,568	5,714	5,485
2044	7,539	5,580	5,728	5,496
2045	7,599	5,594	5,744	5,509

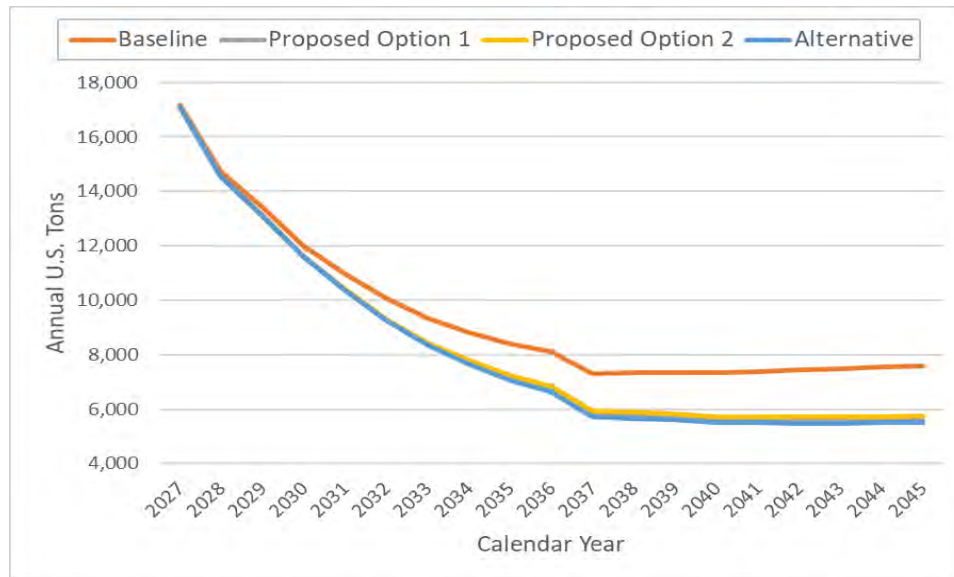


Figure 5-27: National Heavy-duty Vehicle PM_{2.5} (Exhaust Only) Emissions (Annual US Tons) For Calendar Years Between 2027 and 2045

Table 5-37: National Heavy-Duty Vehicle CO Emissions (Annual US Tons) For Calendar Years Between 2027 and 2045

Calendar Year	Baseline	Proposed Option 1	Proposed Option 2	Alternative
2027	1,731,776	1,719,562	1,719,562	1,719,562
2028	1,665,353	1,640,479	1,640,479	1,640,479
2029	1,649,108	1,611,269	1,611,269	1,611,269
2030	1,622,980	1,571,826	1,571,826	1,571,826
2031	1,607,158	1,537,808	1,540,247	1,535,479
2032	1,585,670	1,498,705	1,503,512	1,494,112
2033	1,579,461	1,471,175	1,476,072	1,457,798
2034	1,573,019	1,444,301	1,449,261	1,422,576
2035	1,569,490	1,419,437	1,427,042	1,398,932
2036	1,580,182	1,410,067	1,420,203	1,390,853
2037	1,575,206	1,381,753	1,399,327	1,369,502
2038	1,581,911	1,366,746	1,391,269	1,360,993
2039	1,592,078	1,363,205	1,388,241	1,357,584
2040	1,593,814	1,351,840	1,377,400	1,346,338
2041	1,616,360	1,362,968	1,388,881	1,357,419
2042	1,633,915	1,370,352	1,396,583	1,364,747
2043	1,650,715	1,377,945	1,404,453	1,372,301
2044	1,668,084	1,386,567	1,413,401	1,380,889
2045	1,686,295	1,396,460	1,423,721	1,390,734

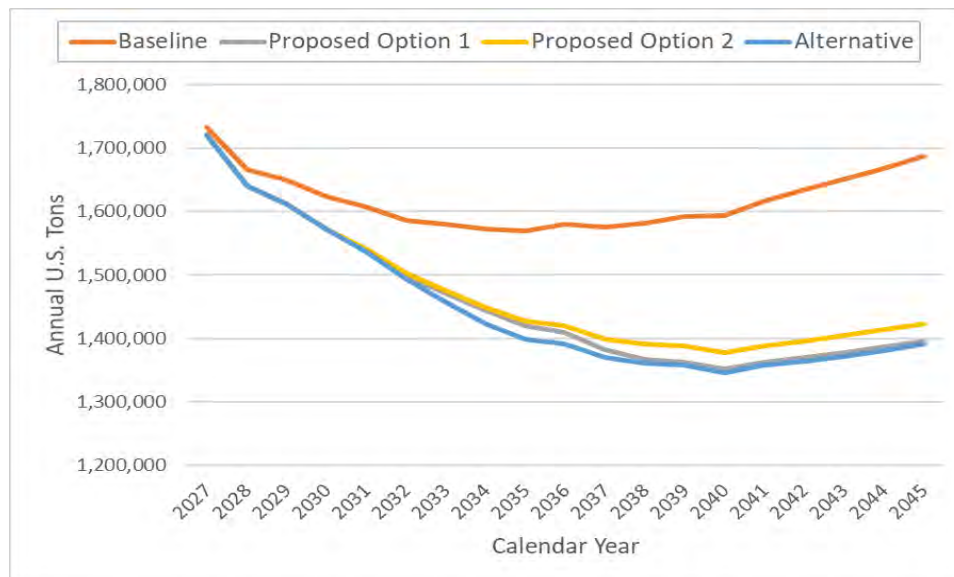


Figure 5-28: National Heavy-Duty Vehicle CO Emissions (Annual US Tons) For Calendar Years Between 2027 and 2045

5.5.6 Sensitivity Analysis for Battery-Electric Vehicles and Fuel Cell Electric Vehicles

As described in Section 1.4.2, we conducted a sensitivity analysis to estimate the potential impact of battery-electric vehicles (BEV) and fuel cell electric vehicles (FCEV) on the national emission inventory for the Baseline, proposed Options 1 and 2, and the Alternative.

Table 5-38 presents the fractions of zero tailpipe emission vehicle populations from the EIA's 2018 Annual Energy Outlook and the NREL study, respectively (see Section 1.4.2 for more discussion on these data sources). Note that the AEO2018 data included both BEV and FCEVs, while the NREL study only included BEV data.

To obtain the fractions of BEVs (plus FCEVs if applicable) in HD vehicle categories for each model year, we first summed the number of battery-electric and fuel-cell electric vehicles in each of the heavy-duty vehicle categories (Buses/Single Unit Trucks/Combination Trucks) by model year. Then, we divided that number by the total number of new vehicles (using all fuel types) for the corresponding category by model year.

Table 5-38: Fractions of the BEVs and FCEVs Based on AEO2018 Compared with the Fractions of the BEVs Based on NREL Study in Each of the Heavy-Duty Vehicle Categories by Model Year

MY	Buses		Single Unit Trucks		Combination Trucks	
	AEO2018	NREL	AEO2018	NREL	AEO2018	NREL
2016	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
2017	0.0000	0.0040	0.0000	0.0034	0.0000	0.0012
2018	0.0058	0.0060	0.0074	0.0045	0.0029	0.0016
2019	0.0060	0.0080	0.0077	0.0060	0.0030	0.0021
2020	0.0063	0.0100	0.0080	0.0079	0.0031	0.0027
2021	0.0065	0.0100	0.0082	0.0105	0.0032	0.0036
2022	0.0068	0.0100	0.0086	0.0138	0.0033	0.0047
2023	0.0071	0.0100	0.0088	0.0180	0.0034	0.0062
2024	0.0072	0.0100	0.0090	0.0235	0.0035	0.0081
2025	0.0074	0.0100	0.0093	0.0305	0.0036	0.0105
2026	0.0077	0.0480	0.0095	0.0392	0.0037	0.0135
2027	0.0079	0.0860	0.0098	0.0499	0.0038	0.0172
2028	0.0081	0.1240	0.0101	0.0628	0.0039	0.0217
2029	0.0084	0.1620	0.0104	0.0780	0.0041	0.0269
2030	0.0086	0.2000	0.0108	0.0953	0.0042	0.0329
2031	0.0089	0.2250	0.0111	0.1144	0.0043	0.0394
2032	0.0091	0.2500	0.0114	0.1347	0.0044	0.0464
2033	0.0094	0.2750	0.0118	0.1553	0.0046	0.0536
2034	0.0097	0.3000	0.0121	0.1756	0.0047	0.0606
2035	0.0100	0.3250	0.0125	0.1947	0.0048	0.0671
2036	0.0103	0.3400	0.0129	0.2120	0.0050	0.0731
2037	0.0106	0.3550	0.0132	0.2272	0.0051	0.0783
2038	0.0109	0.3700	0.0136	0.2401	0.0053	0.0828
2039	0.0112	0.3850	0.0140	0.2508	0.0054	0.0865
2040	0.0116	0.4000	0.0144	0.2595	0.0056	0.0895
2041	0.0119	0.4150	0.0149	0.2665	0.0058	0.0919
2042	0.0123	0.4300	0.0153	0.2720	0.0059	0.0938
2043	0.0127	0.4450	0.0158	0.2762	0.0061	0.0953
2044	0.0130	0.4600	0.0162	0.2795	0.0063	0.0964
2045	0.0134	0.4750	0.0167	0.2821	0.0065	0.0973
2046	0.0138	0.4800	0.0172	0.2840	0.0067	0.0979
2047	0.0142	0.4850	0.0177	0.2855	0.0069	0.0984
2048	0.0147	0.4900	0.0182	0.2866	0.0071	0.0988
2049	0.0151	0.4950	0.0187	0.2874	0.0073	0.0991
2050	0.0155	0.5000	0.0192	0.2881	0.0075	0.0993

The estimated annual percent emission reductions for proposed Option 1 adjusted for BEV/FCEVs based on AEO2018 and NREL study are shown in Table 5-39.⁰⁰⁰⁰ For comparison, the emission reductions from proposed Option 1 (previously presented in draft RIA Chapter 5.3) are also included. Similarly, Table 5-40 and Table 5-41 show the estimated annual percent reductions adjusted for BEV/FCEVs for proposed Option 2 and the Alternative

⁰⁰⁰⁰ Although BEVs and FCEVs have brakewear and tirewear particulate emissions, we are not accounting for them in this sensitivity analysis due to insufficient data.

scenarios, respectively. These reductions are compared to the reductions from the main analysis for proposed Option 2 and the Alternative (previously presented in draft RIA Chapter 5.3).

Table 5-39: Percent Reduction from the Baseline for Proposed Option 1 and Sensitivity Cases Based on AEO2018 and NREL in Calendar Years 2030, 2040, and 2045

Pollutant	% Reduction in 2030			% Reduction in 2040			% Reduction in 2045		
	Option 1	AEO2018	NREL	Option 1	AEO2018	NREL	Option 1	AEO2018	NREL
NO _x	16.4%	16.4%	15.9%	55.9%	55.8%	54.4%	60.5%	60.5%	59.5%
VOC	5.0%	5.0%	4.7%	18.7%	18.6%	17.1%	21.0%	20.9%	19.0%
Primary Exhaust PM _{2.5} - Total	3.4%	3.4%	3.2%	23.7%	23.7%	22.7%	26.4%	26.3%	25.2%
Carbon Monoxide (CO)	3.2%	3.1%	3.0%	15.2%	15.1%	14.2%	17.2%	17.1%	15.9%
1,3-Butadiene	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Acetaldehyde	0.4%	0.4%	0.4%	2.5%	2.5%	2.4%	2.7%	2.7%	2.6%
	0.5%	0.5%	0.5%	4.2%	4.2%	4.1%	4.6%	4.6%	4.4%
Benzene	4.1%	4.1%	3.8%	23.1%	23.0%	21.3%	26.8%	26.7%	24.7%
Formaldehyde	0.5%	0.5%	0.5%	4.1%	4.1%	3.9%	4.6%	4.6%	4.4%
Methane (CH ₄)	0.2%	0.2%	0.1%	0.7%	0.7%	0.7%	0.7%	0.7%	0.7%
Naphthalene	0.9%	0.9%	0.8%	14.3%	14.3%	13.4%	16.7%	16.7%	15.5%

Table 5-40: Percent Reduction from the Baseline for Proposed Option 2 and Sensitivity Cases Based on AEO2018 and NREL in Calendar Years 2030, 2040, and 2045

Pollutant	% Reduction in 2030			% Reduction in 2040			% Reduction in 2045		
	Option 2	AEO2018	NREL	Option 2	AEO2018	NREL	Option 2	AEO2018	NREL
NO _x	15.0%	15.0%	14.6%	43.6%	43.6%	42.5%	47.4%	47.4%	46.7%
VOC	5.0%	4.9%	4.6%	18.0%	17.9%	16.4%	20.2%	20.1%	18.2%
Primary Exhaust PM _{2.5} - Total	3.4%	3.4%	3.2%	21.8%	21.8%	20.8%	24.4%	24.4%	23.3%
Carbon Monoxide (CO)	3.2%	3.1%	3.0%	13.6%	13.5%	12.6%	15.6%	15.5%	14.2%
1,3-Butadiene	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Acetaldehyde	0.4%	0.4%	0.4%	1.8%	1.7%	1.7%	1.9%	1.9%	1.8%
	0.5%	0.5%	0.5%	3.1%	3.1%	2.9%	3.4%	3.4%	3.2%
Benzene	4.0%	3.9%	3.7%	21.3%	21.2%	19.7%	24.5%	24.5%	22.6%
Formaldehyde	0.5%	0.5%	0.5%	3.3%	3.3%	3.1%	3.7%	3.7%	3.5%
Methane (CH ₄)	0.1%	0.1%	0.1%	0.5%	0.5%	0.5%	0.6%	0.6%	0.5%
Naphthalene	0.8%	0.8%	0.8%	12.6%	12.6%	11.8%	14.6%	14.6%	13.5%

Table 5-41: Percent Reduction from the Baseline for the Alternative and Sensitivity Cases Based on AEO2018 and NREL in Calendar Years 2030, 2040, and 2045

Pollutant	% Reduction in 2030			% Reduction in 2040			% Reduction in 2045		
	Alternative	AEO2018	NREL	Alternative	AEO2018	NREL	Alternative	AEO2018	NREL
NOX	16.7%	16.6%	16.2%	56.9%	56.9%	55.6%	61.3%	61.3%	60.4%
VOC	5.0%	5.0%	4.7%	18.9%	18.8%	17.2%	21.1%	21.1%	19.1%
Primary Exhaust PM _{2.5} - Total	3.4%	3.4%	3.2%	24.8%	24.8%	23.8%	27.5%	27.5%	26.3%
Carbon Monoxide (CO)	3.2%	3.1%	3.0%	15.5%	15.5%	14.5%	17.5%	17.5%	16.2%
1,3-Butadiene	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Acetaldehyde	0.4%	0.4%	0.4%	2.7%	2.7%	2.6%	2.9%	2.9%	2.8%
	0.5%	0.5%	0.5%	4.5%	4.5%	4.4%	4.9%	4.9%	4.7%
Benzene	4.3%	4.3%	4.0%	23.3%	23.2%	21.6%	26.9%	26.8%	24.8%
Formaldehyde	0.6%	0.6%	0.5%	4.3%	4.2%	4.1%	4.7%	4.7%	4.5%
Methane (CH ₄)	0.2%	0.2%	0.2%	0.7%	0.7%	0.7%	0.8%	0.8%	0.8%
Naphthalene	0.9%	0.9%	0.9%	14.6%	14.6%	13.7%	16.9%	16.8%	15.7%

5.5.7 National Heavy-duty Vehicle Emissions Inventory Comparison of the California Heavy-duty Omnibus Regulation and the Proposed Option 1

This section presents a sensitivity analysis of the estimated emission inventory impacts from two scenarios based on the California Heavy-Duty Omnibus Program (Omnibus). The first scenario assumes nationwide adoption of the Omnibus starting in MY 2024. The second scenario assumes nationwide adoption of the MY 2027 and later Omnibus program.^{PPPP} We compare these two scenarios to the EPA proposed Option 1 scenario.^{QQQQ} In summary, the three scenarios presented include: 1) EPA proposed Option 1, 2) a national program that has the same stringency level as the Omnibus starting in MY 2024 (Omnibus Nationwide 2024), and 3) Omnibus Nationwide starting in MY 2027 (Omnibus Nationwide 2027).

The EPA proposed Option 1 largely aligns with the MY 2027 standards, regulatory useful life periods, and emissions warranty periods in the Omnibus (See Preamble Sections I.D, III, and IV for details). The results of the sensitivity analysis presented in this Appendix show that the differences between the Omnibus Nationwide 2027 scenario and EPA proposed Option 1 result in only slight differences (approximately 0.2%) in NO_x emission inventory impacts in 2045, although there are larger differences in earlier years of the program. Additional details on the differences between proposed Option 1 and the Omnibus requirements are included in Preamble Sections III and IV.^{RRRR}

Below, we describe the methods used to analyze the three scenarios included in the sensitivity analysis, and then present detailed results of the comparison.

5.5.7.1 MOVES input development for Omnibus Nationwide Scenarios

We estimated the emission impacts of the EPA proposed Option 1 and Omnibus Nationwide scenarios using the same version of MOVES (MOVES CTI NPRM); the MOVES inputs for the EPA proposed Option 1 are described in Chapter 5.2.2. The MOVES inputs for Omnibus Nationwide scenarios are based on the Omnibus duty-cycle test standards, warranty and useful life requirements, as detailed in the subsections immediately below.

5.5.7.2 Heavy-duty Diesel Running Emission Rates Based on Duty-Cycle and Off-Cycle Standards

For estimating NO_x running emissions based on duty-cycle test standards for LHD and MHD vehicles under the Omnibus, we used the standards on the FTP and SET-RMC cycles from the Omnibus shown in Table 5-42. For HHD vehicles, the duty-cycle test standards in the Omnibus

^{PPPP} The Omnibus does not include updated spark-ignition HC and CO emission standards; however, for this analysis we assumed nationwide adoption of the HC and CO standards for SI engines. See additional discussion of HD gasoline running exhaust emission rates in this appendix. HD CI engines are already meeting those emissions levels and we did not model HC and CO reductions for CI engines.

^{QQQQ} As discussed in Section 5.4, there are differences between the proposed Option 1 and the control case analyzed for air quality modeling. This section (5.5.6) presents emission reductions from the EPA proposed Option 1, which is discussed in further detail in Section 5.3.

^{RRRR} In addition to the difference in ORVR requirements between our EPA proposed Option 1 and the Omnibus, the Omnibus Nationwide 2027 scenario includes a slightly lower NO_x standard in MY 2027-2030 than proposed Option 1, while proposed Option 1 includes NMHC and CO standards not included in the Omnibus Nationwide 2027 scenario. There are also slight differences between the Omnibus Nationwide 2027 scenario and the proposed Option 1 for duty-cycle and off-cycle standards for SI engines (See Preamble Section III for details).

have two separate standards for MY 2027 and later vehicles. The HHD vehicles have a duty-cycle standard at both an intermediate useful life of 435,000 miles and a full useful life of 600,000 miles for MY 2027-2030. For MY 2031 and later, both the CARB Omnibus program and the EPA proposed Option 1 have an intermediate useful life of 435,000 miles and a full useful life of 800,000 miles. For comparison, we also present the duty-cycle NO_x standards for EPA proposed Option 1 in Table 5-42.

Table 5-42: Duty-Cycle NO_x Standards for the CARB Omnibus and EPA Proposed Option 1^A

Model Year	Engine	Duty Cycle	CARB Omnibus	EPA Proposed Option 1
2024	HHD, MHD, LHD	FTP	50	(200)
		SET	50	(200)
		LLC	200	-
		Idle	10 g/hr	-
	HD SI	FTP	50	(200)
		SET	-	-
2027	HHD, MHD, LHD	FTP	20 [HHD 20/35] ^C	35
		SET	20 [HHD 20/35] ^C	35
		LLC	50 [HHD 50/90] ^C	90
		Idle ^B	5 g/hr	5 g/hr
	HD SI	FTP	20	35
		SET	-	35
2031+	HHD, MHD, LHD	FTP	20 [HHD 20/40] ^C	20 [HHD 20/40] ^C
		SET	20 [HHD 20/40] ^C	20 [HHD 20/40] ^C
		LLC	50 [HHD 50/100] ^C	50 [HHD 50/100] ^C
		Idle ^B	5 g/hr	5 g/hr
	HD SI	FTP	20	20
		SET	-	-

^A (#) = current standard with no change in the noted model year

^B We assumed compliance with the voluntary idle standard

^C [HHD intermediate useful life standard/full useful life standard]. The HHD intermediate useful life in the CARB Omnibus program for MY 2027-2030 is 435,000 miles, and the full useful life is 600,000 miles. For the MY 2031+ model years the HHD intermediate useful life is 435,000 miles and the full useful life is 800,000 miles in both the CARB Omnibus program and the EPA proposed Option 1.

As was done for the EPA proposed Option 1, we calculated a weighted average HHD duty-cycle standard from the CARB Omnibus program using the intermediate and full useful life using Equation 5-1. The resulting values are shown in Table 5-43.

Table 5-43: Weighted Average Heavy Heavy-duty Compression Ignition Duty-Cycle Test NO_x Standards used to estimate NO_x emission rates for the Omnibus Nationwide Scenarios

Applicable Model Years	LLC (g/hp-hr)	FTP (g/hp-hr)	SET-RMC (g/hp-hr)
Model Year 2024-2026	0.2	0.05	0.05
Model Year 2027-2030	0.061	0.024	0.024
Model Year 2031+	0.073	0.029	0.029

Using the FTP Omnibus duty-cycle test standards for LHD and MHD in Table 5-42 and the weighted average FTP & SET-RMC duty-cycle standards for HHD in Table 5-43, we applied the methods outlined in Chapter 5.2.2.1.1.1 to estimate the zero-mile emission running emission rates based on duty-cycle test standards.

The Omnibus has off-cycle standards with three bins, to represent idle, low-load and medium to high-load operations, consistent with the EPA proposed program. The off-cycle standards for the Omnibus program are set to be twice the engine-cycle standards for model year 2024-2029, and 1.5 times the engine-cycle standards for 2030+ that correspond to similar engine-loads.³¹⁴ For developing inputs for MOVES, we did not apply a scaling factor to the off-cycle idling operation, to be consistent with the assumptions used to estimate off-cycle idling emissions from the EPA proposed Option 1, which assumed that the voluntary EPA idle standard would be complied with during off-cycle idling operation with no scaling factor (See 5.2.2.1.1.2). For developing inputs to MOVES, we multiplied the Omnibus duty-cycle standards, including the weighted average NO_x standards from Table 5-43, by the corresponding off-cycle scaling factors, as shown in Table 5-44.

Table 5-44: Calculated Average Off-Cycle Standards for the Omnibus from the Average Idling and Engine Cycles Standards and Off-Cycle Scaling Factors

Regulatory Class	Model Year	Engine Cycle	Engine cycle NO _x Standard	In-use Bin	In-use scaling factor	Calculated In-use NO _x Standards (g/hr for idling, g/hp-hr for low-load and medium to high-load)
LHD/MHD/HHD	2024-2026	Idle (g/hr)	10	Idle, < 6% power	1*	10
		LLC (g/hp-hr)	0.2	Low-load, 6-20% power	2	0.4
		FTP & SET (g/hp-hr)	0.05	Medium to High Load, >20% power	2	0.1
LHD/MHD	2027-2030	Idle (g/hr)	5	Idle, < 6% power	1*	5
		LLC (g/hp-hr)	0.05	Low-load, 6-20% power	2	0.1
		FTP & SET (g/hp-hr)	0.02	Medium to High Load, >20% power	2	0.04
	2031+	Idle (g/hr)	5	Idle, < 6% power	1*	5
		LLC (g/hp-hr)	0.05	Low-load, 6-20% power	1.5	0.075
		FTP & SET (g/hp-hr)	0.02	Medium to High Load, >20% power	1.5	0.03
HHD	2027-2030	Idle (g/hr)	5	Idle, < 6% power	1*	5
		LLC (g/hp-hr)	0.061	Low-load, 6-20% power	2	0.122
		FTP & SET (g/hp-hr)	0.024	Medium to High Load, >20% power	2	0.048
	2031+	Idle (g/hr)	5	Idle, < 6% power	1*	5
		LLC (g/hp-hr)	0.073	Low-load, 6-20% power	1.5	0.109
		FTP & SET (g/hp-hr)	0.029	Medium to High Load, >20% power	1.5	0.0435

* The Omnibus includes off-cycle scaling factors of 2 and 1.5 for all off-cycle modes, including idling. For developing the MOVES inputs, we did not apply the scaling factors for idling, to be consistent with the methods used to estimate emissions for off-cycle idling operation from the EPA proposed Option 1

We developed MOVES emission rates for the Omnibus scenarios using the methods discussed in Chapter 5.2.2.1.1 along with the duty-cycle standards (Table 5-42 and Table 5-43) and off-cycle standards (Table 5-44) discussed in this section.

5.5.7.3 Heavy-Duty Diesel Running Emission Rates Based on Changes to Warranty and Useful Life

The warranty and useful life standards for the Omnibus program are presented in Table 5-45 and Table 5-46. For comparison, we also present the warranty and useful life periods for the EPA proposed Option 1 which matches the Omnibus program for MY 2027 and later (see Preamble Section IV for more details on our proposed warranty and useful life standards).^{SSSS}

We used the methods outlined in Chapter 5.2.2.1.2 to estimate the impact of the lengthened warranty and useful life program using the warranty and useful life standards specific to the Omnibus program. As for the EPA proposal options, we did not account for the impact of the longer warranty and useful life for heavy-duty gasoline and heavy-duty NG vehicles.

Table 5-45: Warranty Mileages and Years in Omnibus and EPA Proposed Option 1^A

Model Year	Engine	Warranty Mileage		Warranty Years	
		Omnibus ^B	Proposed Option 1	Omnibus ^B	Proposed Option 1
2024	HHD	(350k)	(100k)	(5 y)	(5 y)
	MHD	(150k)	(100k)		
	LHD	(110k)	(50k)		
	HD SI	(50k)	(50k)	(5 y)	(5 y)
2027	HHD	450k	450k	7 y	7 y
	MHD	220k	220k		
	LHD	150k	150k		
	HD SI	110k	160k	7 y	7 y
2031	HHD	600k	600k	10 y	10 y
	MHD	280k	280k		
	LHD	210k	210k		
	HD SI	160k	160k	10 y	10 y

^A (#) = current standard with no change in the noted model year

^B CARB' Step 1 Warranty program begins in MY 2022

^{SSSS} As noted in Preamble Section VI, the warranty and useful requirements included in the Omnibus and the EPA proposed Option 1 would lower emissions of NO_x, exhaust PM, THC, and CO, whereas the standards presented in Table 5-42 would lower emissions of NO_x.

Table 5-46: Useful Life Mileages and Years in Omnibus Program and EPA Proposed Option 1^A

Model Year	Engine	Useful Life Mileage		Useful Life Years	
		Omnibus	EPA Proposed Option 1	Omnibus	EPA Proposed Option 1
2024	HHD	(435k)	(435k)	(10 y)	(10 y)
	MHD	(185k)	(185k)		
	LHD	(110k)	(110k)		
	HD SI	(110k)	(110k)	(10 y)	(10 y)
2027	HHD	600k	600k	11 y	11 y
	MHD	270k	270k	11 y	11 y
	LHD	190k	190k	12 y	12 y
	HD SI	155k	155k	12 y	12 y
2031	HHD	800k	800k	12 y	12 y
	MHD	350k	350k	12 y	12 y
	LHD	270k	270k	15 y	15 y
	HD SI	200k	200k	15 y	15 y

^A (#) = current standard with no change in the noted model year

5.5.7.4 Heavy-Duty Diesel Start Emission Rates

The heavy-duty diesel start emission rates were developed using the CARB duty-cycle standards for LHD and MHD in Table 5-42 and the weighted average duty-cycle standards for HHD in Table 5-43, and the methods outlined in Section 5.2.2.2.

5.5.7.5 Heavy-Duty Diesel Extended Idle Emission Rates

As discussed in Chapter 5.2.2.3, the off-cycle rates for the EPA proposed Option 1 for running exhaust idle operating mode bin (MOVES operating mode 1) were derived from the voluntary idle emission standard and converted to g NO_x/kg CO₂. Similarly, we used the same method to estimate the extended idle emission rates for the Omnibus program, which has an idling standard of 10 g/hr for MY 2024-2026 and 5 g/hr for MY 2027 and later. Applying the extended idle CO₂ emission rate in MOVES CTI NPRM yielded the extended idle emission rates for NO_x shown in Table 5-47.

Table 5-47: Extended Idle NO_x emission rates for the Omnibus Program

Applicable Model Years	NO _x Idling Standard (g/hr)	MOVES Extended Idle NO _x Emission Rate (g/hr)
Model Year 2024-2026	10	8.96
Model Year 2027+	5	4.48

5.5.7.6 Light Heavy-Duty Class 2b and 3 Diesel Emission Rates

We assumed that engine-certified light-heavy-duty Class 2b and 3 diesel emission rates in the Omnibus nationwide scenarios have the same emission rates as the corresponding LHD45

emission rates. We also assumed they represent 5.1% of the Class 2b and 3 diesel vehicles in MY 2024 and later, similar to the assumption made for the EPA proposed Option 1 for MY 2027 and later model years as documented in Chapter 5.2.2.5.

5.5.7.7 Heavy-Duty Gasoline Running Emission Rates

Table 5-48 provides the FTP duty-cycle standards from the Omnibus program for Otto-cycle engines, which are referred to as spark-ignition engines in the EPA proposed rule. Both heavy-duty gasoline and heavy-duty NG engines are subject to the Otto-cycle engine standards; however, we did not assume a reduction in NG emissions from the more stringent standards in this sensitivity analysis because we did not estimate reductions in NG emissions for the control scenario analyzed (see Chapter 5.2.2).

We used the methods described in Chapter 5.2.2.6 to estimate the impact of the Omnibus FTP standard on heavy-duty gasoline emissions as shown in Table 5-48. The Omnibus scenarios include NO_x and PM emission rate reductions for heavy-duty gasoline engines that start in MY 2024 or 2027; we also included CO and HC reductions in these scenarios that are consistent with the methodology described in Chapter 5.2.2.6 which assumes lower THC emissions as a function of lower NO_x emission standards. We also assumed 60% lower CO emissions as consistent with the EPA proposed Options 1 and 2. We note that spark-ignition engine standards in the Omnibus do not change in MY 2031 and emission rates modeled in both Omnibus scenarios apply for MY 2027 and later. As discussed in Section III of the Preamble, the Omnibus is also setting an off-cycle standard for Otto-cycle engines; however, we did not estimate the impact of the off-cycle standard for Otto-cycle engines in the Omnibus Nationwide scenarios in this sensitivity analysis. The EPA proposed Options and the Alternative 1 did not include an off-cycle standard for heavy-duty gasoline engines.

Table 5-48: Running Emission Rate Reductions From Heavy-duty Gasoline Vehicles For the EPA Proposed Option 1 and Omnibus Nationwide Scenarios

Control Scenario	Model Years	Regulatory Class	FTP/SET standard (g/hp-hr)	NO _x	THC	CO	PM _{2.5}
Proposed Option 1	2027-2030	LHD, MHD, HHD	0.035	82.5%	87.8%	60%	50%
	2031+	LHD, MHD, HHD	0.02	90.0%	93.0%	60%	50%
Omnibus Nationwide 2024	2024-2026	LHD, MHD, HHD	0.05	75%	82.50%	60%	50%
	2027+	LHD, MHD, HHD	0.02	90%	93%	60%	50%
Omnibus Nationwide 2027	2027+	LHD, MHD, HHD ^A	0.02	90%	93%	60%	50%

5.5.7.8 Heavy-Duty Gasoline Refueling Emission Rates

The Omnibus does not include ORVR requirements. In contrast, the EPA proposed Options include an ORVR requirement for heavy-duty gasoline vehicles >14,000 lbs. No changes were made to the baseline refueling vapor emissions in MOVES for modeling the Omnibus

Nationwide Scenarios. We expect inclusion of onboard refueling vapor requirements in the EPA proposed Option 1 results in VOC emission reductions not expected from the Omnibus Nationwide Scenarios.

5.5.7.9 Comparisons of NO_x Emission Reductions

Below, we present national heavy-duty vehicle NO_x emission reductions across multiple calendar years (2024-2045) for the EPA proposed Option 1 and the two Omnibus Nationwide scenarios.

Table 5-49 National Heavy-duty Vehicle NO_x Emission Reductions Relative to the Baseline Case For Omnibus Nationwide Scenarios (Reductions Relative to EPA Proposed Option 1 Shown for Comparison)

Calendar Year	Reductions in US Tons				% Difference: Omnibus Nationwide 2027 - EPA Proposed Option 1
	Omnibus Nationwide 2024	Omnibus Nationwide 2027	EPA Proposed Option 1	Omnibus Nationwide 2027 - EPA Proposed Option 1	
2024	26,189	0	0	0	0.0%
2025	52,379	0	0	0	0.0%
2026	79,372	0	0	0	0.0%
2027	117,691	37,353	35,841	1,512	4.2%
2028	153,371	76,742	73,638	3,104	4.2%
2029	188,785	117,671	112,914	4,757	4.2%
2030	224,101	160,395	153,608	6,786	4.4%
2031	270,725	211,533	204,855	6,677	3.3%
2032	314,700	260,513	254,055	6,459	2.5%
2033	340,751	291,555	285,553	6,002	2.1%
2034	365,058	320,834	315,415	5,419	1.7%
2035	391,527	352,103	347,201	4,903	1.4%
2036	415,921	381,194	376,851	4,343	1.2%
2037	450,242	420,140	416,178	3,962	1.0%
2038	481,867	456,227	452,667	3,560	0.8%
2039	496,843	475,429	472,275	3,155	0.7%
2040	511,423	494,062	491,318	2,744	0.6%
2041	524,580	510,254	507,893	2,361	0.5%
2042	536,369	524,318	522,318	2,001	0.4%
2043	547,107	536,521	534,855	1,666	0.3%
2044	557,685	548,460	547,067	1,393	0.3%
2045	567,886	559,947	558,780	1,166	0.2%
Total	7,614,572	6,735,251	6,663,280	71,970	1.1%

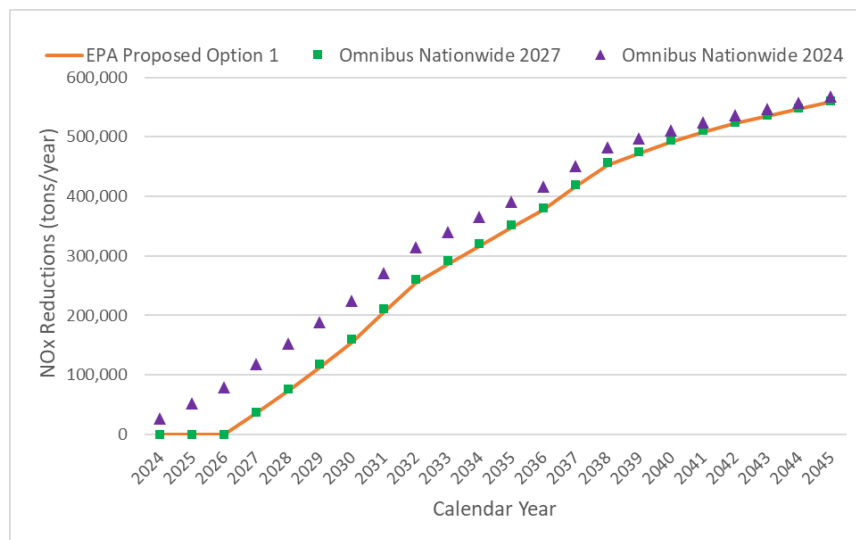


Figure 5-29: National Heavy-duty Vehicle NO_x Emission Reductions (Annual US Tons) Relative to the Baseline Case For Omnibus Nationwide Scenarios (Symbols) As Compared with EPA Proposed Option 1 (Line)

Chapter 6 Air Quality Impacts

This chapter presents information on air quality, including a discussion of current air quality in Section 6.1, details related to the methodology used for the air quality modeling analysis in Section 6.2, and results from the air quality modeling analysis which are summarized in Section 6.3. We expect the proposal's reductions in emissions of NO_x, VOC, PM_{2.5}, and CO would lead to decreases in ambient concentrations of ozone, PM_{2.5}, NO₂, and CO. We performed air quality modeling of proposed Option 1 to quantify these impacts.^{TTTT} Specifically, proposed Option 1 would significantly decrease ozone concentrations across the country, with a population-weighted average decrease of 2 ppb in 2045. Ambient PM_{2.5}, NO₂ and CO concentrations are also predicted to improve in 2045 as a result of proposed Option 1. The emission reductions provided by the proposed rule would be important in helping areas attain the National Ambient Air Quality Standards (NAAQS) and prevent future nonattainment. In addition, the air quality modeling predicts improvements in nitrogen deposition and visibility but relatively little impact on ambient concentrations of air toxics.

6.1 Current Air Quality

In this section we present information related to current levels of air pollutants, visibility levels, and deposition amounts. This provides context for the need for this proposed rule and a comparison for the modeled projections presented in Section 6.3.

6.1.1 Ozone

As described in Chapter 4 of this draft RIA, 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.^{UUUU} EPA recently announced that it will reconsider the previous administration's decision to retain the ozone NAAQS.^{VVVV} EPA is also implementing the previous 8-hour ozone primary standard, set in 2008 at a level of 0.075 ppm. As of May 31, 2021, there were 34 ozone nonattainment areas for the 2008 primary ozone NAAQS, composed of 151 full or partial counties, with a population of more than 99 million (see Figure 6-1); there were 50 ozone nonattainment areas for the 2015 primary ozone NAAQS, composed of 205 full or partial counties, with a population of more than 122 million (see Figure 6-2). In total, there were, as of May 31, 2021, 57 ozone nonattainment areas with a population of more than 122 million people.^{WWWW}

^{TTTT} As noted in Chapter 5.4 of the draft RIA, while we refer to this modeling as for the proposed Option 1, there are differences between the proposed Option 1 standards, emission warranty, and useful life provisions presented in Sections III and IV of the preamble and those included in the control scenario modeled for the air quality analysis.

^{UUUU} <https://www.epa.gov/ground-level-ozone-pollution/ozone-national-ambient-air-quality-standards-naaqs>

^{VVVV} <https://www.epa.gov/ground-level-ozone-pollution/epa-reconsider-previous-administrations-decision-retain-2015-ozone>

^{WWWW} 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-Hour Ozone Nonattainment Areas (2008 Standard)

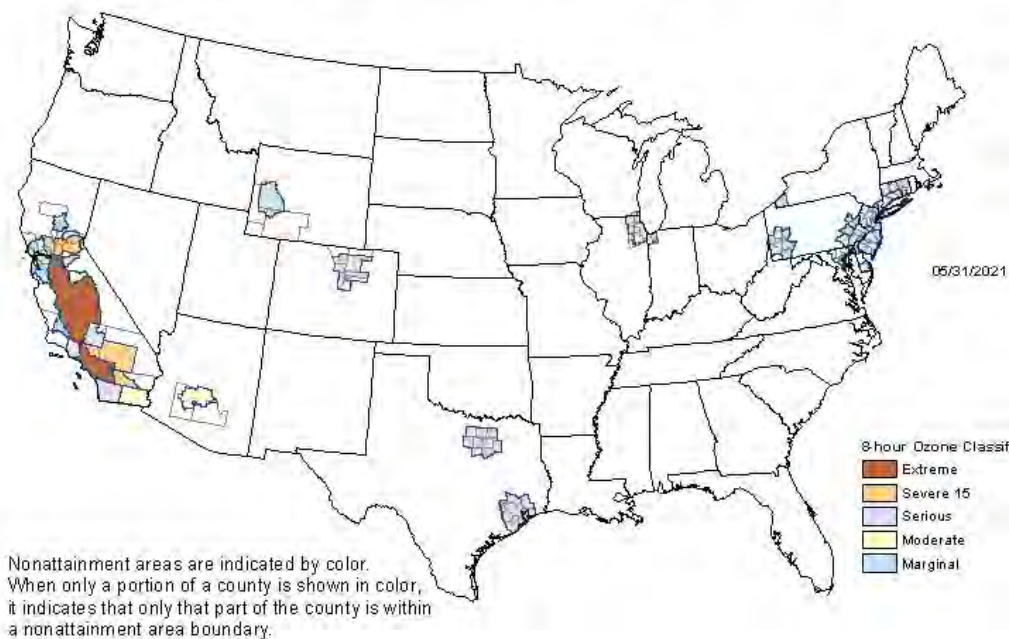


Figure 6-1: 8-Hour Ozone Nonattainment Areas (2008 Standard)

8-Hour Ozone Nonattainment Areas (2015 Standard)

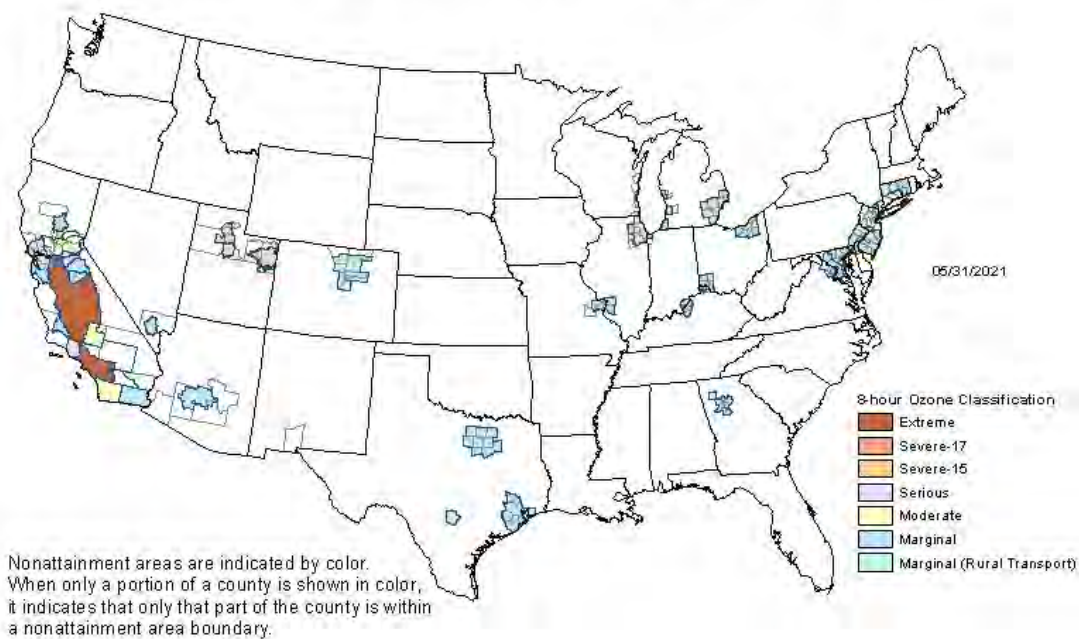


Figure 6-2: 8-Hour Ozone Nonattainment Areas (2015 Standard)

States with ozone nonattainment areas are required to take action to bring those areas into attainment. The attainment date assigned to an ozone nonattainment area is based on the area's classification. The attainment dates for areas designated nonattainment for the 2008 8-hour ozone NAAQS are in the 2015 to 2032 timeframe, depending on the severity of the problem in each area. Attainment dates for areas designated nonattainment for the 2015 ozone NAAQS will be in the 2021 to 2038 timeframe, again depending on the severity of the problem in each area.^{XXXX} The proposed rule would begin to take effect in 2027 and would assist areas with attaining the NAAQS and may relieve areas with already stringent local regulations from some of the burden associated with adopting additional local controls.^{YYYY} The proposed rule would also provide assistance to counties with ambient concentrations near the level of the NAAQS who are working to ensure long-term attainment or maintenance of the NAAQS.

6.1.2 **PM_{2.5}**

As described in Chapter 4 of this draft RIA, 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 (µg/m³)) and a 24-hour standard (35 µg/m³), and there are two secondary NAAQS for PM_{2.5}: an annual standard (15.0 µg/m³) and a 24-hour standard (35 µg/m³). 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 June 10, 2021, EPA announced that it will reconsider the previous administration's decision to retain the PM NAAQS.^{ZZZZ}

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 May 31, 2021, more than 19 million people lived in the 4 areas that are designated as nonattainment for the 1997 annual PM_{2.5} NAAQS. Also, as of May 31, 2021, more than 31 million people lived in the 14 areas that are designated as nonattainment for the 2006 24-hour PM_{2.5} NAAQS, and more than 20 million people lived in the 6 areas designated as nonattainment for the 2012 annual PM_{2.5} NAAQS. In total, there are currently 17 PM_{2.5} nonattainment areas with a population of more than 32 million people.^{AAAAA} Nonattainment areas for the PM_{2.5} NAAQS are pictured in Figure 6-3.

^{XXXX} <https://www.epa.gov/ground-level-ozone-pollution/ozone-naaqs-timelines>.

^{YYYY} While not quantified in the air quality modeling analysis for this proposed rule, the Early Adoption Incentives under the proposed program could encourage manufacturers to introduce new emission control technologies prior to the 2027 model year, which may help to accelerate some benefits of the proposed program (See Preamble Section IV.H for more details on the proposed Early Adoption Incentives). In addition, the proposed option for manufacturers to generate NO_x emission credits from BEVs and FCEVs as early as MY 2024 may also help to accelerate some benefits of the proposed program (See Preamble Sections III.A and IV.I for more details on the proposal to allow manufacturers to generate NO_x emission credits from BEVs and FCEVs).

^{ZZZZ} <https://www.epa.gov/pm-pollution/national-ambient-air-quality-standards-naaqs-pm>

^{AAAAA} The population total is calculated by summing, without double counting, the 1997, 2006 and 2012 PM_{2.5} nonattainment populations contained in the Criteria Pollutant Nonattainment Summary report (<https://www.epa.gov/green-book/green-book-data-download>).

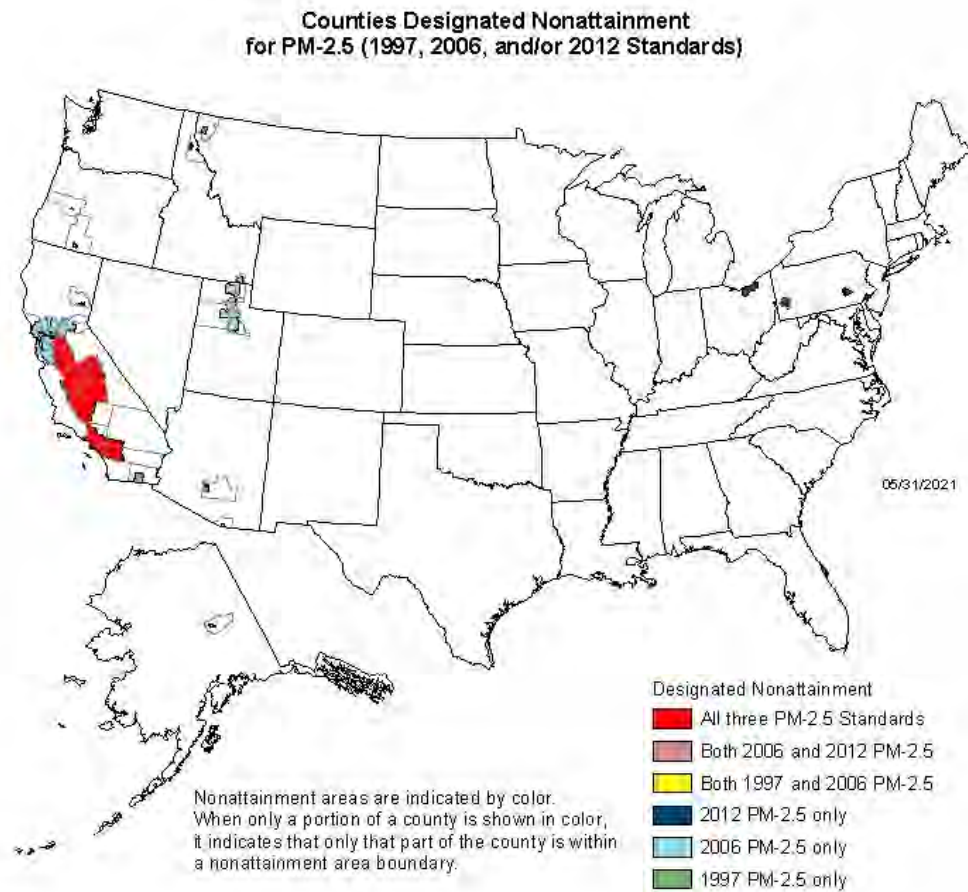


Figure 6-3: Counties Designated Nonattainment for PM_{2.5} (1997, 2006, and/or 2012 standards)

The proposed rule begins to take effect in 2027 and would assist areas with attaining the NAAQS and may relieve areas with already stringent local regulations from some of the burden associated with adopting additional local controls.^{BBBBB} The proposed rule would also provide assistance to counties with ambient concentrations near the level of the NAAQS who are working to ensure long-term attainment or maintenance of the PM_{2.5} NAAQS.

6.1.3 **NO₂**

There are two primary NAAQS for NO₂: an annual standard (53 ppb) and a 1-hour standard (100 ppb).^{CCCCC} In 2010, EPA established requirements for monitoring NO₂ near roadways

^{BBBBB} While not quantified in the air quality modeling analysis for this proposed rule, the Early Adoption Incentives under the proposed program could encourage manufacturers to introduce new emission control technologies prior to the 2027 model year, which may help to accelerate some benefits of the proposed program (See Preamble Section IV.H for more details on the proposed Early Adoption Incentives). In addition, the proposed option for manufacturers to generate NO_x emission credits from BEVs and FCEVs as early as MY 2024 may also help to accelerate some benefits of the proposed program (See Preamble Sections III.A and IV.I for more details on the proposal to allow manufacturers to generate NO_x emission credits from BEVs and FCEVs).

^{CCCCC} 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.

expected to have the highest concentrations of NO₂ 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 NO₂.

6.1.4 CO

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.

6.1.5 Air Toxics

The majority of Americans continue to be exposed to ambient concentrations of air toxics at levels which have the potential to cause adverse health effects.³²³ 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 (MSAT) Rule.³²⁴ In order to identify and prioritize air toxics, emission source types, and locations which are of greatest potential concern, EPA conducts the National-Scale Air Toxics Assessment (NATA). The most recent NATA was conducted for calendar year 2014, and it was released in 2018.³²⁵ The 2014 NATA includes four steps:

- 1) Compiling a national emissions inventory of air toxics emissions from outdoor sources
- 2) Estimating ambient concentrations of air toxics across the United States
- 3) Estimating population exposures across the United States
- 4) Characterizing potential public health risk due to inhalation of air toxics including both cancer and noncancer effects

According to the National Air Toxic Assessment (NATA) for 2014, mobile sources were responsible for over 40 percent of outdoor anthropogenic toxic emissions and were the largest contributor to national average cancer and noncancer risk from directly emitted pollutants.^{325, DDDDD} Mobile sources are also significant contributors to precursor emissions which react to form air toxics.³²⁶ Formaldehyde is the largest contributor to cancer risk of all 71 pollutants quantitatively assessed in the 2014 NATA. Mobile sources were responsible for more than 25 percent of primary anthropogenic emissions of this pollutant in 2014 and are significant contributors to formaldehyde precursor emissions. Benzene is also a large contributor to cancer risk, and mobile sources account for almost 70 percent of ambient exposure. Over the years, EPA has implemented a number of mobile source and fuel controls which have resulted in VOC reductions, which also reduced formaldehyde, benzene and other air toxic emissions.

^{DDDDD} NATA 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.

6.1.6 **Visibility**

As of May 31, 2021, over 32 million people live in areas that are designated nonattainment for the PM_{2.5} NAAQS. Overall, the evidence is sufficient to conclude that a causal relationship exists between PM and visibility impairment.³²⁷ Thus, the populations who live in nonattainment areas and travel to these areas would likely be experiencing visibility impairment. Additionally, while visibility trends have improved in Mandatory Class I Federal areas, these areas continue to suffer from visibility impairment.^{328,329,EEEE} In summary, visibility impairment is experienced throughout the U.S., in multi-state regions, urban areas, and remote Mandatory Class I Federal areas.

6.1.7 **Deposition**

Over the past two decades, the EPA has undertaken numerous efforts to reduce nitrogen deposition across the U.S. Analyses of monitoring data for the U.S. show that deposition of nitrogen 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.^{330,FFFF} Although total nitrogen deposition has decreased over time, many areas continue to be negatively impacted by deposition.

6.2 **Air Quality Modeling Methodology**

This section describes the air quality modeling done to support the proposed rule.

6.2.1 **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.^{GGGG}

The air quality modeling analysis used the 2016v1 platform with the most recent multi-pollutant CMAQ code available at the time of air quality modeling (CMAQ version 5.3.1). 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, with the most recent review completed in 2019 on version 5.2 and 5.3beta.³³¹

6.2.2 **Model Domain and Configuration**

The CMAQ modeling analyses used a domain covering the continental United States, as shown in Figure 6-4. This single domain covers the entire continental U.S. (CONUS) and large

^{EEEE} Mandatory Class I Federal areas are the 156 national parks and wilderness areas where state and federal agencies work to improve visibility, <https://www.epa.gov/visibility/regional-haze-program>.

^{FFFF} Trends data comes from the EPA Report on the Environment. Accessed in 2020, <https://cfpub.epa.gov/roe/indicator.cfm?i=1#4> Based on data from the NADP/National Trends Network, 2018.

^{GGGG} More information available at: <https://www.epa.gov/cmaq>

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.



Figure 6-4: Map of the CMAQ 12 km modeling domain (noted by the purple box)

6.2.3 **Model Inputs**

The key inputs to the CMAQ model include emissions from anthropogenic and biogenic sectors, meteorological data, and initial and boundary conditions.

The onroad emissions inputs used for the 2045 reference and control scenarios are summarized in Chapter 5 of this draft RIA, and emissions inputs for other sectors are described in the documentation for the 2016v1 modeling platform.³³² The reference scenario represents projected 2045 emissions without the proposed rule, and the control scenario represents projected 2045 emissions with proposed Option 1.^{HHHHH} The emissions inventories used for the

^{HHHHH} As noted in Chapter 5.4 of the draft RIA, while we refer to this modeling as for the proposed Option1, there are differences between the proposed Option 1 standards, emission warranty, and useful life provisions presented in Sections III and IV of the preamble and those included in the control scenario modeled for the air quality analysis.

air quality modeling control scenario and the national-scale emissions inventories presented in Chapter 5.3 of the draft RIA and Section VI of the preamble are consistent in many ways, but there are some differences. Chapter 5.4 of the draft RIA has more detail on the differences between the air quality control scenario and national-scale inventories. The AQM TSD also contains a detailed discussion of the emissions inventory inputs used in our air quality modeling.³⁴⁰

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.^{333,334} The WRF Model is a state-of-the-science mesoscale numerical weather prediction system developed for both operational forecasting and atmospheric research applications.³³⁵ 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.³³⁶

The boundary and initial species concentrations were provided by a northern hemispheric CMAQ modeling platform for the year 2016.^{337,338} 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.³³⁹ 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.

6.2.4 CMAQ Evaluation

The CMAQ predictions for ozone, fine particulate matter, sulfate, nitrate, ammonium, organic carbon, elemental carbon, nitrogen deposition, and specific air toxics (formaldehyde, acetaldehyde, benzene and naphthalene) 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 Air Quality Modeling TSD for this proposed rulemaking (AQM TSD).³⁴⁰

6.2.5 Model Simulation Scenarios

As part of our analysis for this rulemaking, the hourly CMAQ outputs were used to calculate 8-hour ozone design values concentrations, daily and annual PM_{2.5} design value concentrations, annual NO₂ concentrations, annual CO concentrations, annual and seasonal (summer and winter) air toxics concentrations, visibility levels and annual total nitrogen deposition for each of the following scenarios:

- 2016 base year
- 2045 reference
- 2045 control

Air quality modeling was done for the future year 2045 when the program would be fully implemented and when most of the regulated fleet would have turned over. We use the predictions from the air quality 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 for the May 1 - Sept 30 ozone season, daily and annual PM_{2.5} concentrations, and visibility impairment for each of the 2045 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).³⁴¹ Additional predictions from the CMAQ model are used in the distributional analysis (Chapter 6.3.9) and in the benefits analysis described in Chapter 8.3.1 of the DRIA. The CO, NO₂, annual and seasonal formaldehyde, acetaldehyde, benzene, naphthalene, and annual nitrate deposition projections were not predicted in a relative sense due to the limited observational data available.

The projected daily and annual PM_{2.5} design values were calculated using the Speciated Modeled Attainment Test (SMAT) approach. 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)."³⁴² Several updated datasets and techniques were used for this analysis. These changes are fully described within the technical support document for the Final Transport Rule Air Quality Modeling Technical Support Document.³⁴³ The projected 8-hour ozone design values were calculated using the approach identified in EPA's guidance on air quality modeling attainment demonstrations.³⁴⁴

6.3 Air Quality Modeling Results

This section describes the results of the air quality modeling analysis. The "reference" scenario represents projected 2045 air quality without the proposed rule and the "control" scenario represents projected 2045 air quality with the proposed Option 1.^{IIII} This chapter of the draft RIA presents modeled changes in ambient concentrations of air pollutants when comparing the "reference" and "control" scenarios. Decreases in concentration mean that the "control" scenario decreases the pollutant concentration compared to the "reference" scenario.

Everything in the reference and control scenarios was held constant except the onroad inventories, which reflected the application of the proposed Option 1 at the time we conducted the modeling.^{JJJJ} This includes the meteorological data (reflecting calendar year 2016 conditions) and the emissions for all other sources, including boundary conditions and initial conditions used in the air quality modeling methodology.

The reference and control scenarios include projections of existing mobile source emission control programs that EPA has already adopted, as well as other federal, state and local programs which are expected to reduce concentrations of pollutants in the ambient air in the future. These control programs include (but are not limited to) the Tier 3 Motor Vehicle Emission and Fuel Standards (79 FR 23414, April 28, 2014), the New Marine Compression-Ignition Engines at or Above 30 Liters per Cylinder Rule (75 FR 22895, April 30, 2010), the Locomotive and Marine Compression-Ignition Engine Rule (73 FR 25098, May 6, 2008), the Clean Air Nonroad Diesel

^{IIII} Due to resource constraints, we only conducted air quality modeling for the proposed Option 1.

^{JJJJ} As noted in Chapter 5.4 of the draft RIA, while we refer to this modeling as for the proposed Option 1, there are differences between the proposed Option 1 standards, emission warranty, and useful life provisions presented in Sections III and IV of the preamble and those included in the control scenario modeled for the air quality analysis.

(69 FR 38957, June 29, 2004), and the Heavy-Duty Engine and Vehicle Standards and Highway Diesel Fuel Sulfur Control Requirements (66 FR 5002, January 18, 2001).

Not included in the reference or control scenarios are additional federal or state programs that were not finalized at the time that the air quality modeling analysis for the proposal was initiated. For example, the CARB Heavy-Duty Low NO_x Omnibus rule and the CA Advanced Clean Trucks (ACT) rule were not final, so the emission reductions associated with these rulemakings are not included in the air quality modeling analysis for the proposed rule.^{KKKKK,LLLLL}

6.3.1 **Ozone Design Value Impacts of Proposed Rulemaking**

This section summarizes the ozone air quality impacts of the proposed rule in 2045, based on our CMAQ modeling. Our modeling indicates that ozone design value concentrations will decrease dramatically in many areas of the country as a result of the proposed rule.

Figure 6-5 presents the changes in 8-hour ozone design value concentrations in 2045.^{MMMMM}

^{KKKKK} Additional information on the CARB Omnibus program is available in Section I.D of the preamble for this proposed rule. Additional discussion on the CARB ACT program is available in Sections I.D, VI.D, and XI.

^{LLLLL} Draft RIA Chapter 5 Appendix 6 presents a sensitivity analysis of the estimated emission inventory impacts from nationwide adoption of the Omnibus rule.

^{MMMMM} An 8-hour ozone design value is the concentration that determines whether a monitoring site meets the NAAQS for ozone. The full details involved in calculating an 8-hour ozone design value are given in appendix I of 40 CFR part 50.

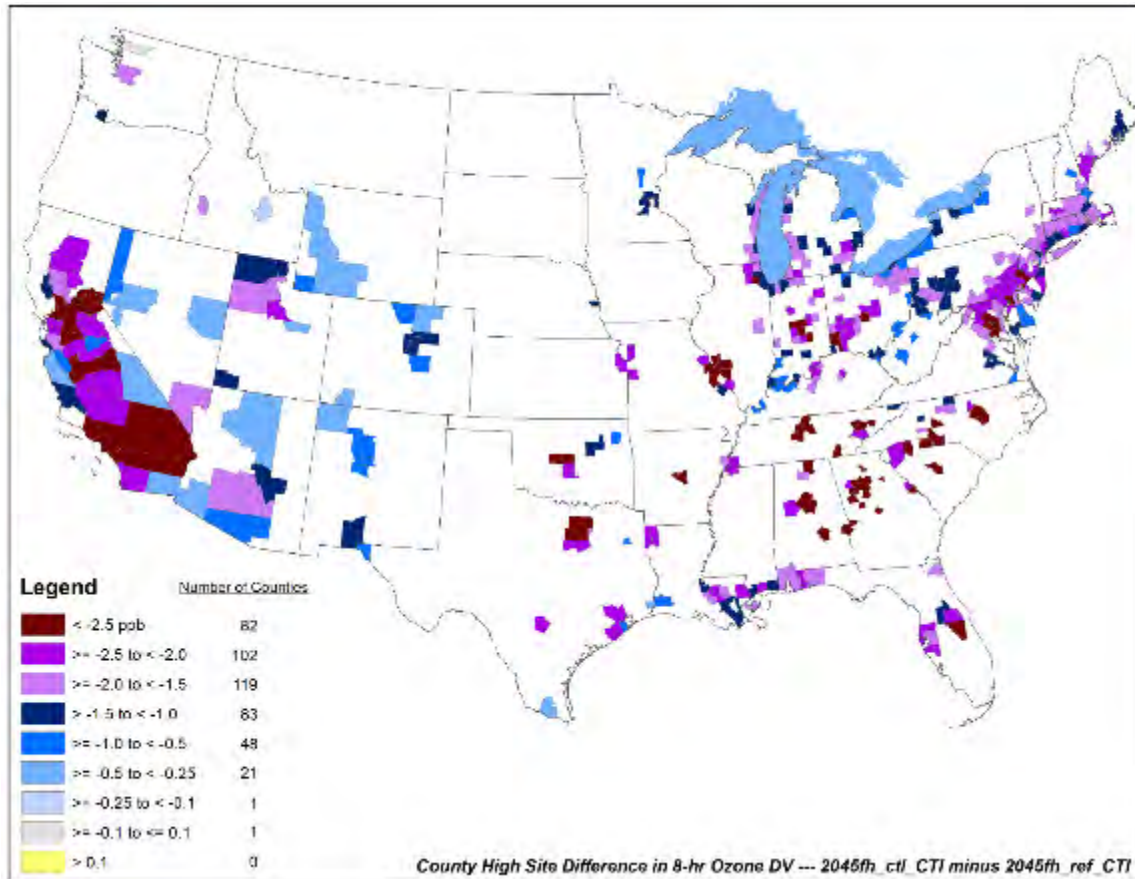


Figure 6-5: Projected Change in 8-hour Ozone Design Values in 2045 due to Proposed Rule

As shown in Figure 6-5, the majority of the design value decreases in 2045 are greater than 1.5 ppb. There are also 82 counties with projected 8-hour ozone design value decreases of more than 2.5 ppb; many of the counties with the largest design value decreases are in California, and in the Atlanta and St. Louis urban areas. The maximum projected decrease in an 8-hour ozone design value in 2045 is 5.1 ppb in Riverside County, California. Not all counties have monitor data that meets the requirements to calculate a design value concentration; counties without a calculated design value are left white.

Table 6-1 shows the average projected change, due to the proposed rule, in 2045 8-hour ozone design values for: (1) all modeled counties (with 2016 base case design values), (2) counties with 2016 base case design values that are above the level of the 2015 ozone NAAQS, (3) counties with 2016 base case design values that are equal to or within 10% below the level of the 2015 NAAQS, (4) counties with 2045 reference scenario design values that are above the level of the 2015 ozone NAAQS, (5) counties with 2045 reference scenario design values that are equal to or within 10% below the level of the 2015 ozone NAAQS, (6) counties with 2045 control scenario design values that are above the level of the 2015 ozone NAAQS, and (7) counties with 2045 control scenario design values that are equal to or within 10% below the level of the 2015 ozone NAAQS. Counties within 10 percent of the level of the NAAQS are intended to reflect counties that although not violating the standards, would also be impacted by changes in ambient levels of ozone as they work to ensure long-term attainment or maintenance of the ozone NAAQS. On a

population-weighted basis, the average modeled future-year 8-hour ozone design value is projected to decrease by over 2 ppb in 2045 due to the proposed rule.

Table 6-1: Average Change in Projected 8-hour Ozone Design Values in 2045 due to Proposed Rule

Projected Design Value Category	Number of Counties	2045 Population^a	Average Change in 2045 Design Value (ppb)	Population-Weighted Average Change in Design Value (ppb)
all modeled counties	457	246,949,949	-1.87	-2.23
counties with 2016 base year design values above the level of the 2015 8-hour ozone standard	118	125,319,158	-2.12	-2.43
counties with 2016 base year design values within 10% of the 2015 8-hour ozone standard	245	93,417,097	-1.83	-2.10
counties with 2045 reference design values above the level of the 2015 8-hour ozone standard	15	37,758,488	-2.26	-3.03
counties with 2045 reference design values within 10% of the 2015 8-hour ozone standard	56	39,302,665	-1.78	-2.02
counties with 2045 control design values above the level of the 2015 8-hour ozone standard	10	27,930,138	-2.36	-3.34
counties with 2045 control design values within 10% of the 2015 8-hour ozone standard	42	31,395,617	-1.69	-1.77

^a Population numbers based on Woods & Poole data. Woods & Poole Economics, Inc. (2015). Complete Demographic Database. Washington, DC. <http://www.woodsandpoole.com/index.php>.

These modeling results project that there would be 15 counties with 8-hour ozone design values above the level of the 2015 ozone NAAQS in 2045 without the proposed rule or any other additional standards in place. Table 6-2 below presents the changes in design values for these counties.

Table 6-2: Change in 8-hour Ozone Design Values for Counties Projected to be Above the Level of the 2015 8-hour Ozone NAAQS in 2045

County Name, State	Population in 2045 ^a	Change in 2045 projected 8-hour Ozone Design Value (DV) (ppb)	2045 Reference Ozone Design Value (ppb)	2045 Control Ozone Design Value (ppb)
San Bernardino, California	3,191,663	-4.6	98.0	93.4
Los Angeles, California	11,755,545	-3.3	92.3	89.0
Riverside, California	3,926,478	-5.1	83.3	78.2
Fairfield, Connecticut	1,050,293	-1.4	79.4	78.0
Imperial, California	296,070	-0.3	76.6	76.3
Kern, California	1,251,350	-2.2	76.5	74.3
San Diego, California	4,452,722	-2.5	75.2	72.7
Fresno, California	1,371,355	-2.8	74.9	72.1
Richmond, New York	614,033	-0.8	73.7	72.9
Mariposa, California	20,630	-0.6	72.0	71.4
<i>Salt Lake, Utah</i>	<i>1,387,960</i>	<i>-1.9</i>	<i>71.9</i>	<i>70.0</i>
<i>Tulare, California</i>	<i>601,851</i>	<i>-2.4</i>	<i>71.5</i>	<i>69.1</i>
<i>Sheboygan, Wisconsin</i>	<i>124,284</i>	<i>-1.9</i>	<i>71.4</i>	<i>69.5</i>
<i>Davis, Utah</i>	<i>556,296</i>	<i>-1.9</i>	<i>71.3</i>	<i>69.4</i>
<i>Harris, Texas</i>	<i>7,157,959</i>	<i>-2.2</i>	<i>71.2</i>	<i>69.0</i>
^a Population numbers based on Woods & Poole data. Woods & Poole Economics, Inc. (2015). Complete Demographic Database. Washington, DC. http://www.woodsandpoole.com/index.php .				

Our modeling predicts that the proposed rule would reduce ozone design values in some counties from above the level of the standard to below it. While the number of counties with projected design values above the level of the NAAQS is less certain than the average projected changes in design values, our modeling projects that in 2045 ozone design values in five counties (Salt Lake and Davis Counties in Utah, Tulare County in California, Sheboygan County in Wisconsin, and Harris County in Texas) will change from being above the level of the standard in the reference scenario to being below the level of the standard in the control scenario. The projected population in these five counties in 2045 is almost 10 million people.

As described in Chapter 4 of this draft RIA, the science of ozone formation, transport, and accumulation is complex. The air quality modeling projects ozone design value decreases as a result of emissions changes from the proposed standards in the vast majority of counties. This change in ozone results from interactions between photochemistry, background concentrations of ozone, VOC and NO_x, local emissions and meteorology. However, there is one county in 2045 that is projected to have no change in modeled ozone design value concentration (Skagit County, Washington).

6.3.2 **Annual PM_{2.5} Design Value Impacts of Proposed Rulemaking**

This section summarizes the annual average PM_{2.5} air quality impacts of the proposed rule in 2045, based on our CMAQ modeling. Our modeling indicates that annual PM_{2.5} design values will decrease due to the proposed rule. The decreases in annual PM_{2.5} design values are due to the projected reductions in NO_x, primary PM_{2.5}, and VOC emissions.

Figure 6-6 presents the changes in annual PM_{2.5} design values in 2045.^{NNNNN}

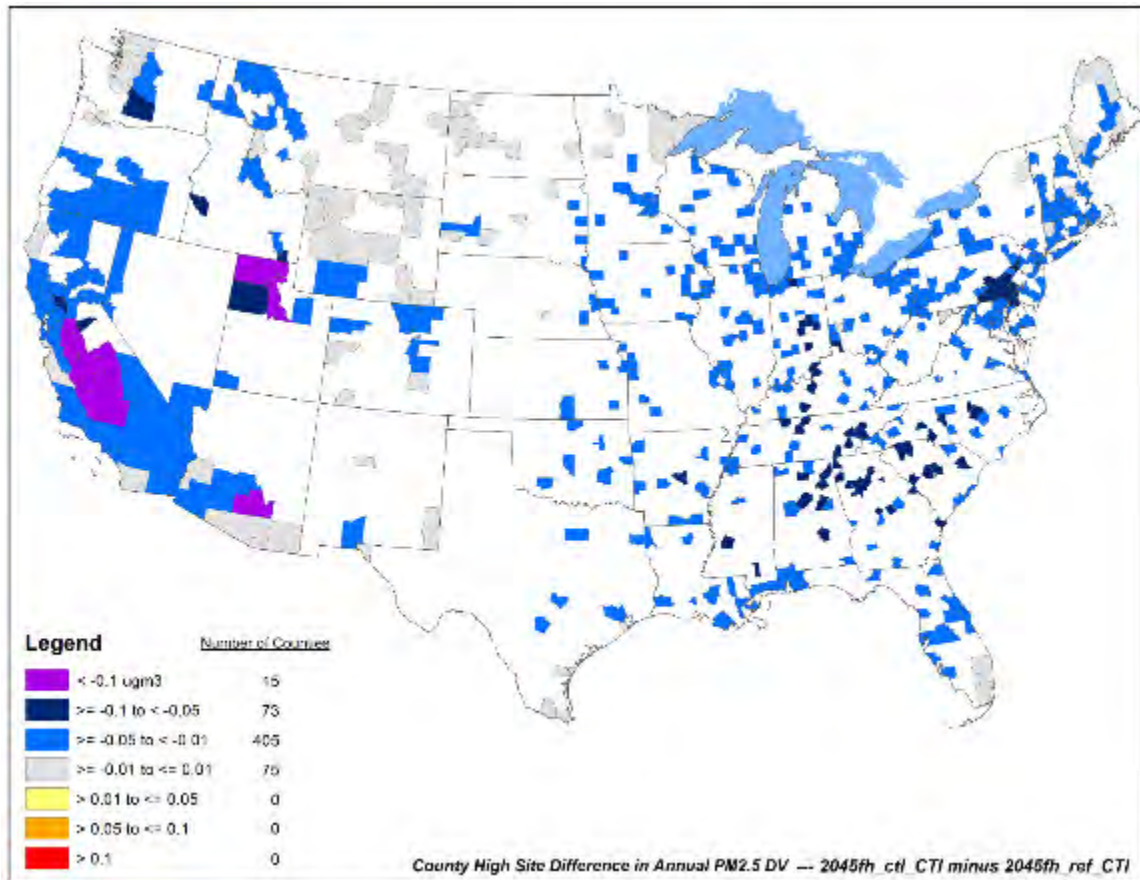


Figure 6-6: Projected Change in Annual PM_{2.5} Design Values in 2045 due to Proposed Rule

As shown in Figure 6-6, we project that in 2045 most counties will have design value decreases of between 0.01 µg/m³ and 0.05 µg/m³. There are also 15 counties with projected annual PM_{2.5} design value decreases of more than 0.1 µg/m³; these counties are in California and Utah. The maximum projected decrease in a 2045 annual PM_{2.5} design value is 0.21 µg/m³ in Tulare County, California. Not all counties have monitor data that meets the requirements to calculate a design value concentration; counties without a calculated design value are left white.

Table 6-3 presents the average projected change, due to the proposed rule, in 2045 annual PM_{2.5} design values for: (1) all modeled counties (with 2016 base case design values), (2) counties with 2016 base case design values that are above the level of the 2012 annual PM_{2.5} standard, (3) counties with 2016 base case design values that are equal to or within 10% below the level of the 2012 standard, (4) counties with 2045 reference scenario design values that are above the level of the 2012 annual PM_{2.5} standard, (5) counties with 2045 reference scenario design values that are equal to or within 10% below the level of the 2012 annual PM_{2.5} standard, (6) counties with 2045 control scenario design values that are above the level of the 2012 annual

^{NNNNN} An annual PM_{2.5} design value is the concentration that determines whether a monitoring site meets the annual NAAQS for PM_{2.5}. The full details involved in calculating an annual PM_{2.5} design value are given in appendix N of 40 CFR part 50.

PM_{2.5} standard and (7) counties with 2045 control scenario design values that are equal to or within 10% below the level of the 2012 annual PM_{2.5} standard. Counties within 10 percent of the level of the standard are intended to reflect counties that although not violating the standards, would also be impacted by changes in ambient levels of PM_{2.5} as they work to ensure long-term attainment or maintenance of the 2012 annual PM_{2.5} NAAQS. On a population-weighted basis, the average modeled future year annual PM_{2.5} design value is projected to decrease by 0.04 µg/m³ due to the proposed rule.

Table 6-3: Average Change in Projected Annual PM_{2.5} Design Values in 2045 due to Proposed Rule

Projected Design Value Category	Number of Counties	2045 Population^a	Average Change in 2045 Design Value (ug/m³)	Population-Weighted Average Change in Design Value (ug/m³)
all modeled counties	568	273,604,437	-0.04	-0.04
counties with 2016 base year design values above the level of the 2012 annual PM _{2.5} standard	17	26,726,354	-0.09	-0.05
counties with 2016 base year design values within 10% of the 2012 annual PM _{2.5} standard	5	4,009,527	-0.06	-0.06
counties with 2045 reference design values above the level of the 2012 annual PM _{2.5} standard	12	25,015,974	-0.10	-0.05
counties with 2045 reference design values within 10% of the 2012 annual PM _{2.5} standard	6	1,721,445	-0.06	-0.06
counties with 2045 control design values above the level of the 2012 annual PM _{2.5} standard	10	23,320,070	-0.10	-0.05
counties with 2045 control design values within 10% of the 2012 annual PM _{2.5} standard	8	3,417,349	-0.08	-0.09

^a Population numbers based on Woods & Poole data. Woods & Poole Economics, Inc. (2015). Complete Demographic Database. Washington, DC. <http://www.woodsandpoole.com/index.php>.

There are 12 counties, mostly in California, that are projected to have annual PM_{2.5} design values above the level of the NAAQS in 2045 without the proposed rule or any other additional standards in place. Table 6-4 below presents the changes in design values for these counties.

Table 6-4: Change in Annual PM_{2.5} Design Values for Counties Projected to be Above the Level of the Annual PM_{2.5} NAAQS in 2045

County Name, State	Population in 2045 ^a	Change in 2045 Projected Annual PM _{2.5} Design Value (DV) (µg/m ³)	2045 Reference Design Value (µg/m ³)	2045 Control Design Value (µg/m ³)
Kern, California	1,251,350	-0.15	15.78	15.63
Kings, California	185,866	-0.19	14.82	14.63
San Bernardino, California	3,191,663	-0.02	14.21	14.19
Plumas, California	21,297	-0.05	14.12	14.06
Tulare, California	601,851	-0.21	14.05	13.84
Riverside, California	3,926,478	-0.04	13.43	13.39
Imperial, California	296,070	-0.02	12.93	12.91
Fresno, California	1,371,355	-0.16	12.87	12.71
Los Angeles, California	11,755,545	-0.02	12.26	12.24
Pinal, Arizona	718,595	-0.11	12.24	12.13
Stanislaus, California	716,019	-0.16	12.17	12.02
San Joaquin, California	979,885	-0.11	12.07	11.96

^a Population numbers based on Woods & Poole data. Woods & Poole Economics, Inc. (2015). Complete Demographic Database. Washington, DC. <http://www.woodsandpoole.com/index.php>.

Our modeling predicts that the proposed rule would reduce annual PM_{2.5} design values in some counties from above the level of the standard to below it. While the number of counties with projected design values above the level of the NAAQS is less certain than the average changes in design values, annual PM_{2.5} design values in two counties (Stanislaus County, California and San Joaquin County, California) are projected to change from being above the level of the standard in the reference scenario to being below the level of the standard in the control scenario. The projected population in these two counties in 2045 is over 1.5 million people.

6.3.3 24-hour PM_{2.5} Design Value Impacts of Proposed Rulemaking

This section summarizes the 24-hour PM_{2.5} air quality impacts of the proposed rule in 2045, based on our CMAQ modeling. Our modeling indicates that most 24-hour PM_{2.5} design values would decrease due to the proposed rule. The decreases in 24-hour PM_{2.5} design values are due to the projected reductions in NO_x, primary PM_{2.5}, and VOC emissions.

Figure 6-7 presents the changes in 24-hour PM_{2.5} design values in 2045.⁰⁰⁰⁰⁰

⁰⁰⁰⁰⁰ A 24-hour PM_{2.5} design value is the concentration that determines whether a monitoring site meets the 24-hour NAAQS for PM_{2.5}. The full details involved in calculating a 24-hour PM_{2.5} design value are given in appendix N of 40 CFR part 50.

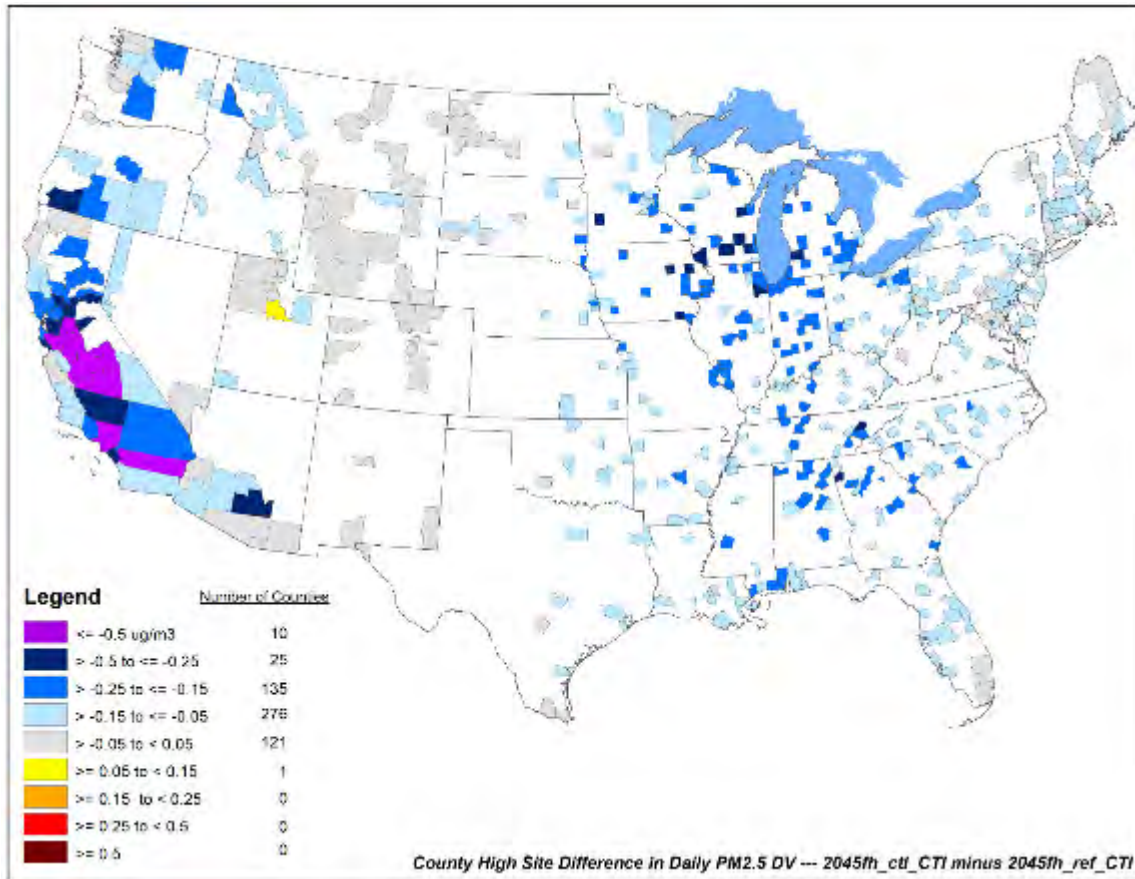


Figure 6-7: Projected Change in 24-hour PM_{2.5} Design Values in 2045 due to Proposed Rule

As shown in Figure 6-7, in 2045 there are 170 counties with projected 24-hour PM_{2.5} design value decreases greater than $0.15 \mu\text{g}/\text{m}^3$. These counties are in mainly in the midwest, southeast and western United States. The maximum projected decrease in a 2045 24-hour PM_{2.5} design value is $1.79 \mu\text{g}/\text{m}^3$ in Tulare County, California. Not all counties have monitor data that meets the requirements to calculate a design value concentration; counties without a calculated design value are left white.

Table 6-5 shows the average projected change, due to the proposed rule, in 2045 24-hour PM_{2.5} design values for: (1) all modeled counties (with 2016 base case design values), (2) counties with 2016 base case design values that are above the level of the 2006 24-hour PM_{2.5} standard, (3) counties with 2016 base case design values that are equal to or within 10% below the level of the 2006 24-hour PM_{2.5} standard, (4) counties with 2045 reference scenario design values that are above the level of the 2006 24-hour PM_{2.5} standard, (5) counties with 2045 reference scenario design values that are equal to or within 10% below the level of the 2006 24-hour PM_{2.5} standard, (6) counties with 2045 control scenario design values that are above the level of the 2006 24-hour PM_{2.5} standard, and (7) counties with 2045 control scenario design values that are equal to or within 10% below the level of the 2006 24-hour PM_{2.5} NAAQS. Counties within 10 percent of the level of the standard are intended to reflect counties that although not violating the standards, would also be impacted by changes in ambient levels of PM_{2.5} as they work to ensure long-term attainment or maintenance of the 2006 24-hour PM_{2.5}

NAAQS. On a population-weighted basis, the average modeled future-year 24-hour PM_{2.5} design value is projected to decrease by 0.17 µg/m³ in 2045 due to the proposed rule.

Table 6-5: Average Change in Projected 24-hour PM_{2.5} Design Values in 2045 due to Proposed Rule

Projected Design Value Category	Number of Counties	2045 Population^a	Average Change in 2045 Design Value (ug/m³)	Population-Weighted Average Change in Design Value (ug/m³)
all modeled counties	568	272,852,777	-0.12	-0.17
counties with 2016 base year design values above the level of the 2006 daily PM _{2.5} standard	33	28,394,253	-0.40	-0.67
counties with 2016 base year design values within 10% of the 2006 daily PM _{2.5} standard	15	13,937,416	-0.18	-0.27
counties with 2045 reference design values above the level of the 2006 daily PM _{2.5} standard	29	14,447,443	-0.38	-0.55
counties with 2045 reference design values within 10% of the 2006 daily PM _{2.5} standard	12	22,900,297	-0.30	-0.59
counties with 2045 control design values above the level of the 2006 daily PM _{2.5} standard	29	14,447,443	-0.38	-0.55
counties with 2045 control design values within 10% of the 2006 daily PM _{2.5} standard	10	19,766,216	-0.26	-0.60

^a Population numbers based on Woods & Poole data. Woods & Poole Economics, Inc. (2015). Complete Demographic Database. Washington, DC. <http://www.woodsandpoole.com/index.php>.

There are 29 counties that are projected to have 24-hour PM_{2.5} design values above the level of the NAAQS in 2045 without the proposed rule or any other additional controls in place. Table 6-6 below presents the changes in design values for these counties.

Table 6-6: Change in 24-hour PM_{2.5} Design Values for Counties Projected to be Above the 24-hour PM_{2.5} NAAQS in 2045

County Name, State	Population in 2045 ^a	Change in 24-hour PM _{2.5} Design Value (µg/m ³)	2045 Reference Design Value (µg/m ³)	2045 Control Design Value (µg/m ³)
Okanogan, Washington	47,922	-0.24	57.02	56.79
Ravalli, Montana	52,336	-0.03	56.93	56.90
Kern, California	1,251,350	-0.49	55.78	55.29
Fresno, California	1,371,355	-0.68	49.86	49.17
Jackson, Oregon	281,974	-0.28	49.22	48.94
Kings, California	185,866	-1.42	47.23	45.81
Plumas, California	21,297	-0.16	46.30	46.14
Klamath, Oregon	71,950	-0.16	44.39	44.24
Siskiyou, California	46,491	-0.03	44.04	44.02
Lincoln, Montana	19,924	-0.14	43.05	42.91
Tulare, California	601,851	-1.79	42.63	40.84
Missoula, Montana	139,759	-0.13	42.49	42.36
Lemhi, Idaho	8,830	-0.08	42.46	42.39
Lewis and Clark, Montana	95,256	-0.06	41.17	41.11
Flathead, Montana	150,424	-0.12	40.75	40.64
Yakima, Washington	289,388	-0.22	40.64	40.42
Lake, Oregon	8,605	-0.10	40.43	40.33
Stanislaus, California	716,019	-1.26	39.54	38.28
Lane, Oregon	440,599	-0.13	39.53	39.39
Josephine, Oregon	106,207	-0.27	39.46	39.19
Alameda, California	1,936,700	-0.30	38.81	38.51
Madera, California	208,957	-0.62	38.49	37.87
San Joaquin, California	979,885	-1.22	38.15	36.93
Kittitas, Washington	53,927	-0.17	37.82	37.65
Riverside, California	3,926,478	-0.51	37.35	36.84
Shoshone, Idaho	11,064	-0.16	37.07	36.91
Crook, Oregon	24,645	-0.19	37.00	36.81
Benewah, Idaho	10,426	-0.13	36.72	36.59
Salt Lake, Utah	1,387,960	0.02	36.04	36.06

^a Population numbers based on Woods & Poole data. Woods & Poole Economics, Inc. (2015). Complete Demographic Database. Washington, DC. <http://www.woodsandpoole.com/index.php>.

While the count of modeled nonattainment counties is much less certain than the average changes in air quality, in 2045, there are no 24-hour PM_{2.5} design values that are projected to change from being above the level of the standard in the reference case to being below the level of the standard in the proposed control case.

As described in Chapter 4 of this draft RIA, PM_{2.5} in the atmosphere can be primary or secondary and its composition, transport, and accumulation is complex. The air quality modeling projects 24-hour PM_{2.5} design value decreases as a result of emissions changes from the proposed rule in the vast majority of counties. However, there are a handful of counties where 24-hour PM_{2.5} design values are projected to increase. These increases are likely due to elevated secondary PM_{2.5} formation rates as a result of increased oxidant levels, which occur during stagnant cold weather due to reductions in NO_x.

6.3.4 **Nitrogen Dioxide Concentration Impacts of Proposed Rulemaking**

This section summarizes the annual average NO₂ air quality impacts of the proposed rule in 2045, based on our CMAQ modeling. Our modeling indicates that annual average NO₂ concentrations would decrease as a result of the proposed rule, if finalized as proposed. Figure 6-8 presents the changes in annual NO₂ concentrations in 2045.

As shown in Figure 6-8, our modeling indicates that by 2045 annual NO₂ concentrations in the majority of the country would decrease between 0.01 and 0.1 ppb due to the proposed rule. However, decreases in annual NO₂ concentrations would be greater than 0.2 ppb along many highway corridors and greater than 0.3 ppb in most urban areas. The absolute reductions correspond to reductions of greater than 5 percent in annual NO₂ concentrations across much of the country, see Figure 6-9. Although we didn't model changes in 1-hour concentrations, the proposed rule would also likely decrease 1-hour NO₂ concentrations and help any potential nonattainment areas attain and maintenance areas maintain the NO₂ standard.^{PPPPP}

^{PPPPP} As noted in Chapter 6.1.3, there are currently no nonattainment areas for the NO₂ NAAQS.

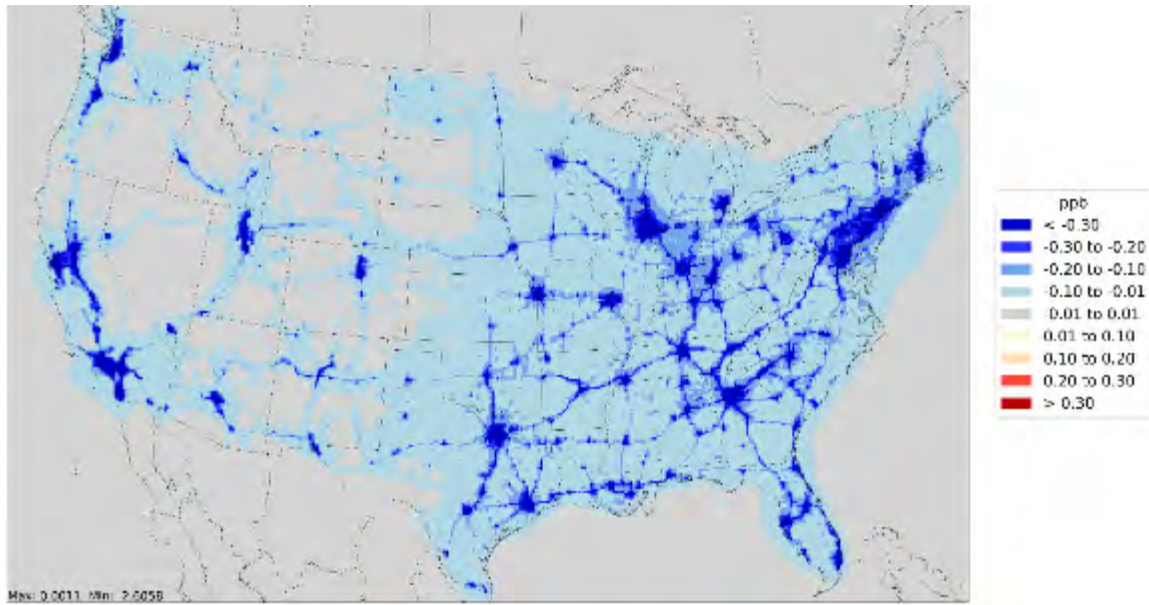


Figure 6-8: Projected Absolute Change in Annual Ambient NO₂ Concentrations in 2045

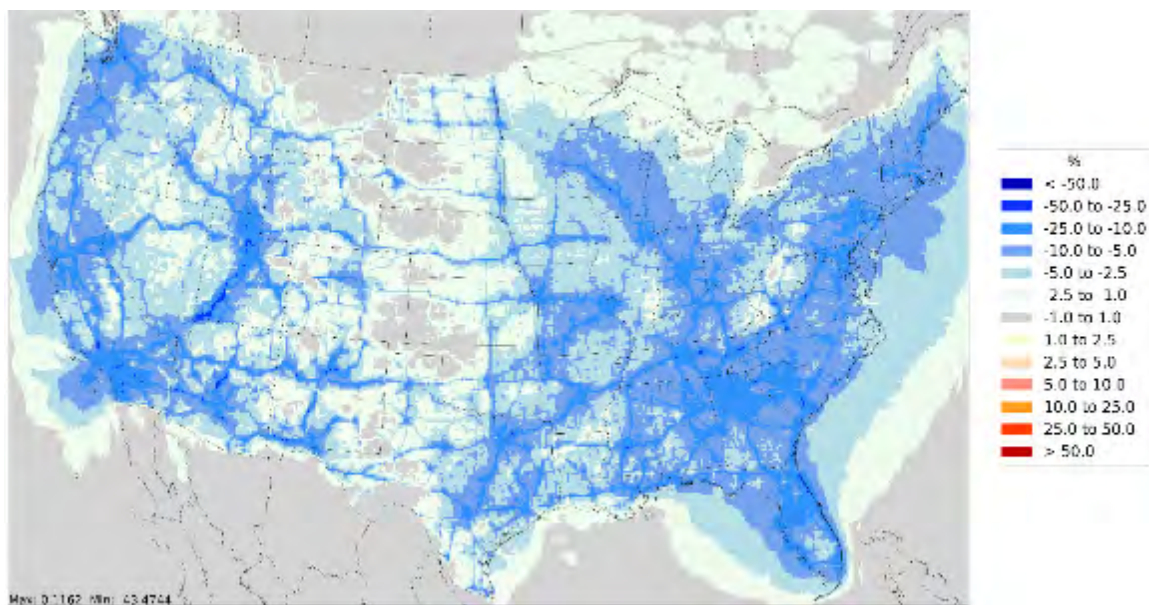


Figure 6-9: Percent Change in Annual Ambient NO₂ Concentrations in 2045

6.3.5 Carbon Monoxide Concentration Impacts of Proposed Rulemaking

This section summarizes the annual average CO air quality impacts of the proposed rule in 2045, based on our CMAQ modeling. Our modeling indicates that annual average CO concentrations would decrease as a result of the proposed rule. Figure 6-10 and Figure 6-11 present the absolute and percent changes in annual CO concentrations in 2045.

As shown in Figure 6-10, our modeling indicates that by 2045 annual CO concentrations in the majority of the country would decrease between 0.02 and 0.5 ppb due to the proposed rulemaking. However, decreases in annual CO concentrations would be greater than 1.5 ppb in some urban areas. The absolute reductions correspond to percent changes of less than 1 percent across the country, except for the Phoenix area, where there are some larger decreases between 1 and 2 percent. Although we didn't model changes in 8-hour or 1-hour concentrations, the proposed standards would also likely decrease 1-hour and 8-hour CO concentrations and help any potential nonattainment areas attain and maintenance areas maintain the CO standard. QQQQ

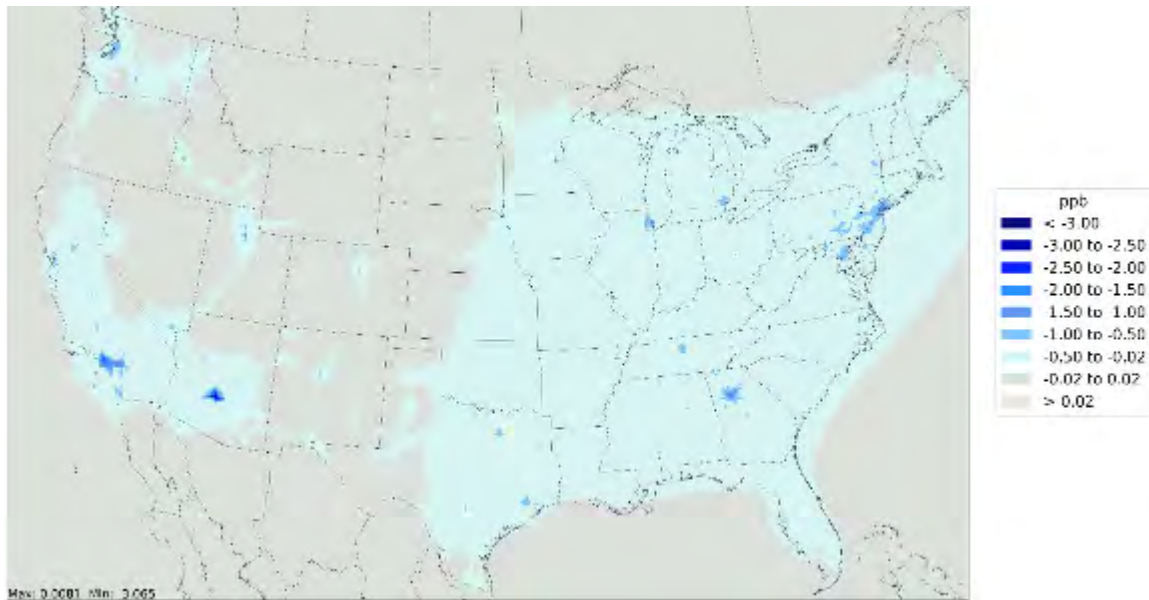


Figure 6-10: Absolute Change in Annual Ambient CO Concentrations in 2045

QQQQ As noted in Chapter 6.1.4, there are currently no nonattainment areas for the CO NAAQS.



Figure 6-11: Percent Change in Annual Ambient CO Concentrations in 2045

6.3.6 Air Toxics Impacts of Proposed Rulemaking

This section summarizes the changes in annual average air toxic (acetaldehyde, benzene, formaldehyde and naphthalene) concentrations in 2045 due to the proposed rule. Our modeling indicates that the proposed rule would have relatively little impact on national average ambient concentrations of the modeled air toxics in 2045. Annual percent changes are less than 1% for air toxics across most of the country. Annual absolute changes in ambient concentrations are generally less than $0.001 \mu\text{g}/\text{m}^3$ for benzene and naphthalene (Figure 6-12 and Figure 6-13 below). There are small increases in acetaldehyde across the country, see Figure 6-14. The increases in acetaldehyde likely occur because species that lead to production or recycling of acetaldehyde increase as their reactions with nitrogen oxides decrease. For formaldehyde there are decreases across most of the country and a few areas with increases, see Figure 6-15. The increases in formaldehyde concentration due to the proposed rule are likely related to higher concentrations of OH radicals in areas where ozone increases due to NO_x emissions reductions (see Chapter 4.1.1.1).

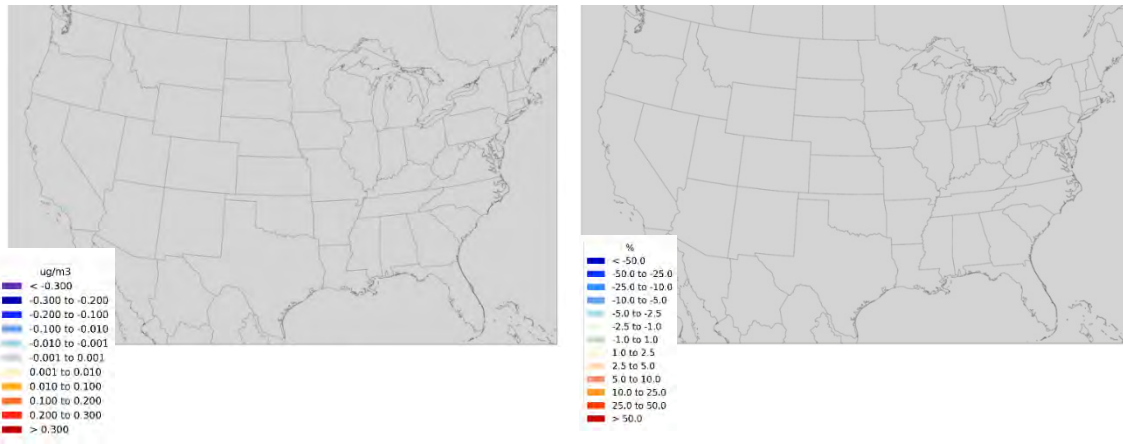


Figure 6-12: Changes in Ambient Benzene Concentrations in 2045 due to Proposed Rule: Absolute Changes in $\mu\text{g}/\text{m}^3$ (left) and Percent Changes (right)

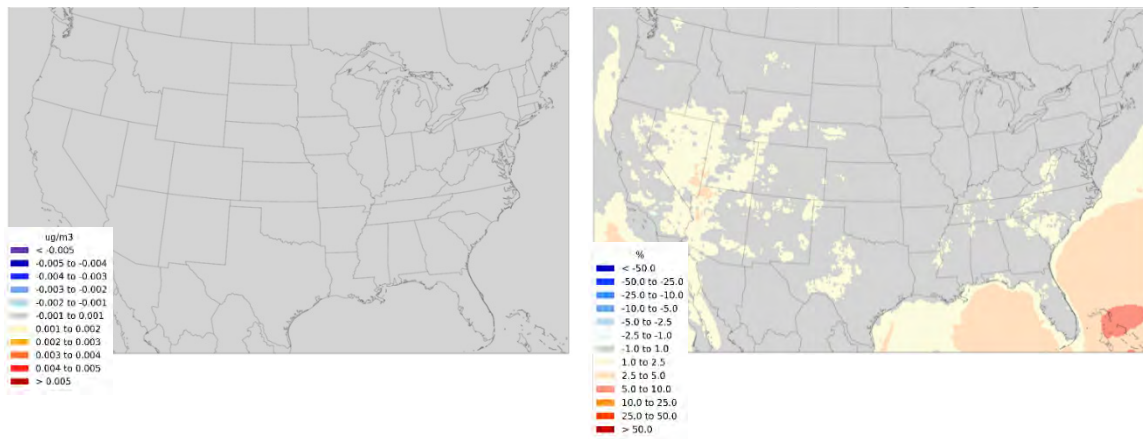


Figure 6-13: Changes in Ambient Naphthalene Concentrations in 2045 due to Proposed Rule: Absolute Changes in $\mu\text{g}/\text{m}^3$ (left) and Percent Changes (right)

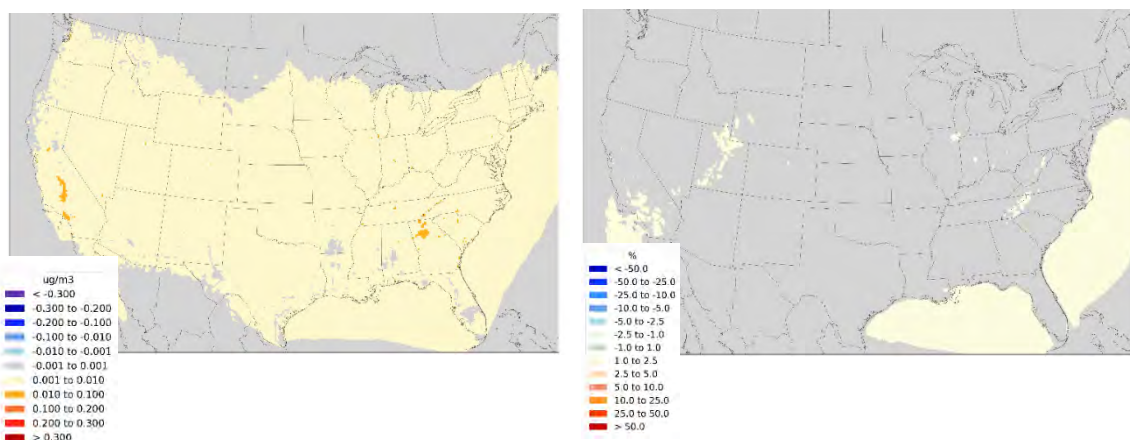


Figure 6-14: Changes in Ambient Acetaldehyde Concentrations in 2045 due to Proposed Rule: Absolute Changes in $\mu\text{g}/\text{m}^3$ (left) and Percent Changes (right)

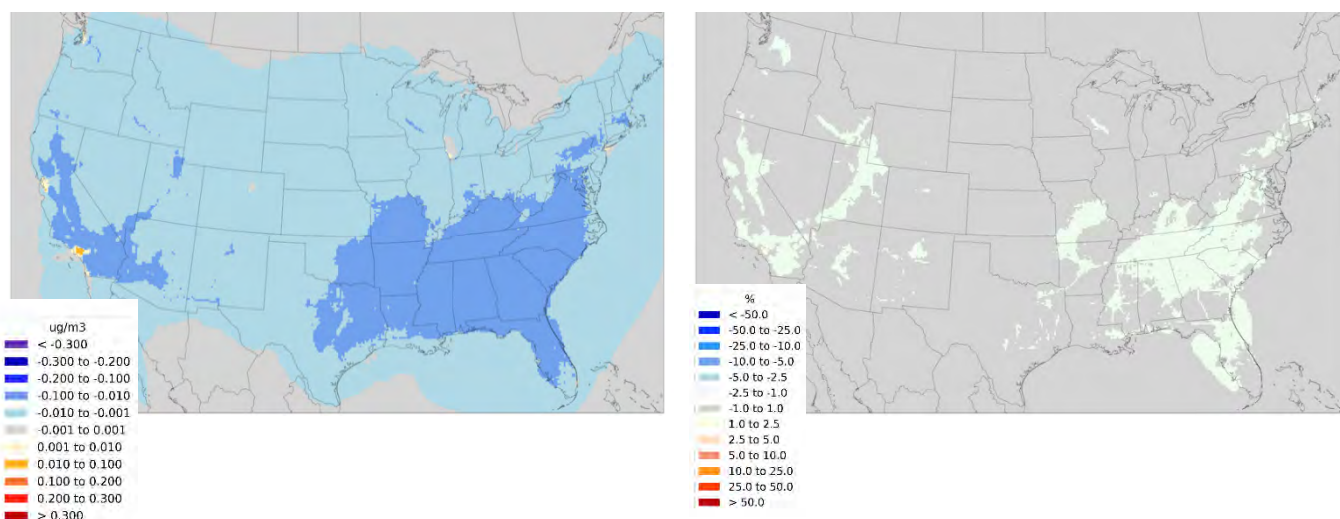


Figure 6-15: Changes in Ambient Formaldehyde Concentrations in 2045 due to Proposed Rule: Absolute Changes in $\mu\text{g}/\text{m}^3$ (left) and Percent Changes (right)

6.3.7 Visibility Impacts of Proposed Rulemaking

Air quality modeling was used to project visibility conditions in 145 Mandatory Class I Federal areas across the U.S. with and without the proposed rule in 2045. The results show that in 2045, the proposed rule would improve projected visibility on the 20% most impaired days in all modeled areas.^{RRRRR} The average visibility on the 20 percent most impaired days at all

^{RRRRR} The level of visibility impairment in an area is based on the light-extinction coefficient and a unitless visibility index, called a “deciview”, which is used in the valuation of visibility. The deciview metric provides a scale for perceived visual changes over the entire range of conditions, from clear to hazy. Under many scenic conditions, the

modeled Mandatory Class I Federal areas is projected to improve by 0.04 deciviews, or 0.37 percent, in 2045. The greatest improvement in visibility would occur in San Geronio and San Jacinto Wilderness Areas in California, where visibility is projected to improve by 1.56 percent (0.21 deciviews) in 2045 due to the proposed rule. The AQM TSD contains the full visibility results from 2045 for the 145 analyzed areas.³⁴⁰

6.3.8 **Deposition Impacts of Proposed Rulemaking**

Our air quality modeling projects decreases in nitrogen deposition due to the proposed rule. Figure 6-16 shows that by 2045 the proposed rule would result in decreases in nitrogen deposition over much of the eastern US and in urban areas of the western US, with the largest decreases in Atlanta and Los Angeles. Figure 6-17 indicates those decreases correspond to annual percent decreases of more than one percent over much of the country, with some localized decreases of over 4 percent.

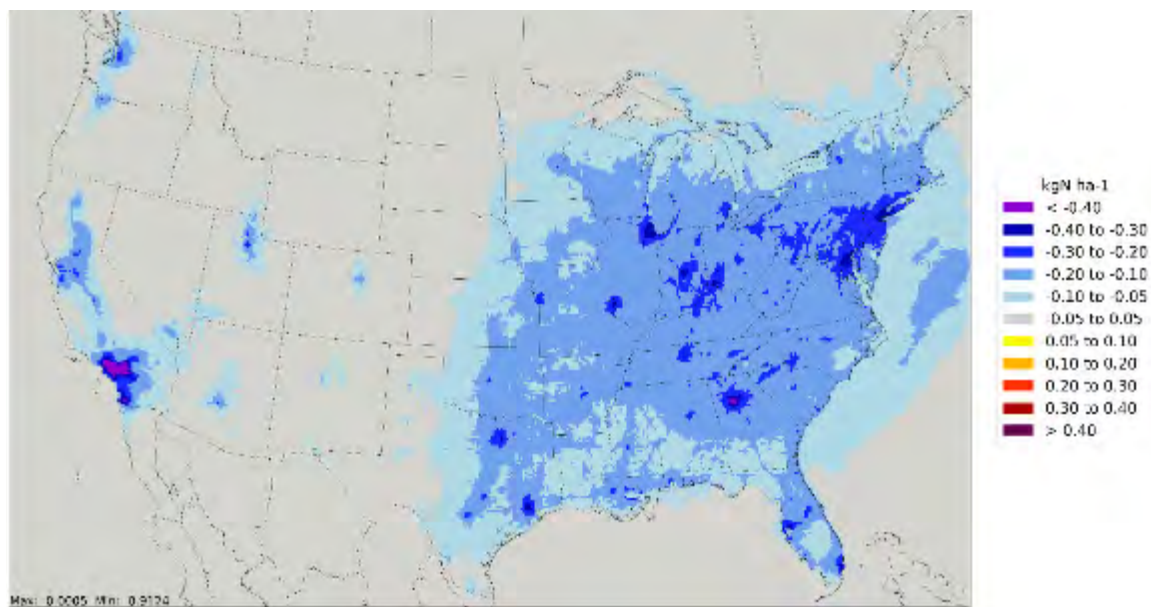


Figure 6-16: Absolute Change in Annual Deposition of Nitrogen in 2045

average person can generally perceive a change of one deciview. The higher the deciview value, the worse the visibility. Thus, an improvement in visibility is a decrease in deciview value.

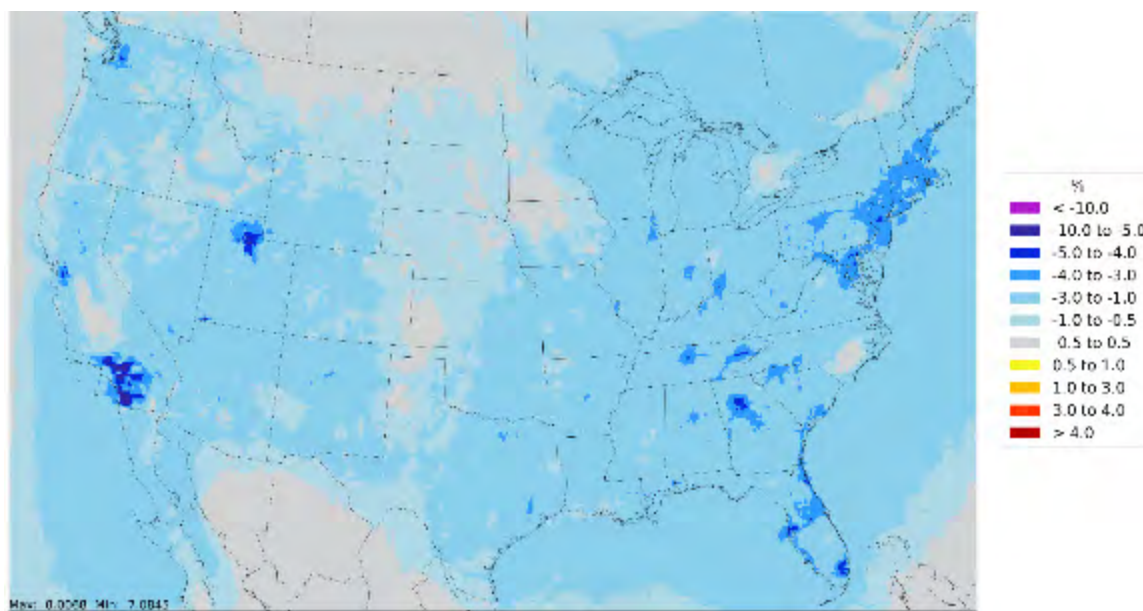


Figure 6-17: Percent Change in Annual Deposition of Nitrogen in 2045

6.3.9 Demographic Analysis of Air Quality

When feasible, EPA’s Office of Transportation and Air Quality 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. As described in Chapter 6.2, the air quality modeling we conducted supports our analysis of future projections of PM_{2.5} and ozone concentrations in a “baseline” scenario absent the proposed standards and in a “control” scenario that assumes the proposed Option 1 is in place.^{SSSS} The incremental reductions in estimated air quality concentrations between the two scenarios are therefore attributed to the proposed rule. These baseline and control scenarios are also used as inputs to the health benefits analysis. As demonstrated in Chapter 6.3 and Chapter 8.6, the ozone and PM_{2.5} improvements that are projected to result from the proposed rule, and the health benefits associated with those pollutant reductions, would be substantial.

This air quality modeling data can also be used to conduct an analysis of how human exposure to future air quality varies with sociodemographic characteristics relevant to potential environmental justice concerns in scenarios with and without the proposed rule in place. To compare trends, we sorted 2045 baseline air quality concentrations from highest to lowest concentration and compared two groups - areas within the contiguous U.S. with the worst air quality (grid cells with the highest 5 percent of concentrations) and the rest of the country (remaining 95 percent of grid cells). This approach can then answer two principal questions to determine disparity of air quality on the basis of race and ethnicity:^{TTTT}

^{SSSS} As noted in Chapter 5.4 of the draft RIA, while we refer to this modeling as for the proposed Option 1, there are differences between the proposed Option 1 standards, emission warranty, and useful life provisions presented in Sections III and IV of the preamble and those included in the control scenario modeled for the air quality analysis.

^{TTTT} Note that we do not have similar projections of income in 2045 and therefore cannot conduct a similar analysis using measures of low income such as poverty status (or other SES measure).

1. What is the racial and ethnic composition of areas with the worst baseline air quality in 2045?
2. Are those with the worst air quality likely to benefit more from the proposed rule?

We found that in the 2045 baseline, nearly double the number of people of color live within areas with the worst ozone and PM_{2.5} air pollution compared to non-Hispanic Whites (NH-Whites).^{UUUUU} We also found that (in absolute terms) the largest predicted improvements in both ozone and PM_{2.5} are estimated to occur in areas with the worst baseline air quality, where a substantially larger number of people of color are expected to reside. This section describes the data and methods used to conduct the demographic analysis and presents our results.

6.3.9.1 Data and Methods

We began with projected 2045 baseline and control scenarios of modeled PM_{2.5} and ozone concentration data (described in draft RIA Chapter 8.3.1). Ambient air quality concentration data (annual average $\mu\text{g}/\text{m}^3$ for PM_{2.5} and May-September daily maximum 8-hour average ppb for ozone) was estimated at a standard grid resolution of 12km x 12km across the contiguous United States (CONUS). Using 2045 baseline air quality data as our reference scenario, we sorted baseline air quality concentrations from highest to lowest concentration and compared two air quality concentration groups – grid cells in the highest 5 percent of the distribution of baseline concentrations and grid cells in the remaining 95 percent.^{VVVVV} The maps in Figure 6-18 display the spatial distribution of grid cells with baseline concentrations in the highest 5 percent for both PM_{2.5} and ozone concentrations. We retain this distinction throughout the analysis in order to track how air quality is distributed by air quality concentration group in the baseline and how the proposal impacts air quality in these same grid cells with the rule in place.

The analysis also used population projections based on economic forecasting models developed by Woods and Poole, Inc. The Woods and Poole database contains county-level projections of population by age, sex, and race/ethnicity out to 2050, relative to a baseline using the 2010 Decennial Census. The projected population for 2045 was extracted from the Environmental Benefits Mapping and Analysis Program – Community Edition (BenMAP-CE)^{WWWWW} at the same 12km x 12km grid resolution as the air quality data. Race and ethnicity of individuals projected to live in a given area were compiled into two broad categories, “people of color” and “Non-Hispanic White (NH-White).”^{XXXXX} In 2045, there are 409 million people projected to be living in the contiguous United States; 208 million are projected to be NH-White and 201 million are projected to be people of color. To put these projections into perspective,

^{UUUUU} The demographic analysis uses air quality modeling that has a contiguous U.S. domain. The analysis does not characterize distributional trends in areas of the U.S. that fall outside of this domain.

^{VVVVV} Using higher and lower percentiles to compare risks, exposures and outcomes has been applied by EPA's Office of Air and Radiation in previous distributional analyses of regulatory air quality modeling (see MATS, CSAPR, PM NAAQS) and is consistent with EPA's EJ Technical Guidance.

^{WWWWW} More information about BenMAP-CE can be found here: <https://www.epa.gov/benmap>. Additional information about the population projections used in this analysis can be found in Appendix J of the BenMAP-CE User's Manual: <https://www.epa.gov/benmap/benmap-ce-manual-and-appendices>.

^{XXXXX} “People of color” includes Black, Asian, Native American, Hawaiian/Pacific Islander, and Hispanic populations.

2010 populations for the contiguous United States were 201 million for NH-White and 106 million for people of color.

Additionally, this analysis looked at the distribution of poverty status within the same air quality concentration groups – 12km x 12km grid cells in the highest 5 percent of the distribution of baseline concentrations and grid cells in the remaining 95 percent. We applied county-level poverty status derived from the Census’ American Community Survey (ACS) 5-year estimates from 2015 to 2019, which represents the fraction of county-level population below and above 200% of the poverty line.^{YYYYY} We note that measures of “current” poverty are not necessarily predictors of future poverty status; poverty status in the 2045 population could be different in terms of both scale and geographic location. However, for the purposes of this analysis, we believe applying a “current” measure of those who live above and below 200% of the poverty line is illustrative.

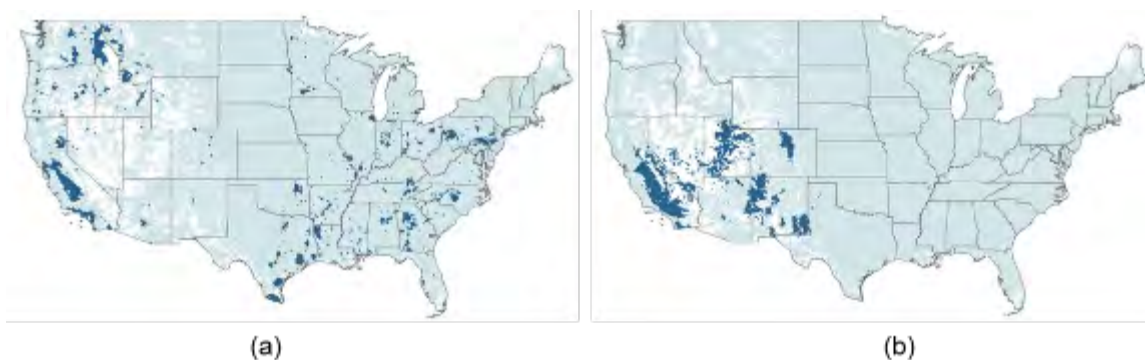


Figure 6-18: Distributional maps of populated 12km grid cells across the contiguous United States in 2045. Darker areas represent the location of grid cells within the highest 5 percent of baseline concentrations for (a) PM_{2.5} and (b) ozone

For each pollutant and air quality concentration group (i.e., highest 5% of concentration or remaining 95% of grid cells), we calculated the average baseline, control, and reduction in concentrations. We then summed the population by group (people of color or NH-White; populations above or below 200% of the poverty line) for each air quality concentration group.

6.3.9.2 Results

Of the approximately 48,000 grid cells that have a population, 2,400 are in the highest 5 percent of the baseline distribution. For PM_{2.5}, the concentration at the 95th percentile is 7.76 $\mu\text{g}/\text{m}^3$ (median: 5.18 $\mu\text{g}/\text{m}^3$), and for ozone it is 49.91 ppb (median: 38.34 ppb). In 2045, 144 million people are projected to live within the highest 5 percent of grid cells for PM_{2.5} and 39 million are projected to live in areas with the highest concentrations of ozone (Figure 6-18).

As shown in Table 6-7, in 2045, the number of people of color projected to live within the grid cells with the highest baseline concentrations of ozone (26 million) is nearly double that of NH-Whites (14 million). Thirteen percent of people of color are projected to live in areas with

^{YYYYY} County-level poverty status was mapped to the 12km x 12km grid cell domain using spatial weighting in BenMAP-CE.

the worst baseline ozone, compared to seven percent of NH-Whites. The proposed rule would reduce human exposures to ambient ozone for all population groups, but those in areas with the worst air quality would experience a greater reduction in ozone than those in the remaining 95 percent of grid cells.

Table 6-7: Demographic Analysis of Projected 2045 Ozone Reductions (ppb) from the Proposed Rule, by Race/Ethnicity

			Seasonal Average Ozone Concentrations in ppb (5% to 95% Range)		
	2045 Population - millions		Baseline	Control	Reduction
All 12km x 12km Grid Cells in CONUS (n=47,795)	Total Population in CONUS – All Grid Cells	409	39.2 (29.9 - 49.9)	38.7 (29.4 - 49.5)	0.468 (0.157 - 0.898)
	Non-Hispanic White Population in CONUS	208			
	People of Color Population in CONUS	201			
Highest 5% of Baseline Ozone Concentrations (n=2,391)	Population in Highest 5% (% of Total in CONUS)	39 (10%)	52.6 (50.0 - 58.2)	51.9 (49.6 - 57.2)	0.640 (0.273 - 1.441)
	Non-Hispanic White (% of NH-W in CONUS)	14 (7%)			
	People of Color (% of POC in CONUS)	26 (13%)			
Remaining 95% of Baseline Ozone Concentrations (n=45,404)	Population in Remaining 95% (% of Total in CONUS)	370 (90%)	38.5 (29.8 - 48.7)	38.0 (29.3 - 48.3)	0.457 (0.156 - 0.866)
	Non-Hispanic White (% of NH-W in CONUS)	194 (93%)			
	People of Color (% of POC in CONUS)	176 (86%)			

PM_{2.5} results have a similar pattern to what we observe for ozone. As shown in Table 6-8, in 2045, the number of people of color projected to live within the grid cells with the highest baseline concentrations of PM_{2.5} (93 million) is nearly double that of NH-Whites (51 million). Forty-six percent of people of color are projected to live in areas with the worst baseline PM_{2.5}, compared to 25 percent of NH-Whites. Those in areas with the worst air quality would experience a greater reduction in PM_{2.5} than those in the remaining 95 percent of grid cells.

Table 6-8: Demographic Analysis of Projected 2045 PM_{2.5} Reductions (µg/m³) from the Proposed Rule, by Race/Ethnicity

			Annual Average PM _{2.5} Concentrations in µg/m ³ (5% to 95% Range)		
	2045 Population - millions		Baseline	Control	Reduction
All 12km x 12km Grid Cells in CONUS (n=47,795)	Total Population in CONUS – All Grid Cells	409	5.23 (2.65 - 7.76)	5.21 (2.65 - 7.72)	0.022 (0.003 - 0.052)
	Non-Hispanic White Population in CONUS	208			
	People of Color Population in CONUS	201			
Highest 5% of Baseline PM _{2.5} Concentrations (n=2,391)	Population in Highest 5% (% of Total in CONUS)	144 (35%)	9.03 (7.80 - 12.07)	8.99 (7.76 - 12.01)	0.044 (0.008 - 0.097)
	Non-Hispanic White (% of NH-W in CONUS)	51 (25%)			
	People of Color (% of POC in CONUS)	93 (46%)			
Remaining 95% of Baseline PM _{2.5} Concentrations (n=45,404)	Population in Remaining 95% (% of Total in CONUS)	265 (65%)	5.03 (2.62 - 7.24)	5.01 (2.62 - 7.20)	0.020 (0.003 - 0.049)
	Non-Hispanic White (% of NH-W in CONUS)	156 (75%)			
	People of Color (% of POC CONUS)	108 (54%)			

In Table 6-9 and Table 6-10, we looked at populations above and below 200% of the federal poverty line. Using 2045 population estimates, 126 million people are projected to live below 200% of the poverty line, 13 million (10 percent) of whom would also be living in an area with the worst baseline concentrations of ozone. Similarly, 10 percent of people projected to live above 200% of the poverty line would also be living in an area with the worst baseline concentrations of ozone. For PM_{2.5}, 37 percent of those living below 200% of the poverty line would also be living in areas with the worst baseline concentrations of PM_{2.5}, compared to 35 percent of the population above 200% of the poverty line projected to live in those same areas. While some disparity exists for PM_{2.5}, overall, the results for those above and below 200% of the poverty line are not as pronounced in the areas with the worst air quality as they are for race and ethnicity.

Table 6-9 Demographic Analysis of Projected 2045 Ozone Reductions (ppb) from the Proposed Rule, by Poverty Status

			Seasonal Average Ozone Concentrations in ppb (5% to 95% Range)		
	2045 Population - millions		Baseline	Control	Reduction
All 12km x 12km Grid Cells in CONUS (n=47,795)	Total Population in CONUS – All Grid Cells	409	39.2 (29.9 - 49.9)	38.7 (29.4 - 49.5)	0.468 (0.157 - 0.898)
	Population Below 200% of the Poverty Line in CONUS ^a	126			
	Population Above 200% of the Poverty Line in CONUS	283			
Highest 5% of Baseline Ozone Concentrations (n=2,391)	Population in Highest 5% (% of Total in CONUS)	39 (10%)	52.6 (50.0 - 58.2)	51.9 (49.6 - 57.2)	0.640 (0.273 - 1.441)
	Population Below 200% of the Poverty Line (% Below 200% in CONUS)	13 (10%)			
	Population Above 200% of the Poverty Line (% Below 200% in CONUS)	26 (10%)			
Remaining 95% of Baseline Ozone Concentrations (n=45,404)	Population in Lowest 95% (% of Total in CONUS)	370 (90%)	38.5 (29.8 - 48.7)	38.0 (29.3 - 48.3)	0.457 (0.156 - 0.866)
	Population Below 200% of the Poverty Line (% Below 200% in CONUS)	112 (90%)			
	Population Above 200% of the Poverty Line (% Below 200% in CONUS)	257 (90%)			

^a Note that the poverty measure used here is based on ACS 5-year estimates from 2015 to 2019 at the county level representing the fraction of county-level population below and above 200% of the poverty line. Counts of 2045 population reflect projections based on 2010 Census Data and population growth factors estimated by Woods & Poole (2015). Measures of “current” poverty are not necessarily predictors of future poverty status.

Table 6-10 Demographic Analysis of Projected 2045 PM_{2.5} Reductions (µg/m³) from the HD 2027 Proposed Rule, by Poverty Status

			Annual Average PM _{2.5} Concentrations in µg/m ³ (5% to 95% Range)		
	2045 Population - millions		Baseline	Control	Reduction
All 12km x 12km Grid Cells in CONUS (n=47,795)	Total Population in CONUS – All Grid Cells	409	5.23 (2.65 - 7.76)	5.21 (2.65 - 7.72)	0.022 (0.003 - 0.052)
	Population Below 200% of the Poverty Line in CONUS ^a	126			
	Population Above 200% of the Poverty Line in CONUS	283			
Highest 5% of Baseline PM _{2.5} Concentrations (n=2,391)	Population in Highest 5% (% of Total in CONUS)	144 (35%)	9.03 (7.80 - 12.07)	8.99 (7.76 - 12.01)	0.044 (0.008 - 0.097)
	Population Below 200% of the Poverty Line (% Below 200% in CONUS)	46 (37%)			
	Population Above 200% of the Poverty Line (% Below 200% in CONUS)	98 (35%)			
Remaining 95% of Baseline PM _{2.5} Concentrations (n=45,404)	Population in Lowest 95% (% of Total in CONUS)	265 (65%)	5.03 (2.62 - 7.24)	5.01 (2.62 - 7.20)	0.020 (0.003 - 0.049)
	Population Below 200% of the Poverty Line (% Below 200% in CONUS)	79 (63%)			
	Population Above 200% of the Poverty Line (% Below 200% in CONUS)	185 (65%)			

^a Note that the poverty measure used here is based on ACS 5-year estimates from 2015 to 2019 at the county level representing the fraction of county-level population below and above 200% of the poverty line. Counts of 2045 population reflect projections based on 2010 Census Data and population growth factors estimated by Woods & Poole (2015). Measures of “current” poverty are not necessarily predictors of future poverty status.

The results of this demographic analysis are dependent on the available input data and its associated uncertainty. As we note in both the air quality modeling and health benefits chapters, uncertainties exist along the entire pathway from emissions to air quality to population projections and exposure. The demographic analysis (including poverty status) is subject to these same sources of uncertainty.

A key source of uncertainty is the accuracy of the projected baseline concentrations of PM_{2.5} and ozone because we use modeled 2045 baseline air quality as the basis for our comparisons. Assumptions that influence projections of future air quality include emissions in the future baseline (stationary source emissions are only projected out to year 2028 and held constant out to 2045) and the meteorology used to model air quality (2016 conditions). With this uncertainty in mind, we prefer to examine the air quality impacts of the proposed standards by comparing the baseline scenario to the control scenario in order to highlight incremental changes in air quality due to the proposed standards. By looking at the incremental change, any underlying uncertainty present in both the modeled baseline and control air quality data is largely offset. However, when we rank grid cells from dirtiest to cleanest using 2045 baseline concentrations, the uncertainties associated with the baseline take on greater importance when interpreting the results of the analysis.

There is also inherent uncertainty in the populations projected out to 2045. The projections take into account patterns of economic growth and migration, and to the extent these patterns and assumptions vary over time, so too will the projections of population. We attempted to address some of this uncertainty by compiling race and ethnicity into two broad categories, “people of color” and “NH-White,” to avoid overly precise interpretations of inherently uncertain projections of population and demographics. The Agency continues to investigate how best to incorporate population projections into our analyses to disaggregate populations of concern by relevant socioeconomic variables, and to identify the interactions between demographic changes and air quality changes. The measure of poverty status used in this analysis is based on data from the American Community Survey representing the rate of poverty between 2015-2019 and is not projected to reflect poverty status in the future. This assumption is inherently uncertain, since measures of “current” poverty are not necessarily predictors of future poverty status.

Finally, we note that the control scenario we modeled to support the air quality, benefits, and demographic analyses is slightly different than the proposed Option 1 standards, useful life, and warranty provisions presented in Sections III and IV. Chapter 5.4 of the draft RIA has more detail on the differences between the air quality control scenario and the proposed Option 1 inventories.

Chapter 7 Program Costs

In this chapter, EPA presents estimates of the costs associated with the emissions-reduction technologies that manufacturers could add in response to the proposed rule. We present these not only in terms of the upfront technology costs per engine as presented in Chapter 3 of this draft RIA, but also how those costs would change in the years following implementation. We also present the costs associated with the proposed program elements of extended regulatory useful life and warranty. These technology costs are presented in terms of direct manufacturing costs and associated indirect costs such as warranty and research and development (R&D). The analysis also includes estimates of the possible operating costs associated with the proposed changes--the addition of new technology and extension of warranty and useful life periods. All costs are presented in 2017 dollars consistent with AEO 2018 unless noted otherwise.

The costs presented here are grouped into three main categories, as described below:

- 1) Technology Package Costs: these are the direct costs of new or modified technology—that EPA projects manufacturers would add—and the associated indirect costs that would be involved with bringing those technologies to market (research, development, warranty, etc.). In our analysis, these costs, while first incurred by manufacturers of new engines, are presumed to be passed on to the consumers of those engines (i.e., heavy-duty truck makers and, ultimately, their purchasers/owners).
- 2) Operating Costs: these are the costs associated with the truck and bus operation that are projected to be impacted by the proposal. For example, costs associated with tire replacement are not included since the proposal is not expected to impact tire replacement, but costs associated with repair of emission-related components are included. These costs are incurred by truck and bus purchasers/owners.
- 3) Program Costs: these are the new technology package costs and operating costs combined (the sum of numbers 1 and 2, above). These costs represent our best estimate of the costs to society. As such, any taxes (e.g., fuel taxes) are excluded since taxes represent a transfer payment from one member of society to another with no net cost to society. Total program costs under the two proposed options are presented in terms of calendar year 2045 costs, present value costs, and annualized costs (see Table 7-98 and Table 7-99).^{ZZZZZ}

The cost analysis is done using a tool written in Python and contained in the docket. The Python tool along with some documentation is contained in the docket to this rule and on our website.³⁴⁵

7.1 Technology Package Costs

As noted, individual technology piece costs were presented in Chapter 3. Those costs are, in general, the direct manufacturing costs (DMC) estimated for the first year of proposed implementation. Those costs are used here as a starting point in estimating program costs. As shown in Chapter 3 and in Section 7.1.3 below, the costs associated with the proposed Option 1

^{ZZZZZ} The costs presented in Table 7-98 and Table 7-99 are presented again in Table ES ,which summarizes the net benefits of the two proposed options.

are implemented in two phases--MY2027 and MY2031. Costs associated with proposed Option 2 are implemented in a single phase--MY2027. Following the year in which costs are first incurred for each phase, we have applied a learning effect to represent the cost reductions expected to occur via the "learning by doing" phenomenon.³⁴⁶ This provides a year-over-year cost for each technology as applied to new engine sales. We have then applied industry standard "retail price equivalent (RPE)" markup factors industry-wide, with adjustments discussed below, to estimate indirect costs associated with each technology. Both the learning effects applied to direct costs and the application of markup factors to estimate indirect costs are consistent with the cost estimation approaches used in EPA's past transportation-related regulatory programs.³⁴⁷ The sum of the direct and indirect costs represents our estimate of technology costs per vehicle on a year-over-year basis where MY2031 and later costs include costs associated with the MY2027 and later. These technology costs multiplied by estimated sales then represent the total technology costs associated with the proposed and proposed alternative standards.

This cost calculation approach presumes that the expected technologies would be purchased by original equipment manufacturers (OEMs) from their suppliers. So, while the DMC estimates include the indirect costs and profits incurred by the supplier, the indirect cost markups we apply cover the indirect costs incurred by OEMs to incorporate the new technologies into their vehicles and to cover profit margins typical of the heavy-duty truck industry. We discuss the indirect costs markups in more detail in Section 7.1.2.

As noted in the introductory text to this chapter, these technology package costs (both direct and indirect), while first incurred by manufacturers of new engines, are presumed to be passed on to the consumers of those engines (i.e., heavy-duty truck makers and, ultimately, their purchasers/owners).

7.1.1 Direct Manufacturing Costs

To produce a unit of output, manufacturers incur direct and indirect costs. Direct costs include cost of materials and labor costs. Indirect costs are discussed in the following section. The direct manufacturing costs presented here include individual technology costs for emission-related engine components and for exhaust aftertreatment systems (EAS).

Notably, for this analysis we include not only the marginal increased costs associated with the proposed Options 1 or 2, but also the emission control system costs for the "no action" baseline case (Table 7-5 and Table 7-6).^{AAAAAA} Throughout this discussion we refer to baseline technology costs, or baseline costs, which are meant to reflect our cost estimate of engine systems--that portion that is emission-related--and the exhaust aftertreatment costs absent the impacts of this proposed rule. This inclusion of baseline system costs contrasts with EPA's approach in recent Greenhouse Gas rules or the light-duty Tier 3 criteria pollutant rule where we estimated costs relative to a "no action" baseline case, which obviated the need to estimate baseline costs. We have included baseline costs in this analysis because under both of the proposed options emissions warranty and regulatory useful life provisions would be expected to have some impact on not only the new technology added to comply with the proposed rule, but

^{AAAAAA} See Chapter 5 for more information about the baseline and how that baseline is characterized. For this cost analysis, the baseline, or no action, case consists of engines and emission control systems meeting 2019 era criteria emission standards but in 2027 and later model years. Why we include costs for the no action case is described in this section.

also on any existing emission control systems (See Chapter 3 for more details on proposed Emissions Warranty and Regulatory Useful Life).^{BBBBBB} The baseline direct manufacturing costs detailed below are thus meant to reflect that portion of baseline case engine hardware and aftertreatment systems for which new indirect costs would be incurred due to the proposed warranty and useful life provisions, even absent any changes in the level of emission standards.

We have estimated the baseline engine costs based on recently completed studies by the International Council on Clean Technology (ICCT) as discussed in more detail below. The baseline EAS costs were presented in Chapter 3 of this draft RIA. The estimated marginal technology costs associated with the proposed Options 1 and 2 were also presented in Chapter 3 of this draft RIA.

As noted, the costs shown in Table 7-5 and Table 7-6 include costs for the baseline case.^{CCCCC} For the baseline diesel engine-related costs associated with emission control (i.e., a portion of the fuel system, the EGR system, etc.), we have relied on a white paper done by the International Council on Clean Transportation (ICCT) entitled, “Costs of Emission Reduction Technologies for Heavy-Duty Diesel Vehicles.”³⁴⁸ In Table 14 of that paper, ICCT presented technology costs to meet U.S. standards at different stages for a 12L engine. The different stages of U.S. standards were the 1998, 2004, 2007 and 2010 standards. Relevant portions of ICCT's Table 14—those portions associated with engine-related technologies—are shown in Table 7-1. For the fuel system and the turbo charger, ICCT shows only 50 percent of the total cost and states in the text that, for components that serve other purposes in addition to emission control, only 50% of the cost is considered in their analysis.³⁴⁹ ICCT notes that their costs are likely conservative since they do not consider learning effects applied to the cost estimates associated with each regulatory stage. Lastly, ICCT notes that their cost estimates are stated in 2015 dollars.

Table 7-1: ICCT Cost Estimates of 12L Diesel Engine-Related Emission Control Costs Associated with Past US Emission Standards (2015 dollars)

Air/fuel control and engine out emissions	US 1998	US2004	US2007	US2010
Fuel system—50% of total cost	-	376	38	41
Variable Geometry Turbo (extra cost)—50% of total cost	-	-	185	-
Exhaust Gas Recirculation (EGR) system	-	439	-	-
EGR cooling	-	108	-	-
Total for air/fuel control and engine out emissions	-	923	223	41

In this analysis, EPA has made use of these ICCT cost estimates by first doubling the fuel system and turbo charger costs to get the full cost of those systems (i.e., to undo the halving of those costs done by ICCT). We then added to that result the EGR costs to get a total cost of \$1,827. We have then scaled them based on engine displacement in a manner consistent with our approach to estimating exhaust aftertreatment costs (EAS, see Chapter 3 of this draft RIA). The engine displacements used in our EAS cost estimates were 7, 8 and 13 liters for light, medium

^{BBBBBB} The proposed warranty and useful life provisions would increase costs not only for the marginal technology added in response to the proposal, but also for the technology to which the new technology is added because the proposed warranty and useful life provisions would apply to the emission-control system, not just the marginal technology added in response to the proposed standards.

^{CCCCC} See draft RIA Chapters 1.1 and 1.2 for more information on emission control technologies available on current, or baseline, engines.

and heavy heavy-duty engines, respectively. We have estimated the class 2b and 3 engines as equivalent to the light heavy-duty (7L) and the urban bus engines as equivalent to the medium-duty (8L) engines. The resultant diesel engine-related costs used in this analysis are shown in Table 7-2.

Table 7-2: Diesel Engine-Related Emission Control System Costs in the "No Action" Baseline*

	LHD2b3	LHD45	MHD67	HHD8	Urban bus
Engine displacement	7	7	8	13	8
Displacement based scalar	7/12=0.58	7/12=0.58	8/12=0.67	13/12=1.08	8/12=0.67
Baseline cost, 2015 dollars (1,827 times Displacement based scalar)	\$1,066	\$1,066	\$1,218	\$1,979	\$1,218
Baseline cost, 2017 dollars (1.03 GPD deflator Baseline cost in 2015 dollars)*	\$1,097	\$1,097	\$1,254	\$2,038	\$1,254

* See Table 7-8 and associated text for information on the GDP deflators used in this analysis; costs shown are by MOVES regulatory class; there are a small number of diesel engines used in LHD2b3 that are engine (rather than chassis) certified and are, therefore, expected to incur costs associated with the proposed rule.

For the baseline gasoline engine-related costs associated with emission control (i.e., a portion of the fuel system, etc.), we have relied on a white paper done by ICCT entitled, “Estimated Cost of Emission Reduction Technologies for Light-Duty Vehicles.”³⁵⁰ In Table 4-10 of that paper, ICCT presented technology costs to meet U.S. light-duty Tier 2, Bin 5 for a 4.5L engine. The ICCT estimate shown was \$306. ICCT notes that their cost estimates are stated in 2011 dollars.

In this analysis, EPA has made use of this ICCT cost estimate by scaling them based on engine displacement from the 4.5L light-duty displacement assumed by ICCT to a more typical gasoline HD engine displacement of 7L. The resultant gasoline engine-related costs used in this analysis are shown in Table 7-3.

Table 7-3: Gasoline Engine-Related Emission Control System Costs in the "No Action" Baseline*

	LHD45	MHD67	HHD8
Engine displacement	7	7	7
Displacement based scalar	7/4.5=1.56	7/4.5=1.56	7/4.5=1.56
Baseline cost, 2011 dollars (306 times Displacement based scalar)	\$476	\$476	\$476
Baseline cost, 2017 dollars (1.099 GPD deflator Baseline cost in 2011 dollars)*	\$523	\$523	\$523

* See Table 7-8 and associated text for information on the GDP deflators used in this analysis; note that there are no engine certified LHD2b3 gasoline engines and, therefore, none are expected to incur costs associated with this proposed rule.

For the baseline CNG engine-related costs associated with emission control (a portion of the fuel system, etc.), we have relied on the ICCT baseline gasoline costs presented in Table 7-3, but have scaled those costs based on more typical diesel engine displacements because CNG engines tend to be converted diesel engines but with fuel systems more typical of gasoline engines. The diesel engine displacements used for scaling gasoline costs were presented in Table 7-2. The resultant baseline engine-related CNG costs are shown in Table 7-4.

Table 7-4: CNG Engine-Related Emission Control System Costs in the "No Action" Baseline*

	HHD8	Urban bus
Engine displacement	12	9
Displacement based scalar	12/4.5=2.67	8/4.5=2.0
Baseline cost, 2011 dollars (306 times Displacement based scalar)	\$816	\$612
Baseline cost, 2017 dollars (1.099 GPD deflator * Baseline cost in 2011 dollars)*	\$896	\$672

* See Table 7-8 and associated text for information on the GDP deflators used in this analysis.

For cylinder deactivation costs under the proposed Options 1 or 2, we have used FEV-conducted teardown-based cylinder deactivation costs as presented in Chapter 3 of this draft RIA.³⁵¹ The marginal technology costs for exhaust aftertreatment components--also detailed and presented in Chapter 3 of this draft RIA--are based on an ICCT methodology with extensive revision by EPA. As discussed in draft RIA Chapter 3, we also have EAS cost estimates from a recent FEV-conducted teardown study.³⁵² These teardown-based estimated EAS costs are similar to the EPA-estimated costs and we may use those FEV-study teardown-based cost estimates in the final rule.

The cost basis (the year dollars) for many of these costs were also presented in a mixed set of cost basis years. For the cost analysis presented here, we use 2017 dollars throughout the analysis for consistency with the AEO 2018 data upon which our MOVES emissions inventory results are based. The costs presented in Chapter 3 are repeated in Table 7-5 for diesel regulatory classes, in Table 7-6 for gasoline regulatory classes, and in Table 7-7 for CNG regulatory classes with the exception that all values presented here are updated to a consistent 2017 dollar basis.^{DDDDDD} See Chapter 5.2 for a discussion of regulatory classes. Table 7-8 shows the gross-domestic product price deflators used to adjust to 2017 dollars. Note that we have estimated costs for regulatory classes that exist in our MOVES runs (see Chapter 5 of this draft RIA) to remain consistent with the inventory impacts we have estimated. Note also that, throughout this section, LHD=light heavy-duty, MHD=medium heavy-duty, HHD=heavy heavy-duty, CDPF=catalyzed diesel particulate filter, DOC=diesel oxidation catalyst, SCR=selective catalytic reduction, HC=hydrocarbon, CNG=compressed natural gas.

^{DDDDDD} The MY2019 engine and aftertreatment costs estimates presented in draft RIA Chapters 3.1.5 and 3.2.3 are used as the MY2027 baseline cost in the tables in this draft RIA Chapter 7.1.1.

Table 7-5 Diesel Technology and Package Direct Manufacturing Costs per Engine by Regulatory Class, 2017 dollars*

MOVES Regulatory Class	Technology	Baseline	Proposed Option 1 (MY2027 increment to Baseline)	Proposed Option 2 (MY2027 increment to Baseline)
LHD2b3	LHD Package	\$3,788	\$1,616	\$1,616
	Engine hardware	\$1,097	\$0	\$0
	Closed crankcase	\$0	\$0	\$0
	Cylinder deactivation	\$0	\$196	\$196
	CDPF	\$504	\$0	\$0
	DOC	\$350	\$0	\$0
	SCR	\$1,837	\$1,174	\$1,174
	Canning	\$0	\$30	\$30
	HC dosing	\$0	\$216	\$216
LHD45	LHD45 Package	\$3,806	\$1,653	\$1,653
	Engine hardware	\$1,097	\$0	\$0
	Closed crankcase	\$18	\$37	\$37
	Cylinder deactivation	\$0	\$196	\$196
	CDPF	\$504	\$0	\$0
	DOC	\$350	\$0	\$0
	SCR	\$1,837	\$1,174	\$1,174
	Canning	\$0	\$30	\$30
	HC dosing	\$0	\$216	\$216
MHD67	MHD67 Package	\$4,032	\$1,619	\$1,619
	Engine hardware	\$1,254	\$0	\$0
	Closed crankcase	\$18	\$37	\$37
	Cylinder deactivation	\$0	\$147	\$147
	CDPF	\$570	\$0	\$0
	DOC	\$316	\$0	\$0
	SCR	\$1,875	\$1,183	\$1,183
	Canning	\$0	\$36	\$36
	HC dosing	\$0	\$216	\$216
HHD8	HHD8Package	\$6,457	\$2,210	\$2,210
	Engine hardware	\$2,038	\$0	\$0
	Closed crankcase	\$18	\$37	\$37
	Cylinder deactivation	\$0	\$206	\$206
	CDPF	\$1,067	\$0	\$0
	DOC	\$585	\$0	\$0
	SCR	\$2,750	\$1,681	\$1,681
	Canning	\$0	\$71	\$71
	HC dosing	\$0	\$216	\$216
Urban bus	Urban bus Package	\$4,082	\$1,653	\$1,653
	Engine hardware	\$1,254	\$0	\$0
	Closed crankcase	\$18	\$37	\$37
	Cylinder deactivation	\$0	\$147	\$147
	CDPF	\$567	\$0	\$0
	DOC	\$314	\$0	\$0
	SCR	\$1,929	\$1,469	\$1,469
	Canning	\$0	\$0	\$0
	HC dosing	\$0	\$0	\$0

* Note that the analysis uses the baseline plus the alternative cost--i.e., Baseline+Proposed Option 1, or Baseline+Proposed Option 2 when estimating total costs; the incremental costs are shown here for ease of understanding the increased costs associated with each option.

Table 7-6 Gasoline Technology and Package Direct Manufacturing Costs per Engine by Regulatory Class, 2017 dollars*

MOVES Regulatory Class	Technology	Baseline	Proposed Option 1 (MY2027 increment to Baseline)	Proposed Option 2 (MY2027 increment to Baseline)
LHD45	LHD45 Package	\$832	\$417	\$417
	Engine hardware	\$523	\$0	\$0
	Aftertreatment	\$309	\$393	\$393
	ORVR	\$0	\$24	\$24
MHD67	MHD67 Package	\$832	\$417	\$417
	Engine hardware	\$523	\$0	\$0
	Aftertreatment	\$309	\$393	\$393
	ORVR	\$0	\$24	\$24
HHD8	HHD8 Package	\$832	\$417	\$417
	Engine hardware	\$523	\$0	\$0
	Aftertreatment	\$309	\$393	\$393
	ORVR	\$0	\$24	\$24

* Note that the analysis uses the baseline plus the alternative cost--i.e., Baseline+Proposed Option 1, or Baseline+Proposed Option 2 when estimating total costs; the incremental costs are shown here for ease of understanding the increased costs associated with each option.

Table 7-7: CNG Technology and Package Direct Manufacturing Costs per Engine by Regulatory Class, 2017 dollars*

MOVES Regulatory Class	HHD8 Package	Baseline	Proposed Option 1 (MY2027 increment to Baseline)	Proposed Option 1 (MY2030 increment to MY2027)	Proposed Option 2 (MY2027 increment to Baseline)
HHD8	HHD8 Package	\$4,108	\$27	\$27	\$27
	Engine hardware	\$896	\$0	\$0	\$0
	Aftertreatment	\$3,212	\$27	\$27	\$27
Urban bus	Urban bus Package	\$3,081	\$19	\$19	\$19
	Engine hardware	\$672	\$0	\$0	\$0
	Aftertreatment	\$2,409	\$19	\$19	\$19

* Note that the analysis uses the baseline plus the alternative cost--i.e., Baseline+Proposed Option 1, or Baseline+Proposed Option 1 or Baseline+Alternative2 when estimating total costs; the incremental costs are shown here for ease of understanding the increased costs associated with each option.

Table 7-8: GDP Price Deflators* Used to Adjust Costs to 2017 Dollars

Cost Basis Year	Conversion Factor
2011	1.099
2015	1.030
2017	1.000
2018	0.977
2019	0.959

* Based on the National Income and Product Accounts, Table 1.1.4 Price Indexes for Gross Domestic Product, Bureau of Economic Analysis, U.S. Department of Commerce, December 20, 2019.

The direct costs are then adjusted to account for learning effects going forward from the first year of implementation. To make that adjustment, the following equation is used.³⁵³

$$y_{t+1} = \left(\frac{x_{t+1}}{x_t} \right)^b y_t$$

Where,

y_t = cost (or price) of a given item at time t

x_t = cumulative production of a given item at time t

x_{t+1} = cumulative production of a given item at time $t+1$

b = the learning rate

In this cost analysis, EPA makes an adjustment to this standard formula by inserting a “seed volume factor” meant to represent the number of years of sales of a technology leading to learning prior to the year for which the technology’s cost estimate is intended (model years 2027 or 2030 as indicated in Table 7-5 and Table 7-6). In other words, manufacturers may sell some of the systems expected for compliance with the proposed rule in years prior to the first year of the new standards, thereby learning and realizing cost reductions in that time. The value of this seed volume factor might be 0 to represent a new, unsold technology, or any value >0 to represent a relatively new technology having had some sales in prior years. A seed volume factor of 0 places the technology at the beginning of the learning curve and, therefore, subsequent learning effects (i.e., cost reductions) will be most rapid in the years immediately following the first year of implementation. An increasing seed volume factor serves to move the effects of learning further along the curve making subsequent learning effects less dramatic in the years immediately following the first year of the analysis. Figure 7-1 shows the effect of the seed volume factor on the levels of learning applied to the direct manufacturing costs assuming constant sales year-over-year and a learning rate of -0.245.^{EEEEEE}

^{EEEEEE} In effect, the “seed volume factor” sets the cumulative number of units produced by an organization, which is a required data point to estimate the conventional form of the learning curve. Throughout this analysis, we have used a learning rate of -0.245 as developed for EPA by ICF and a foremost Subject Matter Expert in, “Cost Reduction through Learning in Manufacturing Industries and in the Manufacture of Mobile Sources, Final Report and Peer Review Report,” EPA-420-R-16-018, November 2016.

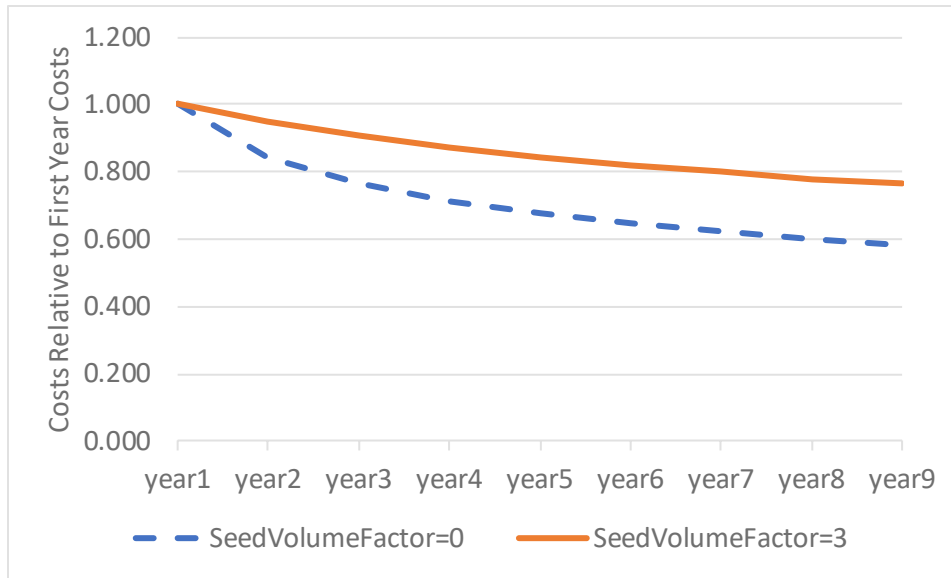


Figure 7-1: Costs Relative to First Year Costs using Different Seed Volume Factors

In the end, the learning effects are calculated using the following formula.

$$y_t = \left(\frac{x_t + (Sales_{t=0} * SeedVolumeFactor)}{Sales_{t=0} + (Sales_{t=0} * SeedVolumeFactor)} \right)^b y_{t=0}$$

Where,

b = the learning rate (-0.245 in this analysis)

$y_{t=0}$ = estimated direct cost in the first year of implementation (e.g., MY2027 or MY2030)

$Sales_{t=0}$ = sales in the first year of implementation (e.g., MY2027 or MY2030)

SeedVolumeFactor = 0 or greater to represent the number of years of learning already having occurred on a technology

x_t = the cumulative sales of vehicles complying with the new standard (equal to first year sales in the first year of implementation, first year sales plus second year sales in the second year of implementation, etc.)

To illustrate the seed volume factor, if we assume the learning rate, b , is -0.245 (the value used in this analysis), the direct cost in the first year of implementation, $y_{t=0}$, is \$100, the sales in the first year of implementation, $Sales_{t=0}$, is 1000 engines, and the seed volume factor is 0 (i.e., no learning having occurred prior to the first year of the analysis), then the cost, y_t , would be \$100. This is because the cumulative production in year t , x_t , equals $Sales_{t=0}$ in the first year of implementation leaving the formula as:

$$(1)^{-0.245} * \$100 = \$100$$

If the sales in the following year were an additional 1000 engines, the cost would decrease to \$84 since x_t would now be 2000 and the formula would be:

$$\left(\frac{2000}{1000} \right)^{-0.245} * \$100 = \$84$$

If the seed volume factor is set to 3 (i.e., to approximate 3 years of learning prior to the first year of the analysis, then the cost in 2027 would again be \$100 since the formula would be

$$\left(\frac{1000 + (3 * 1000)}{1000 + (3 * 1000)} \right)^{-0.245} * \$100 = \$100$$

However, in 2028, the formula would be

$$\left(\frac{2000 + (3 * 1000)}{1000 + (3 * 1000)} \right)^{-0.245} * \$100 = \$95$$

With 3 years of learning estimated to have already occurred, the costs going forward from the first year reduce at a slower pace than in the previous example. Therefore, increasing the seed volume factor results in less rapid learning effects going forward. The seed volume factors used in this analysis are shown in Table 7-9. A factor of 10 has been used for the baseline technologies since those technologies will have undergone considerable learning by 2027. We have used a factor of 3 for the proposed Options 1 and 2 to reflect at least 3 years of sales with technologies very similar to those expected under the proposed options thereby resulting in conservative learning-based cost reductions moving forward from 2027.

Table 7-9: Seed volume factors used in this analysis for each Option

Fuel	Regulatory Class	Baseline	Proposed Option 1 (MY2027 increment to Baseline)	Proposed Option 2 (MY2027 increment to Baseline)
Diesel	LHD	10	3	3
	LHD45	10	3	3
	MHD67	10	3	3
	HHD8	10	3	3
	Urban Bus	10	3	3
Gasoline	LHD45	10	3	3
	MHD67	10	3	3
	HHD8	10	3	3
CNG	HHD8	10	3	3
	Urban Bus	10	3	3

Learning factors were applied on a technology package cost basis, and MOVES projected sales volumes were used to determine first year sales ($Sales_{t=0}$) and cumulative sales (x_t). The resultant direct manufacturing costs and how those costs reduce over time are presented in both Chapter 7.1.3 (on a per vehicle basis) and in Chapter 7.3.1 (on a total cost basis).

7.1.2 **Indirect 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 ensure that regulatory analysis capture the changes in indirect costs, markup factors, which relate total indirect costs to total direct costs, have been developed and used by EPA and other stakeholders. These factors are often referred to as retail price equivalent (RPE) multipliers. RPE multipliers provide, at an aggregate level, the relative shares of revenues, where:

$$\text{Revenue} = \text{Direct Costs} + \text{Indirect Costs}$$

so that:

$$\text{Revenue/Direct Costs} = 1 + \text{Indirect Costs/Direct Costs} = \text{RPE}$$

and,

$$\text{Indirect Costs} = \text{Direct Costs} \times (\text{RPE} - 1).$$

If the relationship between revenues and direct costs (i.e., RPE) can be shown to equal an average value over time, then an estimate of direct costs can be multiplied by that average value to estimate revenues, or total costs. Further, that difference between estimated revenues, or total costs, and estimated direct costs can be taken as the indirect costs. Cost analysts and regulatory agencies have frequently used these multipliers to predict the resultant impact on costs associated with manufacturers' responses to regulatory requirements and we are using that approach in this analysis.

Using RPE multipliers implicitly assumes that incremental changes in direct manufacturing costs produce common incremental changes in all indirect cost contributors as well as net income. In the past, EPA has expressed a concern with using the RPE multiplier for all technologies, because it is not likely that the indirect costs of vehicle modifications are the same for all technologies.³⁵⁴ 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 RPEs, with their 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. EPA developed an alternative indirect cost methodology--the Indirect Cost Multiplier (ICM)--to address those concerns.³⁵⁵

The cost of different technologies was an important distinction in modeling efforts supporting EPA's greenhouse gas rulemakings (GHG) since a variety of GHG technologies were available to manufacturers and EPA wanted to project which combinations of technologies were most cost effective toward achieving compliance. For this proposed rule, we do not have that consideration since we are projecting the same technologies for all vehicles within a given regulatory class and are not attempting to project from a variety of technologies which are most cost effective toward achieving compliance. For that reason, EPA is using the RPE approach to estimate indirect costs in this analysis.

RPEs themselves are also inherently difficult to estimate because the accounting statements of manufacturers do not neatly categorize all cost elements as either direct or indirect costs. Hence, each researcher developing an RPE estimate must apply a certain amount of judgment to the allocation of the costs.³⁵⁶

This cost analysis estimates indirect costs by applying markup factors used in past rulemakings setting new greenhouse gas standards for heavy-duty trucks.³⁵⁷ The markup factors are based on financial filings with the Securities and Exchange Commission for several engine and engine/truck manufacturers in the heavy-duty industry as detailed in a study done by RTI International for EPA.³⁵⁸ The RPE factors developed by RTI for HD engine manufacturers, HD truck manufacturers and for the HD truck industry as a whole are shown in Table 7-10.^{FFFFF} Also shown in Table 7-10 are the RPE factors developed by RTI for light-duty vehicle manufacturers.³⁵⁹

Table 7-10: Retail Price Equivalent Factors in the Heavy-Duty and Light-Duty Industries

Cost Contributor	HD Engine Manufacturer	HD Truck Manufacturer	HD Truck Industry	LD Vehicle Industry
Direct manufacturing cost	1.00	1.00	1.00	1.00
Warranty	0.02	0.04	0.03	0.03
R&D	0.04	0.05	0.05	0.05
Other (admin, retirement, health, etc.)	0.17	0.22	0.29	0.36
Profit (cost of capital)	0.05	0.05	0.05	0.06
RPE	1.28	1.36	1.42	1.50

For this analysis, EPA has based cost estimates for diesel and CNG regulatory classes on the HD Truck Industry values shown in Table 7-10. Because most of the proposed changes apply to engines, we first considered using the HD Engine Manufacturer values. However, the industry is becoming more vertically integrated and the costs we are trying to estimate are those that occur at the end purchaser, or retail, level. For that reason, we believe that the truck industry values represent the factors of most interest to this analysis. For gasoline regulatory classes, we have used the LD Vehicle Industry values shown in Table 7-10. We have chosen those values since they more closely represent the cost structure of manufacturers in that industry--Ford, General Motors, and Fiat Chrysler.

Of the cost contributors listed in Table 7-10, Warranty and R&D are the elements of indirect costs that the proposed requirements are expected to impact. As discussed in Chapter 3 of this draft RIA, EPA is proposing to lengthen the warranty period, which we expect to increase the contribution of warranty costs to the RPE. EPA is also proposing to extend the regulatory useful life, which we expect to result in increased R&D expenses as systems are developed to deal with the longer life during which compliance with standards would be required. We would expect that the minor OBD-related R&D efforts being proposed--an expanded list of public OBD parameters and expanded scan tool tests discussed in Section IV.C of the preamble--could be done given the R&D estimated here. Profit is listed to highlight that profit is being considered and included in the analysis. All other indirect cost elements--those encapsulated by the "Other" category, including General and Administrative Costs, Retirement Costs, Healthcare Costs, and other

^{FFFFF} The engine manufacturers included were Hino and Cummins; the truck manufacturers included were PACCAR, Navistar, Daimler and Volvo. Where gaps existed such as specific line items not reported by these companies due to differing accounting practices, data from the Heavy Duty Truck Manufacturers Industry Report by Supplier Relations LLC (2009) and Census (2009) data for Other Engine Equipment Manufacturing Industry (NAICS 333618) and Heavy Duty Truck Manufacturing Industry (NAICS 336120) were used to fill the gaps. This is detailed in the study report at Appendix A.1.

overhead costs--as well as Profits, are expected to scale according to their historic levels of contribution.

As mentioned, Warranty and R&D are the elements of indirect costs that the proposed requirements are expected to impact. Warranty expenses are the costs that a business expects to or has already incurred for the repair or replacement of goods that it has sold. The total amount of warranty expense is limited by the warranty period that a business typically allows. After the warranty period for a product has expired, a business no longer incurs a warranty liability; thus, a longer warranty period results in a longer period of liability for a product. At the time of sale, companies are expected to set aside money in a warranty liability account to cover any potential future warranty claims. If and when warranty claims are made by customers, the warranty liability account is debited and a warranty claims account is credited to cover warranty claim expenses.

To address the expected increased indirect cost contributions associated with warranty (increased funding of the warranty liability account) due to the proposed longer warranty requirements, we have applied scaling factors commensurate with the changes in proposed Options 1 or 2 to the number of miles included in the warranty period (i.e., VMT-based scaling factors). For example, the current required emission warranty periods for Class 8 diesel trucks are 5 years or 100,000 miles. Proposed Option 1 would extend the required warranty period for a Class 8 diesel to 7 years or 450,000 miles for MYs 2027 through 2030, and then extend further to 10 years or 600,000 miles for MYs 2031 and beyond. As such, in our analysis of proposed Option 1 for Class 8 diesel trucks we applied a scaling factor of 4.5 (450/100) to the 0.03 warranty contribution factor for MYs 2027 through 2030, and applied a scaling factor of 6.0 (600/100) for MYs 2031 and later. This same approach is followed for the other regulatory classes, and for our analysis of proposed Option 2.

Similarly, for R&D on that same Class 8 truck, the proposed Option 1 would extend regulatory useful life from 10 years or 435,000 miles to 11 years or 600,000 miles beginning in MY2027, and then extend further to 12 years or 800,000 miles for MYs 2031 and later, we have applied a scaling factor of 1.38 (600/435) to the 0.05 R&D contribution factor for MYs 2027 through 2029, and then 1.33 (800/600) for MYs 2031 through 2033. Notice the different treatment of the scaling factors for R&D versus those for warranty. We would expect that once the development efforts into longer useful life is complete, increased expenditures would return to their normal levels of contribution. As such, we have implemented the R&D scalars in three-year increments (2027 through 2029 under proposed Options 1 and 2, and then 2031 through 2033 under proposed Option 1). In MY2034 and later (under the proposed Option 1) and in MY2029 and later in proposed Options 1 and 2, the R&D scaling factor would no longer be applied.

The VMT-based scaling factors applied to warranty and R&D cost contributors used in our cost analysis of proposed Options 1 and 2 are shown in Table 7-11 for diesel and CNG regulatory classes and in Table 7-12 for gasoline regulatory classes.

Table 7-11: Scaling Factors Applied to RPE Contribution Factors to Reflect Changes in their Contributions, Diesel & CNG Regulatory Classes*

Scenario	MOVES Regulatory Class	Warranty Scalars		R&D Scalars		
		MY2027 through MY2030	MY2031+	MY2027 through MY2029	MY2031 through MY2033	MY2034+
Baseline	LHD	1.00	1.00	1.00	1.00	1.00
	LHD45	1.00	1.00	1.00	1.00	1.00
	MHD67	1.00	1.00	1.00	1.00	1.00
	HHD8	1.00	1.00	1.00	1.00	1.00
	Urban Bus	1.00	1.00	1.00	1.00	1.00
Option 1	LHD	1.50	2.10	1.73	1.42	1.00
	LHD45	1.50	2.10	1.73	1.42	1.00
	MHD67	2.20	2.80	1.46	1.30	1.00
	HHD8	4.50	6.00	1.38	1.33	1.00
	Urban Bus	4.50	6.00	1.38	1.33	1.00
Option 2	LHD	1.10	1.10	2.27	1.00	1.00
	LHD45	1.10	1.10	2.27	1.00	1.00
	MHD67	1.50	1.50	1.76	1.00	1.00
	HHD8	3.50	3.50	1.49	1.00	1.00
	Urban Bus	3.50	3.50	1.49	1.00	1.00

Table 7-12: Scaling Factors Applied to RPE Contribution Factors to Reflect Changes in their Contributions, Gasoline Regulatory Classes

Scenario	MOVES Regulatory Class	Warranty Scalars		R&D Scalars		
		MY2027 through MY2030	MY2031+	MY2027 through MY2029	MY2031 through MY2033	MY2034+
Baseline	LHD45	1.00	1.00	1.00	1.00	1.00
	MHD67	1.00	1.00	1.00	1.00	1.00
	HHD8	1.00	1.00	1.00	1.00	1.00
Option 1	LHD45	2.20	3.20	1.41	1.29	1.00
	MHD67	2.20	3.20	1.41	1.29	1.00
	HHD8	2.20	3.20	1.41	1.29	1.00
Option 2	LHD45	2.20	2.20	1.82	1.00	1.00
	MHD67	2.20	2.20	1.82	1.00	1.00
	HHD8	2.20	2.20	1.82	1.00	1.00

Lastly, as mentioned in section 7.1.1, the markups for estimating indirect costs are applied to our estimates of the absolute direct manufacturing costs for emission-control technology shown in Table 7-5, Table 7-6 and Table 7-7, not just the incremental costs associated with the proposal (i.e., the Baseline+Proposed Option 1 and Baseline+Proposed Option 2 costs, not just the incremental costs of proposed Option 1 or 2).^{GGGGG} This is an important element of the analysis as shown by the example in Table 7-13. In the example, which is only for illustration, we assume that the baseline technology cost is \$5000, the proposed incremental cost is \$1000, and the indirect cost warranty contribution is 0.03 with a simple scalar of 1.5 associated with a longer

^{GGGGG} Increased indirect costs are included for the baseline technology because the extended warranty and useful life provisions would impact those technologies too, not just the new, incremental technology.

warranty period. In this case, the costs could be calculated according to two approaches as shown. By including the baseline costs, we are estimating considerable new warranty costs in the proposal as illustrated by the example where including baseline costs results in warranty costs of \$270 while excluding baseline costs results in warranty costs of just \$45.^{HHHHHH}

Table 7-13: Simplified Example of Indirect Warranty Costs Calculated on an Incremental vs. Absolute Technology Package Cost (values are not from the analysis and are for presentation only)

	Excluding Baseline Costs	Including Baseline Costs
Direct Manufacturing Cost (DMC)	\$1000	\$5000 + \$1000 = \$6000
Indirect Warranty Costs	$\$1000 \times 0.03 \times 1.5 = \45	$\$6000 \times 0.03 \times 1.5 = \270
DMC + Warranty	$\$1000 + \$45 = \$1045$	$\$1000 + \$270 = \$1270$

We are aware of a recent study conducted by the National Renewable Energy Lab (NREL) for the California Air Resources Board (CARB).³⁶⁰ In that study, NREL surveyed parts suppliers and engine/vehicle manufacturers regarding estimated costs associated with the technologies being considered within the context of CARB's Heavy-Duty Low NO_x program. As part of that study, NREL considered costs associated with increased warranties and increased useful life periods being considered by CARB. Our understanding is that, while the costs associated with warranty and useful life are quite high, they were in fact estimates associated with complete system replacement at some point during the useful life of the engine/vehicle. We have assumed that manufacturers would not pursue such an approach and would, instead, include upfront (i.e., at the point of end user purchase) with the expectation that the parts would last the full useful life without a mandatory replacement. Such has been the practice in industry by and large since emission controls were introduced in the 1970s and 1980s. For that reason, we have chosen not to use the warranty and useful life estimates presented by NREL and have instead used the approach described here. CARB has more recently published their Omnibus analysis, but we have not had time to adequately digest the details of that analysis to adequately compare it to the analysis we have done.

7.1.3 Technology Costs per Vehicle

The following tables present the technology costs estimated for the proposed Options 1 and 2 on a per-vehicle basis for MY2027 and for MY2031. Reflected in these tables are learning effects on direct manufacturing costs and scaling effects--associated with increased costs due to proposed program elements--on indirect costs. The sum is also shown and reflects the cost per vehicle in the specific model year that would be multiplied by sales to estimate the total costs associated with each proposed option.^{IIIIII} Also reflected in these tables is the phase-in of implementation for the proposed Option 1 and the differences between the proposed options due to different standard levels and different warranty and useful life provisions.

^{HHHHHH} As noted earlier, we have included baseline costs in this analysis because the proposed emissions warranty and regulatory useful life provisions would be expected to have some impact on not only the new technology added to comply with the proposed standards, but also on any existing emission control systems (See Chapter 3 for more details on proposed Emissions Warranty and Regulatory Useful Life).

^{IIIIII} Note that we have not estimated sales impacts associated with the proposed rule (see Chapter 10), so sales projections are equivalent across scenarios.

Note that, while we show costs per vehicle here, it is important to remember that these are costs and not prices. We make no effort at estimating how manufacturers would price their products. Manufacturers may pass costs along to purchasers via price increases in a manner consistent with what we show here. However, manufacturers may also price certain products higher than what we show while pricing others lower--the higher-priced products thereby subsidizing the lower-priced products. This is true in any market, not just the heavy-duty highway industry. This is perhaps especially true with respect to the indirect costs we have estimated because, for example, R&D done to improve emission durability can readily transfer across different engines but the technology added to an engine is uniquely tied to that engine.

Table 7-14: MY2027 Technology Costs for LHD2b3 Diesel, Average per Vehicle, 2017 Dollars

Scenario	DMC	Warranty	R&D	Other	Profit	Tech Cost Sum
Baseline	\$3,788	\$114	\$189	\$1,099	\$189	\$5,379
Baseline+Proposed Option 1	\$5,404	\$243	\$467	\$1,567	\$270	\$7,952
Baseline+Proposed Option 2	\$5,404	\$178	\$614	\$1,567	\$270	\$8,034
Option 1 increase from Baseline	\$1,616	\$130	\$277	\$469	\$81	\$2,572
Option 2 increase from Baseline	\$1,616	\$65	\$425	\$469	\$81	\$2,655

Table 7-15: MY2031 Technology Costs for LHD2b3 Diesel, Average per Vehicle, 2017 Dollars

Scenario	DMC	Warranty	R&D	Other	Profit	Tech Cost Sum
Baseline	\$3,504	\$105	\$175	\$1,016	\$175	\$4,976
Baseline+Proposed Option 1	\$4,863	\$306	\$346	\$1,410	\$243	\$7,168
Baseline+Proposed Option 2	\$4,863	\$160	\$243	\$1,410	\$243	\$6,920
Option 1 increase from Baseline	\$1,358	\$201	\$170	\$394	\$68	\$2,192
Option 2 increase from Baseline	\$1,358	\$55	\$68	\$394	\$68	\$1,944

Table 7-16: MY2027 Technology Costs for LHD45 Diesel, Average per Vehicle, 2017 Dollars

Scenario	DMC	Warranty	R&D	Other	Profit	Tech Cost Sum
Baseline	\$3,806	\$114	\$190	\$1,104	\$190	\$5,405
Baseline+Proposed Option 1	\$5,459	\$246	\$471	\$1,583	\$273	\$8,032
Baseline+Proposed Option 2	\$5,459	\$180	\$620	\$1,583	\$273	\$8,115
Option 1 increase from Baseline	\$1,653	\$131	\$281	\$479	\$83	\$2,627
Option 2 increase from Baseline	\$1,653	\$66	\$430	\$479	\$83	\$2,710

Table 7-17: MY2031 Technology Costs for LHD45 Diesel, Average per Vehicle, 2017 Dollars

Scenario	DMC	Warranty	R&D	Other	Profit	Tech Cost Sum
Baseline	\$3,515	\$105	\$176	\$1,019	\$176	\$4,991
Baseline+Proposed Option 1	\$4,900	\$309	\$348	\$1,421	\$245	\$7,223
Baseline+Proposed Option 2	\$4,900	\$162	\$245	\$1,421	\$245	\$6,973
Option 1 increase from Baseline	\$1,385	\$203	\$172	\$402	\$69	\$2,232
Option 2 increase from Baseline	\$1,385	\$56	\$69	\$402	\$69	\$1,982

Table 7-18: MY2027 Technology Costs for MHD67 Diesel, Average per Vehicle, 2017 Dollars*

Scenario	DMC	Warranty	R&D	Other	Profit	Tech Cost Sum
Baseline	\$4,032	\$121	\$202	\$1,169	\$202	\$5,725
Baseline+Proposed Option 1	\$5,651	\$373	\$412	\$1,639	\$283	\$8,358
Baseline+Proposed Option 2	\$5,651	\$254	\$496	\$1,639	\$283	\$8,323
Option 1 increase from Baseline	\$1,619	\$252	\$211	\$470	\$81	\$2,632
Option 2 increase from Baseline	\$1,619	\$133	\$295	\$470	\$81	\$2,598

Table 7-19: MY2031 Technology Costs for MHD67 Diesel, Average per Vehicle, 2017 Dollars*

Scenario	DMC	Warranty	R&D	Other	Profit	Tech Cost Sum
Baseline	\$3,723	\$112	\$186	\$1,080	\$186	\$5,287
Baseline+Proposed Option 1	\$5,080	\$427	\$329	\$1,473	\$254	\$7,563
Baseline+Proposed Option 2	\$5,080	\$229	\$254	\$1,473	\$254	\$7,290
Option 1 increase from Baseline	\$1,357	\$315	\$143	\$394	\$68	\$2,276
Option 2 increase from Baseline	\$1,357	\$117	\$68	\$394	\$68	\$2,003

Table 7-20 MY2027 Technology Costs for HHD8 Diesel, Average per Vehicle, 2017 Dollars

Scenario	DMC	Warranty	R&D	Other	Profit	Tech Cost Sum
Baseline	\$6,457	\$194	\$323	\$1,873	\$323	\$9,169
Baseline+Proposed Option 1	\$8,668	\$1,170	\$598	\$2,514	\$433	\$13,382
Baseline+Proposed Option 2	\$8,668	\$910	\$648	\$2,514	\$433	\$13,172
Option 1 increase from Baseline	\$2,210	\$976	\$275	\$641	\$111	\$4,213
Option 2 increase from Baseline	\$2,210	\$716	\$325	\$641	\$111	\$4,003

Table 7-21: MY2031 Technology Costs for HHD8 Diesel, Average per Vehicle, 2017 Dollars

Scenario	DMC	Warranty	R&D	Other	Profit	Tech Cost Sum
Baseline	\$5,961	\$179	\$298	\$1,729	\$298	\$8,465
Baseline+Proposed Option 1	\$7,813	\$1,406	\$521	\$2,266	\$391	\$12,396
Baseline+Proposed Option 2	\$7,813	\$820	\$391	\$2,266	\$391	\$11,680
Option 1 increase from Baseline	\$1,851	\$1,227	\$223	\$537	\$93	\$3,931
Option 2 increase from Baseline	\$1,851	\$641	\$93	\$537	\$93	\$3,215

Table 7-22: MY2027 Technology Costs for Urban bus Diesel, Average per Vehicle, 2017 Dollars

Scenario	DMC	Warranty	R&D	Other	Profit	Tech Cost Sum
Baseline	\$4,082	\$122	\$204	\$1,184	\$204	\$5,796
Baseline+Proposed Option 1	\$5,734	\$774	\$395	\$1,663	\$287	\$8,854
Baseline+Proposed Option 2	\$5,734	\$602	\$428	\$1,663	\$287	\$8,715
Option 1 increase from Baseline	\$1,653	\$652	\$191	\$479	\$83	\$3,058
Option 2 increase from Baseline	\$1,653	\$480	\$224	\$479	\$83	\$2,918

Table 7-23: MY2031 Technology Costs for Urban bus Diesel, Average per Vehicle, 2017 Dollars

Scenario	DMC	Warranty	R&D	Other	Profit	Tech Cost Sum
Baseline	\$3,769	\$113	\$188	\$1,093	\$188	\$5,352
Baseline+Proposed Option 1	\$5,153	\$928	\$344	\$1,494	\$258	\$8,177
Baseline+Proposed Option 2	\$5,153	\$541	\$258	\$1,494	\$258	\$7,704
Option 1 increase from Baseline	\$1,385	\$815	\$155	\$402	\$69	\$2,825
Option 2 increase from Baseline	\$1,385	\$428	\$69	\$402	\$69	\$2,353

Table 7-24: MY2027 Technology Costs for LHD45, MHD67 & HHD8 Gasoline, Average per Vehicle, 2017 Dollars

Scenario	DMC	Warranty	R&D	Other	Profit	Tech Cost Sum
Baseline	\$832	\$25	\$42	\$299	\$50	\$1,248
Baseline+Proposed Option 1	\$1,249	\$82	\$88	\$450	\$75	\$1,944
Baseline+Proposed Option 2	\$1,249	\$82	\$114	\$450	\$75	\$1,969
Option 1 increase from Baseline	\$417	\$57	\$46	\$150	\$25	\$696
Option 2 increase from Baseline	\$417	\$57	\$72	\$150	\$25	\$722

Table 7-25: MY2031 Technology Costs for LHD45, MHD67 & HHD8 Gasoline, Average per Vehicle, 2017 Dollars

Scenario	DMC	Warranty	R&D	Other	Profit	Tech Cost Sum
Baseline	\$768	\$23	\$38	\$277	\$46	\$1,152
Baseline+Proposed Option 1	\$1,118	\$107	\$72	\$402	\$67	\$1,767
Baseline+Proposed Option 2	\$1,118	\$74	\$56	\$402	\$67	\$1,717
Option 1 increase from Baseline	\$350	\$84	\$34	\$126	\$21	\$614
Option 2 increase from Baseline	\$350	\$51	\$17	\$126	\$21	\$565

Table 7-26: MY2027 Technology Costs for HHD8 CNG, Average per Vehicle, 2017 Dollars

Scenario	DMC	Warranty	R&D	Other	Profit	Tech Cost Sum
Baseline	\$4,108	\$123	\$205	\$1,191	\$205	\$5,833
Baseline+Proposed Option 1	\$4,135	\$558	\$285	\$1,199	\$207	\$6,384
Baseline+Proposed Option 2	\$4,135	\$434	\$309	\$1,199	\$207	\$6,284
Option 1 increase from Baseline	\$27	\$435	\$80	\$8	\$1	\$551
Option 2 increase from Baseline	\$27	\$311	\$104	\$8	\$1	\$450

Table 7-27: MY2031 Technology Costs for HHD8 CNG, Average per Vehicle, 2017 Dollars

Scenario	DMC	Warranty	R&D	Other	Profit	Tech Cost Sum
Baseline	\$3,793	\$114	\$190	\$1,100	\$190	\$5,386
Baseline+Proposed Option 1	\$3,816	\$687	\$254	\$1,107	\$191	\$6,054
Baseline+Proposed Option 2	\$3,816	\$401	\$191	\$1,107	\$191	\$5,705
Option 1 increase from Baseline	\$23	\$573	\$65	\$7	\$1	\$668
Option 2 increase from Baseline	\$23	\$287	\$1	\$7	\$1	\$318

Table 7-28: MY2027 Technology Costs for Urban bus CNG, Average per Vehicle, 2017 Dollars

Scenario	DMC	Warranty	R&D	Other	Profit	Tech Cost Sum
Baseline	\$3,081	\$92	\$154	\$893	\$154	\$4,375
Baseline+Proposed Option 1	\$3,100	\$419	\$214	\$899	\$155	\$4,787
Baseline+Proposed Option 2	\$3,100	\$326	\$232	\$899	\$155	\$4,711
Option 1 increase from Baseline	\$19	\$326	\$60	\$6	\$1	\$412
Option 2 increase from Baseline	\$19	\$233	\$78	\$6	\$1	\$336

Table 7-29: MY2031 Technology Costs for Urban bus CNG Average per Vehicle, 2017 Dollars

Scenario	DMC	Warranty	R&D	Other	Profit	Tech Cost Sum
Baseline	\$2,845	\$85	\$142	\$825	\$142	\$4,039
Baseline+Proposed Option 1	\$2,861	\$515	\$191	\$830	\$143	\$4,539
Baseline+Proposed Option 2	\$2,861	\$300	\$143	\$830	\$143	\$4,277
Option 1 increase from Baseline	\$16	\$430	\$48	\$5	\$1	\$500
Option 2 increase from Baseline	\$16	\$215	\$1	\$5	\$1	\$237

7.2 Operating Costs

We have estimated three impacts on operating costs associated with the proposed criteria pollutant standards: increased diesel exhaust fluid (DEF) consumption by diesel vehicles due to

increased DEF dose rates to enable compliance with more stringent NO_x standards; decreased fuel costs by gasoline vehicles due to new onboard refueling vapor recovery systems that allow burning (in engine) of otherwise evaporated hydrocarbon emissions; and, emission repair impacts. For the repair impacts we expect that the longer duration useful life period would increase emission control system durability resulting in fewer failing parts needing repair and that the longer warranty period would result in fewer repairs paid for by owners/operators. However, the possibility exists that the higher-cost emission control systems may result in higher repair costs if and when repairs are needed. We have estimated the net effect on repair costs and describe our approach, along with increased DEF consumption and reduced gasoline consumption below.

As noted in the introductory text to this chapter, the operating costs we estimate here are for the heavy-duty truck operation impacted by the proposal (e.g., repair of emission-related components). These costs (and savings) are incurred by heavy-duty truck purchasers/owners.

7.2.1 Costs Associated with Increased Diesel Exhaust Fluid (DEF) Consumption in Diesel Engines

To estimate baseline case DEF consumption in heavy-duty vehicles with diesel engines, this analysis uses the relationship, shown below, of DEF dose rate relative to the reduction in NO_x over the SCR catalyst.^{JJJJJ,361}

$$NO_x \text{ reduction} = -73.679x + 0.0149$$

where x is equal to the DEF dose rate. This relationship was developed giving consideration to FTP emissions. By estimating the FTP NO_x reduction across the SCR catalyst, the DEF dose rate can be calculated. NO_x reduction is estimated from the difference between estimated engine-out and FTP tailpipe NO_x emissions; these variables along with the calculated DEF dose rate for the baseline case are shown in Table 7-30.

Table 7-30: Diesel Exhaust Fluid Consumption Rates for Diesel Vehicles in the Baseline Case

	Value
Engine-out NO_x (FTP g/hp-hr)	4.0
Tailpipe NO_x (FTP mg/hp-hr)	200
DEF Dose Rate (% of fuel consumed)	5.18%

Because both proposed options involve changes to not only the FTP emission standard, but also tightened SET and LLC standards along with new idle standards, the above approach was considered insufficient to estimate increased DEF consumption. Therefore, we have instead scaled DEF consumption with the NO_x reductions achieved under each of the alternatives. To do this, we considered the molar mass of NO_x, the molar mass of urea, the molar ratio of NO to NO₂, the mass concentration of urea in DEF along with the density of DEF to estimate the

^{JJJJJ} The relationship between DEF dose rate and NO_x reduction across the SCR catalyst is based on methodology presented in the Technical Support Document to the 2012 Non-conformance Penalty rule (the NCP Technical Support Document, or NCP TSD).

theoretical gallons of DEF consumed per ton of NO_x reduced at 442 gallons/ton. The theoretical DEF dosing rates was then compared to the data collected from the Stage 3 test program for the hot FTP, SET and LLC (see Chapter 3 of the draft RIA). The data from this testing showed that the NO_x specific DEF dosing was 536, 478, and 568 gallons/ton for the hot FTP, SET and LLC, respectively. Since this data takes into account any over dosing that occurs for part of the cycle, and NO₂/NO ratio being greater than 1 for parts of the cycle, we have adjusted the theoretical 442 gallons/ton NO_x to the average of the hot FTP, SET and LLC, which is 527 gallons/ton. These values are shown in Table 7-31

Table 7-31: Derivation of DEF Consumption per Ton of NO_x Reduced

	Value
Molar mass of NO _x (g/mol)	46.0055
Molar mass of urea (g/mol)	60.07
Molar ratio of NO to NO ₂	1
Mass concentration of urea in DEF	0.325
Density of DEF (g/mL)	1.09
Theoretical gallons DEF/ton NO _x reduced	442
Proposed gallons DEF/ton NO _x reduced	527

The final calculation of DEF consumption in each option is to multiply the gallons of diesel fuel consumed by 5.18%, to account for the baseline DEF consumption and add to that amount 527 gallons of DEF for each ton of NO_x reduced from the baseline. Both the gallons of diesel fuel consumed and the tons of NO_x reduced are taken directly from the year-over-year MOVES results.

The gallons of DEF consumed are then multiplied by the estimated price of DEF per gallon. This analysis uses the DEF prices presented in the NCP Technical Support Document with growth beyond 2042 projected at the same 1.3 percent rate as noted in the NCP TSD. Note that the DEF prices presented in Table 7-32 update the NCP TSD's 2011 prices to 2017 dollars using the GDP deflator presented in Table 7-8.

Table 7-32: Diesel Exhaust Fluid Price per Gallon (2017 dollars)

Calendar Year	DEF Price/Gallon
2027	3.25
2028	3.30
2029	3.33
2030	3.37
2031	3.42
2032	3.46
2033	3.52
2034	3.56
2035	3.60
2036	3.65
2037	3.69
2038	3.75
2039	3.79
2040	3.85
2041	3.89
2042	3.94
2043	4.00
2044	4.04
2045	4.10

The impacts on DEF costs per mile for the first 10 years of the indicated model year lifetime and under each alternative are shown in Table 7-36 through Table 7-37.

Table 7-33: Diesel Exhaust Fluid Average Cost per Mile during the first 10 Years of each MY Lifetime by MOVES Sourcetypes equipped with LHD Engines (*cents/mile* in 2017 dollars, Undiscounted) *

MOVES Sourcetype	Scenario	MY2027	MY2031	MY2035
Passenger Trucks	Baseline	0.85	0.90	0.94
	Baseline+Proposed Option 1	0.86	0.95	1.00
	Baseline+ Proposed Option 2	0.85	0.90	0.95
	Option 1 increase from Baseline	0.01	0.05	0.06
	Option 2 increase from Baseline	0.00	0.00	0.00
Light Commercial Trucks	Baseline	0.87	0.92	0.96
	Baseline+ Proposed Option 1	0.88	0.97	1.02
	Baseline+ Proposed Option 2	0.87	0.92	0.97
	Option 1 increase from Baseline	0.01	0.05	0.06
	Option 2 increase from Baseline	0.00	0.00	0.00
Short-Haul Single Unit Trucks	Baseline	1.14	1.20	1.26
	Baseline+ Proposed Option 1	1.14	1.25	1.31
	Baseline+ Proposed Option 2	1.13	1.19	1.26
	Option 1 increase from Baseline	0.00	0.05	0.05
	Option 2 increase from Baseline	0.00	0.00	0.00
Long-Haul Single Unit Trucks	Baseline	1.07	1.13	1.19
	Baseline+ Proposed Option 1	1.07	1.16	1.23
	Baseline+ Proposed Option 2	1.06	1.12	1.18
	Option 1 increase from Baseline*	0.00	0.04	0.04
	Option 2 increase from Baseline	-0.01	-0.01	-0.01

* As discussed in Section 5.2.2.5, we did not include diesel-fueled, engine-certified LHD2b3 vehicles in the baseline emission inventory, but did include these vehicles in our emission inventory estimates for the Proposal and Alternative 1 control scenarios. We decided to include the engine-certified LHD2b3 vehicles in the emissions inventories of the control scenario to better estimate the projected emissions of heavy-duty vehicles in the control scenarios, even though it will conservatively underestimate the benefits of controlling these vehicles. As a result, the NO_x emission inventories may demonstrate an increase in emissions from sourcetypes containing diesel-fueled LHD2b3 vehicles for certain calendar years. We plan to update our baseline modeling to reflect any requirements for diesel-fueled, engine-certified LHD2b3 vehicles in the final rulemaking. In addition, the MOVES baseline emission rates for all LHD diesel (not just 2b3 vehicles) were incorrectly developed using a warranty period of 100K instead of 50K, and thus we underestimated the LHD diesel emissions impact of the longer warranty periods in the proposal and alternative scenarios. We will update the baseline warranty period for LHD diesel in the FRM analysis.

Table 7-34: Diesel Exhaust Fluid Average Cost per Mile during the first 10 Years of each MY Lifetime by MOVES Sourcetypes equipped with LHD45 Engines (*cents/mile* in 2017 dollars, Undiscounted)

MOVES Sourcetype	Scenario	MY2027	MY2031	MY2035
Other Buses	Baseline	1.99	2.10	2.21
	Baseline+Proposed Option 1	2.21	2.39	2.52
	Baseline+Proposed Option 2	2.20	2.32	2.44
	Option 1 increase from Baseline	0.22	0.30	0.31
	Option 2 increase from Baseline	0.21	0.23	0.24
Transit Buses	Baseline	2.00	2.10	2.21
	Baseline+Proposed Option 1	2.20	2.39	2.51
	Baseline+Proposed Option 2	2.20	2.32	2.44
	Option 1 increase from Baseline	0.21	0.28	0.30
	Option 2 increase from Baseline	0.21	0.22	0.23
School Buses	Baseline	1.49	1.57	1.66
	Baseline+Proposed Option 1	1.66	1.80	1.90
	Baseline+Proposed Option 2	1.66	1.75	1.84
	Option 1 increase from Baseline	0.17	0.23	0.24
	Option 2 increase from Baseline	0.16	0.17	0.18
Short-Haul Single Unit Trucks	Baseline	1.27	1.33	1.40
	Baseline+Proposed Option 1	1.41	1.53	1.62
	Baseline+Proposed Option 2	1.41	1.48	1.56
	Option 1 increase from Baseline	0.15	0.20	0.21
	Option 2 increase from Baseline	0.14	0.15	0.16
Long-Haul Single Unit Trucks	Baseline	1.19	1.25	1.31
	Baseline+Proposed Option 1	1.31	1.41	1.49
	Baseline+Proposed Option 2	1.30	1.37	1.44
	Option 1 increase from Baseline	0.12	0.17	0.18
	Option 2 increase from Baseline	0.12	0.12	0.13

Table 7-35: Diesel Exhaust Fluid Average Cost per Mile during the first 10 Years of each MY Lifetime by MOVES Sourcetypes equipped with MHD67 Engines (*cents/mile* in 2017 dollars, Undiscounted)

MOVES Sourcetype	Scenario	MY2027	MY2031	MY2035
Other Buses	Baseline	2.18	2.29	2.42
	Baseline+Proposed Option 1	2.37	2.54	2.68
	Baseline+Proposed Option 2	2.35	2.47	2.60
	Option 1 increase from Baseline	0.19	0.25	0.26
	Option 2 increase from Baseline	0.17	0.18	0.19
Transit Buses	Baseline	2.17	2.29	2.41
	Baseline+Proposed Option 1	2.35	2.52	2.65
	Baseline+Proposed Option 2	2.33	2.45	2.58
	Option 1 increase from Baseline	0.18	0.23	0.24
	Option 2 increase from Baseline	0.16	0.17	0.18
School Buses	Baseline	1.69	1.78	1.88
	Baseline+Proposed Option 1	1.85	2.00	2.10
	Baseline+Proposed Option 2	1.84	1.94	2.04
	Option 1 increase from Baseline	0.16	0.21	0.22
	Option 2 increase from Baseline	0.15	0.16	0.16
Refuse Trucks	Baseline	2.30	2.42	2.55
	Baseline+Proposed Option 1	2.49	2.67	2.82
	Baseline+Proposed Option 2	2.47	2.60	2.74
	Option 1 increase from Baseline	0.20	0.26	0.27
	Option 2 increase from Baseline	0.17	0.18	0.19
Short-Haul Single Unit Trucks	Baseline	1.64	1.73	1.82
	Baseline+Proposed Option 1	1.82	1.95	2.06
	Baseline+Proposed Option 2	1.80	1.89	1.99
	Option 1 increase from Baseline	0.17	0.22	0.23
	Option 2 increase from Baseline	0.15	0.16	0.17
Long-Haul Single Unit Trucks	Baseline	1.52	1.60	1.68
	Baseline+Proposed Option 1	1.66	1.78	1.88
	Baseline+Proposed Option 2	1.64	1.73	1.82
	Option 1 increase from Baseline	0.14	0.18	0.19
	Option 2 increase from Baseline	0.13	0.13	0.14
Motor Homes	Baseline	1.63	1.72	1.81
	Baseline+Proposed Option 1	1.78	1.91	2.01
	Baseline+Proposed Option 2	1.77	1.86	1.96
	Option 1 increase from Baseline	0.14	0.19	0.20
	Option 2 increase from Baseline	0.14	0.14	0.15
Short-Haul Combination Trucks	Baseline	2.12	2.23	2.35
	Baseline+Proposed Option 1	2.27	2.43	2.56
	Baseline+Proposed Option 2	2.26	2.38	2.50
	Option 1 increase from Baseline	0.15	0.20	0.21
	Option 2 increase from Baseline	0.14	0.14	0.15

Table 7-36: Diesel Exhaust Fluid Average Cost per Mile during the first 10 Years of each MY Lifetime by MOVES Sourcetypes equipped with HHD8 Engines (*cents/mile* in 2017 dollars, Undiscounted)

MOVES Sourcetype	Scenario	MY2027	MY2031	MY2035
Other Buses	Baseline	2.46	2.59	2.73
	Baseline+Proposed Option 1	2.87	3.09	3.25
	Baseline+Proposed Option 2	2.81	2.96	3.12
	Option 1 increase from Baseline	0.41	0.50	0.53
	Option 2 increase from Baseline	0.35	0.37	0.39
School Buses	Baseline	1.97	2.07	2.18
	Baseline+Proposed Option 1	2.29	2.46	2.59
	Baseline+Proposed Option 2	2.25	2.37	2.50
	Option 1 increase from Baseline	0.32	0.39	0.41
	Option 2 increase from Baseline	0.28	0.30	0.31
Refuse Trucks	Baseline	2.60	2.74	2.89
	Baseline+Proposed Option 1	3.03	3.27	3.44
	Baseline+Proposed Option 2	2.97	3.12	3.29
	Option 1 increase from Baseline	0.43	0.52	0.55
	Option 2 increase from Baseline	0.36	0.38	0.40
Short-Haul Single Unit Trucks	Baseline	2.17	2.29	2.41
	Baseline+Proposed Option 1	2.58	2.77	2.92
	Baseline+Proposed Option 2	2.52	2.66	2.80
	Option 1 increase from Baseline	0.40	0.49	0.51
	Option 2 increase from Baseline	0.35	0.37	0.39
Long-Haul Single Unit Trucks	Baseline	2.01	2.12	2.23
	Baseline+Proposed Option 1	2.34	2.52	2.65
	Baseline+Proposed Option 2	2.29	2.41	2.54
	Option 1 increase from Baseline	0.33	0.40	0.42
	Option 2 increase from Baseline	0.28	0.30	0.31
Motor Homes	Baseline	2.12	2.23	2.35
	Baseline+Proposed Option 1	2.48	2.66	2.81
	Baseline+Proposed Option 2	2.45	2.58	2.71
	Option 1 increase from Baseline	0.36	0.44	0.46
	Option 2 increase from Baseline	0.33	0.35	0.37
Short-Haul Combination Trucks	Baseline	2.42	2.54	2.68
	Baseline+Proposed Option 1	2.75	2.95	3.11
	Baseline+Proposed Option 2	2.71	2.85	3.00
	Option 1 increase from Baseline	0.33	0.41	0.43
	Option 2 increase from Baseline	0.29	0.31	0.32
Long-Haul Combination Trucks	Baseline	2.21	2.33	2.45
	Baseline+Proposed Option 1	2.49	2.67	2.81
	Baseline+Proposed Option 2	2.46	2.59	2.73
	Option 1 increase from Baseline	0.28	0.34	0.36
	Option 2 increase from Baseline	0.25	0.27	0.28

Table 7-37: Diesel Exhaust Fluid Average Cost per Mile during the first 10 Years of each MY Lifetime by MOVES Sourcetypes equipped with Urban Bus Engines (*cents/mile* in 2017 dollars, Undiscounted)

MOVES Sourcetype	Scenario	MY2027	MY2031	MY2035
Transit Buses	Baseline	2.46	2.59	2.73
	Baseline+Proposed Option 1	2.85	3.03	3.19
	Baseline+Proposed Option 2	2.79	2.93	3.09
	Option 1 increase from Baseline	0.39	0.44	0.46
	Option 2 increase from Baseline	0.32	0.34	0.36

7.2.2 Costs Associated with ORVR and the Estimated Reduction in Fuel Costs for Gasoline Engines

This analysis estimates a small decrease in fuel costs, i.e., fuel savings, by vehicles equipped with gasoline engines because the proposed ORVR system would be expected to capture previously evaporated fuel and then burn that fuel in the engine (see Table 7-6 for our estimated ORVR direct manufacturing cost). To estimate these impacts, we first converted grams of hydrocarbon captured by the ORVR system to milliliters of gasoline that would ultimately be burned in the engine. Based on that relationship, we estimate that 1.48 milliliters of gasoline would be consumed for each gram of hydrocarbon emissions reduced under the proposed Options 1 or 2. We estimated this value, 1.48, by assuming that the ORVR system would exchange captured butane for gasoline on an energy basis and Tier 3 certification fuel has a density of 0.7482 g/ml, or 2832 g/gal at 60 degrees F.³⁶² We then used a butane energy density of 45.8 MJ/kg, or 19752 Btu/lb,³⁶³ and the Tier 3 cert fuel energy density of 17890 Btu/lb,³⁶⁴ giving a ratio of 1.117 grams of gasoline displaced for each gram of butane burned. Using the density of Tier 3 certification fuel, we get $1.117 / 2832 = 0.0003943$ gallons, or 1.48 ml, of gasoline saved for each gram of butane captured.^{KKKKKK} The effect being that the owner/operator is no longer paying for evaporated fuel since it would be burned in the engine. Using AEO 2018 reference case gasoline prices, the impacts on gasoline costs per mile for the first 10 years of each model year lifetime and under each alternative are shown in Table 7-38 through Table 7-40.

^{KKKKKK} We estimate that the ORVR requirements in both the proposed Options 1 and 2 would result in a reduction of approximately 0.3 million (calendar year 2027) to 4.8 million (calendar year 2045) gallons of gasoline, representing roughly 0.1 percent of gasoline consumption from impacted vehicles.

Table 7-38: Gasoline Vehicle Average Retail Fuel Cost per Mile during the first 10 Years of each Model Year Lifetime by MOVES Sourcetype equipped with LHD45 Engines* (cents/mile in 2017 dollars, Undiscounted)

MOVES Sourcetype	Scenario	MY2027	MY2031	MY2035
Other Buses	Baseline	59.12	60.77	62.17
	Baseline+Proposed Option 1	58.99	60.63	62.04
	Baseline+Proposed Option 2	58.99	60.64	62.04
	Option 1 increase from Baseline	-0.13	-0.13	-0.14
	Option 2 increase from Baseline	-0.13	-0.13	-0.13
Transit Buses	Baseline	58.29	59.92	61.30
	Baseline+Proposed Option 1	58.18	59.80	61.18
	Baseline+Proposed Option 2	58.18	59.80	61.18
	Option 1 increase from Baseline	-0.11	-0.12	-0.12
	Option 2 increase from Baseline	-0.11	-0.12	-0.12
School Buses	Baseline	43.78	45.00	46.03
	Baseline+Proposed Option 1	43.70	44.91	45.94
	Baseline+Proposed Option 2	43.70	44.91	45.94
	Option 1 increase from Baseline	-0.08	-0.08	-0.08
	Option 2 increase from Baseline	-0.08	-0.08	-0.08
Short-Haul Single Unit Trucks	Baseline	38.57	39.64	40.57
	Baseline+Proposed Option 1	38.53	39.60	40.53
	Baseline+Proposed Option 2	38.53	39.60	40.53
	Option 1 increase from Baseline	-0.04	-0.04	-0.04
	Option 2 increase from Baseline	-0.04	-0.04	-0.04
Long-Haul Single Unit Trucks	Baseline	36.19	37.20	38.07
	Baseline+Proposed Option 1	36.16	37.16	38.04
	Baseline+Proposed Option 2	36.15	37.16	38.04
	Option 1 increase from Baseline	-0.04	-0.04	-0.04
	Option 2 increase from Baseline	-0.04	-0.04	-0.04
Motor Homes	Baseline	37.72	38.77	39.66
	Baseline+Proposed Option 1	37.66	38.70	39.59
	Baseline+Proposed Option 2	37.66	38.70	39.59
	Option 1 increase from Baseline	-0.07	-0.07	-0.07
	Option 2 increase from Baseline	-0.07	-0.07	-0.07

* Negative values denote lower costs, i.e., savings in fuel expenditures.

Table 7-39: Gasoline Vehicle Average Retail Fuel Cost per Mile during the first 10 Years of each Model Year Lifetime by MOVES Sourcetype equipped with MHD67 Engines* (cents/mile in 2017 dollars, Undiscounted)

MOVES Sourcetype	Scenario	MY2027	MY2031	MY2035
Short-Haul Single Unit Trucks	Baseline	48.76	50.11	51.28
	Baseline+Proposed Option 1	48.70	50.05	51.22
	Baseline+Proposed Option 2	48.70	50.05	51.22
	Option 1 increase from Baseline	-0.05	-0.06	-0.06
	Option 2 increase from Baseline	-0.06	-0.06	-0.06
Long-Haul Single Unit Trucks	Baseline	45.04	46.29	47.38
	Baseline+Proposed Option 1	44.99	46.24	47.33
	Baseline+Proposed Option 2	44.99	46.24	47.33
	Option 1 increase from Baseline	-0.05	-0.05	-0.05
	Option 2 increase from Baseline	-0.05	-0.05	-0.05
Motor Homes	Baseline	47.68	49.00	50.13
	Baseline+Proposed Option 1	47.59	48.90	50.03
	Baseline+Proposed Option 2	47.58	48.90	50.03
	Option 1 increase from Baseline	-0.09	-0.09	-0.10
	Option 2 increase from Baseline	-0.09	-0.09	-0.10

* Negative values denote lower costs, i.e., savings in fuel expenditures.

Table 7-40: Gasoline Vehicle Average Retail Fuel Cost per Mile during the first 10 Years of each Model Year Lifetime by MOVES Sourcetype equipped with HHD8 Engines* (cents/mile in 2017 dollars, Undiscounted)

MOVES Sourcetype	Scenario	MY2027	MY2031	MY2035
Short-Haul Single Unit Trucks	Baseline	62.22	63.95	65.44
	Baseline+Proposed Option 1	62.14	63.87	65.36
	Baseline+Proposed Option 2	62.14	63.87	65.36
	Option 1 increase from Baseline	-0.07	-0.08	-0.08
	Option 2 increase from Baseline	-0.08	-0.08	-0.08
Long-Haul Single Unit Trucks	Baseline	57.62	59.22	60.61
	Baseline+Proposed Option 1	57.55	59.15	60.54
	Baseline+Proposed Option 2	57.54	59.15	60.54
	Option 1 increase from Baseline	-0.07	-0.07	-0.08
	Option 2 increase from Baseline	-0.07	-0.07	-0.08
Motor Homes	Baseline	60.77	62.46	63.89
	Baseline+Proposed Option 1	60.65	62.33	63.77
	Baseline+Proposed Option 2	60.65	62.33	63.77
	Option 1 increase from Baseline	-0.12	-0.13	-0.13
	Option 2 increase from Baseline	-0.12	-0.13	-0.13

* Negative values denote lower costs, i.e., savings in fuel expenditures.

7.2.3 Repair Cost Impacts Associated with Longer Warranty and Useful Life Periods

As noted above, we would expect that the longer warranty and useful life requirements being proposed would have an impact on emission-related repair costs incurred by truck owners. Researchers have noted the relationships among quality, reliability, and warranty for a variety of goods.³⁶⁵ Wu, for instance, examines how analyzing warranty data can provide “early warnings” on product problems that can then be used for design modifications.³⁶⁶ Guajardo et al. describe one of the motives for warranties to be “incentives for the seller to improve product quality;” specifically for light-duty vehicles, they find that buyers consider warranties to substitute for

product quality, and to complement service quality.³⁶⁷ The other rationales are protection for consumers against failures, provision of product quality information to consumers, and a means to distinguish consumers according to their risk preferences. Murthy and Jack, for new products, and Saidi-Mehrabad et al. for second-hand products, consider the role of warranties in improving a buyer's confidence in quality of the good.^{368,369}

On the one hand, we would expect that owner incurred emission repair costs would decrease due to the proposed program because the longer regulatory useful life requirements would encourage more durable parts to ensure compliance over the longer timeframes (i.e., reduced part failure rates), and because costs for emission repairs that might be needed during the warranty period would have to be covered by the OEM (see the discussion in Section 7.1.2 regarding expected increased funding of warranty liability accounts to cover warranty claims). However, on the other hand, we would also expect that repair costs might increase marginally in the same way that direct manufacturing costs are increasing (i.e., more costly emission control systems might have more costly repairs), which could increase OEM costs during the warranty period and owner costs outside the warranty period. Overall for OEMs, while the longer warranty period could be seen as potentially increasing repair costs incurred by OEMs, such costs would have already been funded as part of the increased indirect costs discussed in Section 7.1.2).

Regarding increased technology costs associated with the proposed warranty and useful life periods, we have estimated the cost of improved emission durability via increased research and development (R&D) costs scaled by the longer useful life period, and increased warranty costs scaled by the longer warranty period. This scaling of warranty and R&D costs is described above in Section 7.1.2. We also included additional aftertreatment costs in the direct manufacturing costs to address the increased useful life requirements (e.g., larger catalyst volume; see Chapters 2 and 4 for detailed discussions). We estimate that these efforts would help to reduce emission repair costs during the emission warranty, regulatory useful life period, and possibly beyond.

Regarding the longer warranty and useful life periods reducing repair costs incurred by owners, we estimated costs by starting with an operating cost analysis presented in a whitepaper.³⁷⁰ On page 8 of that whitepaper, a figure shows estimated repair and maintenance costs as reproduced in Table 7-41. A note on the figure states that the seven-year average would be 10.48 cents/mile. This figure is considerably lower than a value of 17.1 cents/mile from a study done by the American Transportation Research Institute (ATRI).³⁷¹ However, the ATRI value includes a more diverse range of truck applications and ages, including tractor-trailers averaging 4.4 years old and straight trucks averaging 8.5 years old. By contrast, the Fleet Advantage study includes Class-8 truck fleets only which, while not explicitly noted in the study, we take to mean both short- and long-haul combination trucks (tractor-trailers). This would suggest a higher weighting of older vehicles with higher repair and maintenance costs/mile relative to the weighting of costs/mile in the Fleet Advantage study. Since we are estimating impacts on repair costs associated with the proposed Options 1 or 2, using the lower cost/mile estimate represents a more conservative approach.

Table 7-41: Class-8 Diesel Repair & Maintenance Costs per Mile (100,000 miles per year, 2018 dollars*)³⁷²

Year in Operation	Cents/Mile
1	2.07
2	5.53
3	6.63
4	10.52
5	14.23
6	14.56
7	19.82

* While not explicitly stated in the study, the 2018 calendar year publication date implies that the dollar figures in the study represent 2018 dollars.

Using the costs/mile shown in Table 7-41, we estimated the impacts on repair and maintenance costs--specifically, emission-related repair costs--as described here. First, we looked at the estimated ages that short- and long-haul combination truck reach their regulatory warranty and useful life periods in the MOVES model, as shown in Table 7-42. For a discussion of how estimated ages are determined, see Section 5.2.2 of this draft RIA; the approach used here is identical except that here we have extended the approach beyond MOVES regulatory class to MOVES sourcetypes to align more closely with likely in-use repair costs.^{LLLLL} Notably, the current regulated warranty period is 5 years/100,000 miles and the current useful life is 10 years/435,000 miles for the trucks summarized in Table 7-44.

^{LLLLL} Two of the primary vehicle characteristics with MOVES are "sourcetype" and "regulatory class." The proposed requirements apply to regulatory classes which refers to engines certified for use in vehicles of a specific weight class (e.g., light heavy-duty, medium heavy-duty, heavy heavy-duty, etc.). The term "sourcetype" refers to the type of vehicle (e.g., refuse truck, single unit short-haul truck, long-haul combination truck, etc.). Any given sourcetype could be equipped with any of several different regulatory class engines. In terms of miles accumulated on a vehicle, the sourcetype designation aligns more closely with the real world since "refuse trucks" tend to be driven similarly regardless of their regulatory class engine. In this analysis, the warranty and useful life provisions are tied to the regulatory class of the engine while the repair costs per mile are tied to the miles accumulated by the sourcetype. Therefore, a refuse truck with a medium heavy-duty engine could have a different cost/mile curve than one equipped with a heavy heavy-duty engine given the different warranty and useful life periods of the engine. This is perhaps most easily understood when considering two different sourcetypes--a refuse truck and a long-haul combination truck--both equipped with a heavy heavy-duty diesel engine. The former would reach its estimated warranty period in 3 years versus 1 year for the latter. Similarly, the former would reach its estimated useful life period in the full 10 years while the latter would reach its within 3. If we tie cost/mile metrics to point where warranty and useful life are reached, then these two vehicles would have different cost/mile curves despite being equipped with the same engine.

Table 7-42: Estimated Vehicle Age at the End of the Warranty Period and the Useful Life for each Heavy Heavy-duty Diesel Combination Truck for the Baseline Case

		Warranty		Useful Life	
		HHD Short-haul Combo Truck	HHD Long-haul Combo Truck	HHD Short-haul Combo Truck	HHD Long-haul Combo Truck
(A)	Age limit	5	5	10	10
(B)	Mileage limit	100,000	100,000	435,000	435,000
(C)	Typical miles/year driven thru 7 years	75,000	144,000	75,000	144,000
(D)	Calculated age when the mileage limit is reached	1	1	6	3
(E)	Estimated age (minimum of rows A and D)	1	1	6	3

We then looked at how the Fleet Advantage data lined up with the estimated ages shown in Table 7-42. This is shown in Table 7-43 for short-haul combination trucks and in Table 7-44 for long-haul combination trucks.

Table 7-43: Class-8 Diesel Short-haul Combination Truck Repair & Maintenance Costs per Mile (see Table 7-41) with MOVES HHD8 Mileage Accumulation

Year of Operating	Fleet Advantage Cents/Mile	Notes
1	2.07	Within current warranty estimated age
2	5.53	Beyond current warranty estimated age but within current useful life estimated age
3	6.63	
4	10.52	
5	14.23	
6	14.56	
7	19.82	Beyond current warranty and current useful life estimated ages

Table 7-44: Class-8 Diesel Long-haul Combination Truck Repair & Maintenance Costs per Mile (see Table 7-41) with MOVES HHD8 Mileage Accumulation

Year of Operating	Fleet Advantage Cents/Mile	Notes
1	2.07	Within current warranty estimated age
2	5.53	Beyond current warranty estimated age but within current useful life estimated age
3	6.63	
4	10.52	Beyond current warranty and current useful life estimated ages
5	14.23	
6	14.56	
7	19.82	

As shown in Table 7-43, trends in the Fleet Advantage data line up well with estimated warranty and useful life ages of short-haul combination trucks, particularly the sharp increase in cost/mile beyond the estimated useful life age. This seeming trend is not as apparent in Table 7-44 which compares the Fleet Advantage data against the long-haul combination truck estimated ages. The docket to this rulemaking contains a memorandum that presents all of the estimated warranty and useful life ages for each sourcetype and for each alternative.³⁷³

While not clear, it is possible that the Fleet Advantage data were derived primarily from long-haul combination trucks rather than short-haul combination trucks. Nonetheless, from these admittedly limited data, it appears that repair and maintenance costs begin to increase beyond the estimated warranty age and through the estimated useful life age. At some point beyond the estimated useful life age, there appears to be a considerable jump in costs/mile. We made use of these trends in developing our repair cost impacts associated with the proposed longer warranty and useful life periods. Further, for this analysis, we have taken the "in-warranty" cost/mile to be the 0.0207 value and the "at-useful-life" cost/mile to be the 14.56 value from the Fleet Advantage data. Between the estimated warranty and useful life ages, the cost/mile is estimated to lie on the slope of a line drawn between these two points. Beyond the estimated useful life age, the cost/mile value increases to the 19.82 value and then, given lack of data, remains at that value for the duration of the vehicle lifetime. The resultant repair and maintenance cost curve we have developed is shown in Figure 7-2. We show the cost/mile remaining flat at that "beyond useful life" value because the Fleet Advantage data did not show values beyond seven years.

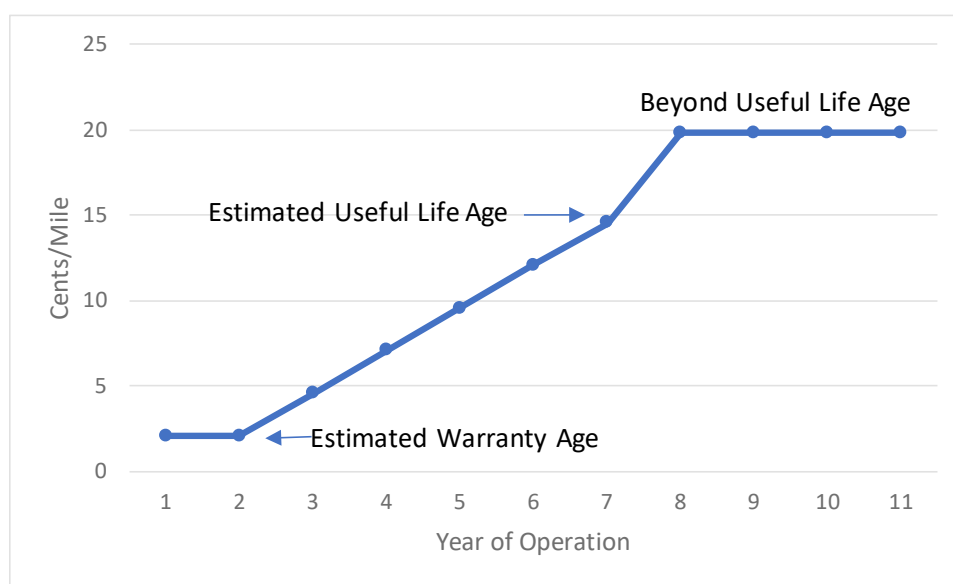


Figure 7-2: Repair & Maintenance Cost/Mile Curve (2018 dollars)

However, these are repair and maintenance costs rather than emission-related repair costs to which the proposed emissions warranty and useful life provisions are tied. To estimate the emission repair portion of these costs, we used the figure on page 3 of the Fleet Advantage whitepaper which showed the percent of total repair and maintenance costs attributable to different systems on the vehicle.³⁷⁴ The details of that chart are recreated below in Table 7-45 along with EPA's estimates for what portion of the repair and maintenance costs could be considered to be emission repairs.

As shown, our analysis estimates that 10.8 percent of repair and maintenance costs are emission repairs that the proposed warranty and useful life provisions are meant to impact. In general, the maintenance/repair shares are estimated to be 50/50 repair/maintenance, with the exception of "Preventive maintenance" and "Exhaust system." Preventive maintenance, by definition, is not repair, and thus 100 percent is considered maintenance. For the exhaust system,

we estimate that 80 percent of those costs are repair costs, with maintenance costs limited to DPF cleaning. The share of emission-related vs. non-emission-related items was broken down, in general, by those that are clearly emission-related, where we attribute 100 percent to the emission-related category, versus those that are clearly not emission-related where 100 percent is attributed to the non-emission-related category. Not shown are the non-emission repair share which totals 35.0 percent, the emission maintenance share which is 7.2 percent and the non-emission maintenance share which is 47.0 percent.

Table 7-45: Percentage of Total Repair & Maintenance Costs Attributable to Different Vehicle Systems³⁷⁵

	Fleet Advantage	EPA Estimates				
System	Percent of Total Repair & Maintenance Cost	Maintenance Share	Repair Share	Non-Emission-Related Share	Emission-Related Share	Emission Repair Share (EPA Estimate)
Tires, tubes, liners & valves	43%	50%	50%	100%	0%	0.0%
Preventive maintenance	12%	100%	0%	100%	0%	0%
Brakes	9%	50%	50%	100%	0%	0%
Expendable items	8%	50%	50%	100%	0%	0%
Lighting	5%	50%	50%	100%	0%	0%
Cranking	5%	50%	50%	100%	0%	0%
Power plant	3%	50%	50%	0%	100%	1.5%
Exhaust system	6%	20%	80%	0%	100%	4.8%
Fuel system	6%	50%	50%	0%	100%	3%
Engine/motor	3%	50%	50%	0%	100%	1.5%
Total	100%	54.2%	45.8%	82.0%	18.0%	10.8%

Applying the 10.8 percent factor to the cost/mile curve shown in Figure 7-2 results in an emission repair cost/mile curve as shown in Figure 7-3.

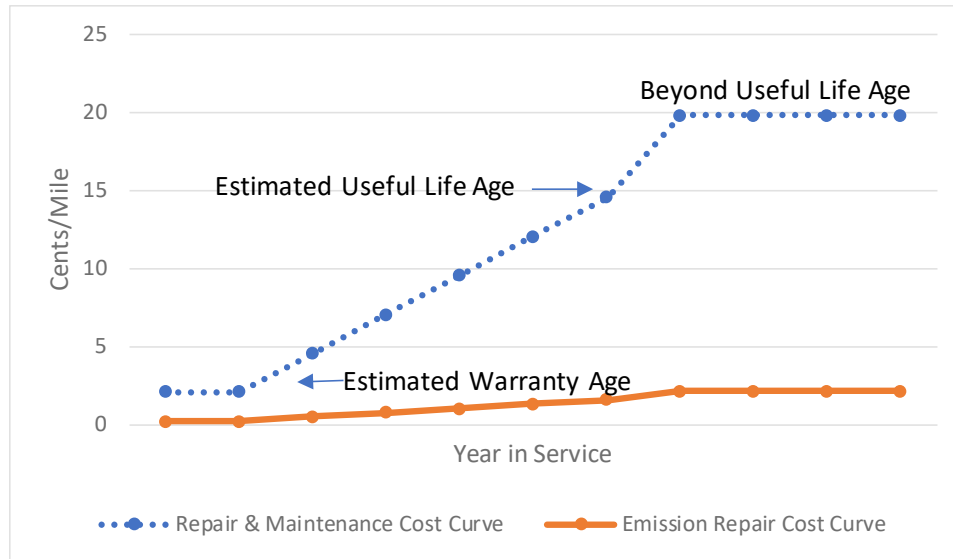


Figure 7-3: Emission Repair Cost/Mile Curve (2018 dollars)

With these cost curves established, we then estimated the repair costs under each alternative assuming that for ages less than the estimated warranty age the in-warranty emission repair cost to the owner would equal the in-warranty emission repair cost shown in Figure 7-3 (0.22 cents/mile). For the ages between the estimated warranty age and the estimated useful life age, the owner's emission repair costs would be on the slope of a line between the in-warranty emission repair cost and the end of useful life emission repair cost shown in Figure 7-3 (1.57 cents/mile). Beyond the estimated useful life age, the owner's emission repair costs would increase to the maximum emission repair cost shown in Figure 7-3 (2.14 cents/mile).

However, the emission repair cost curve shown in Figure 7-3 represents today's Class-8 trucks, but future trucks will have marginally more costly emission control systems due to the proposed requirements. To estimate that effect, we have scaled the curve using the direct costs of every regulatory class within each alternative relative to the direct cost of a HHD8 diesel engine in the baseline case.

For example, for a short-haul combination HHD8 diesel truck in the baseline case, with a baseline case 1 year estimated warranty age and a 6-year estimated useful life age, the emission repair costs would be as shown in Figure 7-4 (dashed line). Under the proposed Option 1, for a MY2027 short-haul combination HHD8 diesel truck with a 450,000 mile warranty and 600,000 mile useful life resulting in an estimated warranty age of 6 years and an estimated useful life age of 8 years, the emission repair cost curve would look like the solid line in Figure 7-4. The cost/mile values during the warranty period have been extended for more years, but the cost/mile has also been scaled by the relative cost of the proposed Option 1 technology package's direct costs (\$8,668 as shown in Table 7-5, adding \$6,457 and \$2,210) to the baseline package (\$6,457 as shown in Table 7-5), or 1.34. So, while the baseline in-warranty emission repair cost/mile would be 0.22 cents/mile (the Fleet Advantage 2.07 cents/mile * 10.8 percent * 0.977 GDP deflator), the proposed Option 1 in-warranty emission repair cost would be 0.30 cents/mile. Similarly, the maximum cost/mile value shown for the "beyond estimated useful life age" in the baseline case is shown as 2.09 cent/mile (the Fleet Advantage 19.82 cents/mile value * 10.8

percent * 0.977 GDP deflator). In the proposed Option 1, that value has been scaled again by the 1.34 direct cost scalar to arrive at the 2.80 cent/mile value shown.

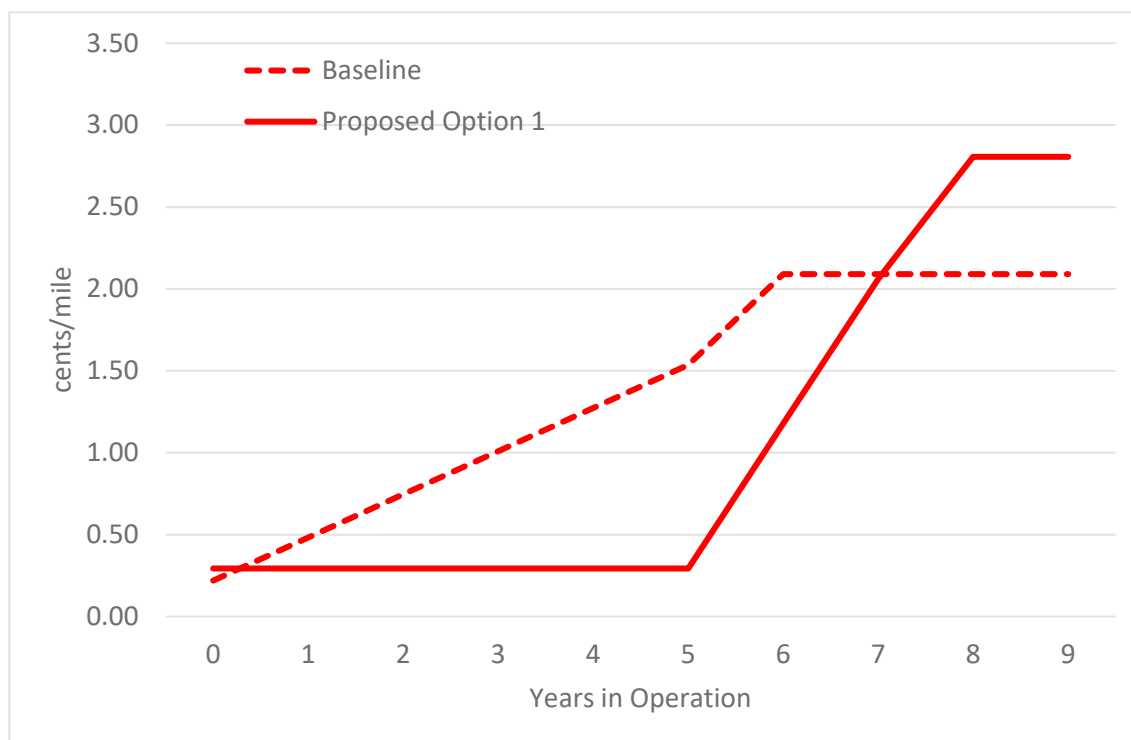


Figure 7-4: Emission Repair Cost Curve in the Baseline Case (dashed line) and the proposed Option 1 (solid line) for a Short-haul Combination Truck equipped with a HHD Class-8 Diesel Engine

The emission repair cost/mile curves shown in Figure 7-4 would result in an incremental cost/mile that is negative for the operating years 2 through 7. During the first year, the incremental cost/mile would be slightly higher due to the marginal technology costs associated with the proposed Option 1 requirements. From years 1 through 7, the cost/mile would be lower on increment due to the longer warranty and useful life periods and the efforts we are estimating manufacturers would undertake to improve durability and to avoid warranty costs after sale (efforts paid for in upfront indirect costs as described in Section 7.1.2 of this draft RIA). In the years of operation beyond the useful life, emission repair costs/mile would then be expected to be marginally higher, again due to the marginal technology costs associated with the proposed Option 1 requirements. Importantly, in those later years of operation, miles driven per year tend to decrease year-over-year which serves to offset somewhat the effect of the higher cost/mile value. In the end, for most vehicle types (i.e., MOVES sourcetypes) our analysis shows that, in general, the net emission repair costs over the first 10 years of operation would decrease (see Table 7-46 through Table 7-55).

To make use of the Fleet Advantage data, and to apply it for all of the MOVES sourcetypes within the scope of the proposed requirements and for each of the proposed options, we have used the following methodology. First, we have determined the estimated warranty and useful life ages analogous to those shown in Table 7-42 for each of the sourcetype and fueltype combinations and for each of the regulatory alternatives. We then scaled the Fleet Advantage cost/mile curve by the direct costs estimated here for each regulatory class relative to the

baseline direct costs for the HHD8 diesel regulatory class. We then adjusted the Fleet Advantage cost/mile curve accordingly for each regulatory class/sourcetype combination in each alternative. Note that the estimated warranty and useful life ages used to determine the in-warranty, beyond-warranty-but-within-useful-life, and beyond-useful-life segments of the cost/mile curves are tied to sourcetypes, which can have very different miles driven per year and, therefore, very different estimated ages.

We believe that it is reasonable to estimate that the emission repair costs would remain at the cost estimated here during the longer warranty periods in each proposed option because of the increased warranty and research and development costs we are estimating in our technology costs. Note that we are also estimating that the emission repair costs beyond the useful life would increase at a slightly higher rate based on the source data which suggested such a trend. Again, cost/mile rates are estimated to flatten beyond the useful life since the source data included operating costs through only 7 years. It is possible that cost/mile rates continue to increase with age and that those would increase at similar rates in the baseline case and under each of the proposed options. If true, the net effect would be the same as estimated here and the net effect is of primary concern in our analysis.

The cost analysis tool developed for this analysis includes the calculations used to determine the emission repair costs per mile for each MOVES sourcetype.³⁷⁶ The resultant emission repair costs/mile under each alternative averaged over the first 10 years of operation are shown in Table 7-46 through Table 7-55.

Table 7-46: Diesel Emission Repair Costs, Average Cost per Mile during the first 10 Years of each MY Lifetime by MOVES Sourcetypes equipped with LHD2b3 Engines (cents/mile in 2017 dollars, Undiscounted)*

MOVES Sourcetype	Scenario	MY2027	MY2031	MY2035
Passenger Trucks	Baseline	0.54	0.54	0.54
	Baseline+Proposed Option 1	0.30	0.18	0.18
	Baseline+Proposed Option 2	0.48	0.47	0.47
	Option 1 increase from Baseline	-0.24	-0.36	-0.36
	Option 2 increase from Baseline	-0.05	-0.07	-0.07
Light Commercial Trucks	Baseline	0.54	0.54	0.54
	Baseline+Proposed Option 1	0.30	0.18	0.18
	Baseline+Proposed Option 2	0.48	0.47	0.47
	Option 1 increase from Baseline	-0.24	-0.36	-0.36
	Option 2 increase from Baseline	-0.05	-0.07	-0.07
Short-Haul Single Unit Trucks	Baseline	0.69	0.69	0.70
	Baseline+Proposed Option 1	0.58	0.22	0.22
	Baseline+Proposed Option 2	0.46	0.45	0.44
	Option 1 increase from Baseline	-0.12	-0.48	-0.48
	Option 2 increase from Baseline	-0.23	-0.25	-0.25
Long-Haul Single Unit Trucks	Baseline	0.93	0.94	0.94
	Baseline+Proposed Option 1	0.97	0.64	0.63
	Baseline+Proposed Option 2	0.83	0.81	0.80
	Option 1 increase from Baseline	0.04	-0.30	-0.31
	Option 2 increase from Baseline	-0.11	-0.13	-0.14

* Negative values denote lower costs, i.e., savings in emission repair expenditures. As discussed in Section 5.2.2.5, we did not include diesel-fueled, engine-certified LHD2b3 vehicles in the baseline emission inventory, but we did include these vehicles in our emission inventory estimates for the proposed Options 1 and 2 control scenarios. We decided to include the engine-certified LHD2b3 vehicles in the emissions inventories of the control scenario to better estimate the projected emissions of heavy-duty vehicles in the control scenarios, even though it will conservatively underestimate the benefits of controlling these vehicles. As a result, the NO_x emission inventories may demonstrate an increase in emissions from Sourcetypes containing diesel-fueled LHD2b3 vehicles for certain calendar years. We plan to update our baseline modeling to reflect any requirements for diesel-fueled, engine-certified LHD2b3 vehicles in the final rulemaking. In addition, the MOVES baseline emission rates for all LHD diesel (not just 2b3 vehicles) were incorrectly developed using a warranty period of 100K instead of 50K, and thus we underestimated the LHD diesel emissions impact of the longer warranty periods in the proposal and alternative scenarios. We will update the baseline warranty period for LHD diesel in the FRM analysis.

Table 7-47: Diesel Emission Repair Costs, Average Cost per Mile during the first 10 Years of each MY Lifetime by MOVES Sourcetypes equipped with LHD45 Engines (*cents/mile* in 2017 dollars, Undiscounted) *

MOVES Sourcetype	Scenario	MY2027	MY2031	MY2035
Other Buses	Baseline	0.95	0.95	0.95
	Baseline+Proposed Option 1	1.03	0.69	0.68
	Baseline+Proposed Option 2	0.88	0.86	0.85
	Option 1 increase from Baseline	0.08	-0.25	-0.26
	Option 2 increase from Baseline	-0.07	-0.09	-0.10
Transit Buses	Baseline	0.95	0.95	0.95
	Baseline+Proposed Option 1	1.03	0.69	0.68
	Baseline+Proposed Option 2	0.88	0.86	0.85
	Option 1 increase from Baseline	0.08	-0.25	-0.26
	Option 2 increase from Baseline	-0.07	-0.09	-0.10
School Buses	Baseline	0.36	0.36	0.36
	Baseline+Proposed Option 1	0.32	0.18	0.18
	Baseline+Proposed Option 2	0.52	0.51	0.50
	Option 1 increase from Baseline	-0.04	-0.18	-0.18
	Option 2 increase from Baseline	0.16	0.14	0.14
Short-Haul Single Unit Trucks	Baseline	0.70	0.70	0.70
	Baseline+Proposed Option 1	0.58	0.22	0.22
	Baseline+Proposed Option 2	0.46	0.45	0.44
	Option 1 increase from Baseline	-0.11	-0.48	-0.48
	Option 2 increase from Baseline	-0.23	-0.25	-0.25
Long-Haul Single Unit Trucks	Baseline	0.94	0.94	0.94
	Baseline+Proposed Option 1	0.98	0.64	0.63
	Baseline+Proposed Option 2	0.84	0.81	0.80
	Option 1 increase from Baseline	0.04	-0.30	-0.31
	Option 2 increase from Baseline	-0.10	-0.13	-0.14

* Negative values denote lower costs, i.e., savings in emission repair expenditures.

Table 7-48: Diesel Emission Repair Costs, Average Cost per Mile during the first 10 Years of each MY Lifetime by MOVES Sourcetypes equipped with MHD67 Engines (*cents/mile* in 2017 dollars, Undiscounted) *

MOVES Sourcetype	Scenario	MY2027	MY2031	MY2035
Other Buses	Baseline	0.80	0.80	0.80
	Baseline+Proposed Option 1	0.74	0.48	0.47
	Baseline+Proposed Option 2	0.65	0.64	0.63
	Option 1 increase from Baseline	-0.06	-0.33	-0.33
	Option 2 increase from Baseline	-0.15	-0.16	-0.17
Transit Buses	Baseline	0.80	0.80	0.80
	Baseline+Proposed Option 1	0.74	0.48	0.47
	Baseline+Proposed Option 2	0.65	0.64	0.63
	Option 1 increase from Baseline	-0.06	-0.33	-0.33
	Option 2 increase from Baseline	-0.15	-0.16	-0.17
School Buses	Baseline	0.38	0.38	0.38
	Baseline+Proposed Option 1	0.36	0.19	0.18
	Baseline+Proposed Option 2	0.54	0.52	0.52
	Option 1 increase from Baseline	-0.02	-0.20	-0.20
	Option 2 increase from Baseline	0.15	0.14	0.13
Refuse Trucks	Baseline	0.72	0.72	0.72
	Baseline+Proposed Option 1	0.48	0.23	0.23
	Baseline+Proposed Option 2	0.50	0.48	0.48
	Option 1 increase from Baseline	-0.24	-0.49	-0.49
	Option 2 increase from Baseline	-0.23	-0.24	-0.25
Short-Haul Single Unit Trucks	Baseline	0.51	0.51	0.51
	Baseline+Proposed Option 1	0.33	0.19	0.18
	Baseline+Proposed Option 2	0.48	0.47	0.46
	Option 1 increase from Baseline	-0.18	-0.33	-0.33
	Option 2 increase from Baseline	-0.03	-0.05	-0.05
Long-Haul Single Unit Trucks	Baseline	0.77	0.77	0.77
	Baseline+Proposed Option 1	0.68	0.39	0.43
	Baseline+Proposed Option 2	0.61	0.60	0.59
	Option 1 increase from Baseline	-0.09	-0.39	-0.35
	Option 2 increase from Baseline	-0.16	-0.18	-0.19
Motor Homes	Baseline	0.38	0.38	0.38
	Baseline+Proposed Option 1	0.36	0.19	0.18
	Baseline+Proposed Option 2	0.53	0.51	0.51
	Option 1 increase from Baseline	-0.02	-0.19	-0.19
	Option 2 increase from Baseline	0.15	0.14	0.13
Short-Haul Combination Trucks	Baseline	1.13	1.13	1.13
	Baseline+Proposed Option 1	1.22	0.99	0.98
	Baseline+Proposed Option 2	1.28	1.24	1.22
	Option 1 increase from Baseline	0.08	-0.14	-0.15
	Option 2 increase from Baseline	0.15	0.11	0.09

Table 7-49: Diesel Emission Repair Costs, Average Cost per Mile during the first 10 Years of each MY Lifetime by MOVES Sourcetypes equipped with HHD8 Engines (*cents/mile* in 2017 dollars, Undiscounted) *

MOVES Sourcetype	Scenario	MY2027	MY2031	MY2035
Other Buses	Baseline	0.70	0.70	0.70
	Baseline+Proposed Option 1	0.53	0.29	0.28
	Baseline+Proposed Option 2	0.77	0.75	0.74
	Option 1 increase from Baseline	-0.18	-0.42	-0.42
	Option 2 increase from Baseline	0.07	0.05	0.04
School Buses	Baseline	0.62	0.61	0.61
	Baseline+Proposed Option 1	0.56	0.29	0.28
	Baseline+Proposed Option 2	0.83	0.81	0.80
	Option 1 increase from Baseline	-0.06	-0.33	-0.33
	Option 2 increase from Baseline	0.21	0.19	0.18
Refuse Trucks	Baseline	0.70	0.70	0.70
	Baseline+Proposed Option 1	0.52	0.29	0.28
	Baseline+Proposed Option 2	0.76	0.74	0.73
	Option 1 increase from Baseline	-0.18	-0.41	-0.41
	Option 2 increase from Baseline	0.06	0.04	0.04
Short-Haul Single Unit Trucks	Baseline	0.61	0.61	0.61
	Baseline+Proposed Option 1	0.50	0.29	0.28
	Baseline+Proposed Option 2	0.73	0.72	0.71
	Option 1 increase from Baseline	-0.11	-0.33	-0.33
	Option 2 increase from Baseline	0.12	0.11	0.10
Long-Haul Single Unit Trucks	Baseline	0.67	0.67	0.67
	Baseline+Proposed Option 1	0.49	0.29	0.28
	Baseline+Proposed Option 2	0.72	0.70	0.70
	Option 1 increase from Baseline	-0.18	-0.38	-0.39
	Option 2 increase from Baseline	0.05	0.03	0.03
Motor Homes	Baseline	0.60	0.60	0.60
	Baseline+Proposed Option 1	0.55	0.29	0.28
	Baseline+Proposed Option 2	0.81	0.79	0.78
	Option 1 increase from Baseline	-0.05	-0.32	-0.32
	Option 2 increase from Baseline	0.21	0.19	0.18
Short-Haul Combination Trucks	Baseline	1.27	1.26	1.26
	Baseline+Proposed Option 1	0.91	0.48	0.47
	Baseline+Proposed Option 2	0.86	0.97	0.95
	Option 1 increase from Baseline	-0.36	-0.79	-0.79
	Option 2 increase from Baseline	-0.41	-0.30	-0.31
Long-Haul Combination Trucks	Baseline	1.69	1.69	1.68
	Baseline+Proposed Option 1	1.90	1.57	1.55
	Baseline+Proposed Option 2	1.82	1.94	1.91
	Option 1 increase from Baseline	0.20	-0.12	-0.13
	Option 2 increase from Baseline	0.12	0.25	0.23

* Negative values denote lower costs, i.e., savings in emission repair expenditures.

Table 7-50: Diesel Emission Repair Costs, Average Cost per Mile during the first 10 Years of each MY Lifetime by MOVES Sourcetypes equipped with Urban Bus Engines (*cents/mile* in 2017 dollars, Undiscounted) *

MOVES Sourcetype	Scenario	MY2027	MY2031	MY2035
Transit Buses	Baseline	0.45	0.45	0.44
	Baseline+Proposed Option 1	0.35	0.19	0.19
	Baseline+Proposed Option 2	0.51	0.50	0.49
	Option 1 increase from Baseline	-0.10	-0.26	-0.26
	Option 2 increase from Baseline	0.07	0.05	0.05

* Negative values denote lower costs, i.e., savings in emission repair expenditures.

Table 7-51: Gasoline Emission Repair Costs, Average Cost per Mile during the first 10 Years of each MY Lifetime by MOVES Sourcetypes equipped with LHD45 Engines (*cents/mile* in 2017 dollars, Undiscounted)*

MOVES Sourcetype	Scenario	MY2027	MY2031	MY2035
Other Buses	Baseline	0.22	0.22	0.22
	Baseline+Proposed Option 1	0.27	0.23	0.22
	Baseline+Proposed Option 2	0.25	0.24	0.24
	Option 1 increase from Baseline	0.06	0.01	0.01
	Option 2 increase from Baseline	0.03	0.02	0.02
Transit Buses	Baseline	0.22	0.22	0.22
	Baseline+Proposed Option 1	0.27	0.23	0.22
	Baseline+Proposed Option 2	0.25	0.24	0.24
	Option 1 increase from Baseline	0.06	0.01	0.01
	Option 2 increase from Baseline	0.03	0.02	0.02
School Buses	Baseline	0.08	0.08	0.08
	Baseline+Proposed Option 1	0.07	0.04	0.04
	Baseline+Proposed Option 2	0.12	0.12	0.11
	Option 1 increase from Baseline	-0.01	-0.04	-0.04
	Option 2 increase from Baseline	0.04	0.04	0.03
Short-Haul Single Unit Trucks	Baseline	0.17	0.17	0.17
	Baseline+Proposed Option 1	0.17	0.10	0.12
	Baseline+Proposed Option 2	0.13	0.12	0.14
	Option 1 increase from Baseline	0.00	-0.07	-0.06
	Option 2 increase from Baseline	-0.05	-0.05	-0.03
Long-Haul Single Unit Trucks	Baseline	0.22	0.22	0.22
	Baseline+Proposed Option 1	0.27	0.22	0.22
	Baseline+Proposed Option 2	0.24	0.23	0.23
	Option 1 increase from Baseline	0.05	0.00	0.00
	Option 2 increase from Baseline	0.02	0.02	0.01
Motor Homes	Baseline	0.08	0.08	0.08
	Baseline+Proposed Option 1	0.07	0.04	0.04
	Baseline+Proposed Option 2	0.12	0.11	0.11
	Option 1 increase from Baseline	-0.01	-0.04	-0.04
	Option 2 increase from Baseline	0.04	0.04	0.03

* Negative values denote lower costs, i.e., savings in emission repair expenditures.

Table 7-52: Gasoline Emission Repair Costs, Average Cost per Mile during the first 10 Years of each MY Lifetime by MOVES Sourcetypes equipped with MHD67 Engines (*cents/mile* in 2017 dollars, Undiscounted)*

MOVES Sourcetype	Scenario	MY2027	MY2031	MY2035
Short-Haul Single Unit Trucks	Baseline	0.17	0.17	0.17
	Baseline+Proposed Option 1	0.17	0.10	0.12
	Baseline+Proposed Option 2	0.13	0.12	0.14
	Option 1 increase from Baseline	0.00	-0.07	-0.06
	Option 2 increase from Baseline	-0.05	-0.05	-0.03
Long-Haul Single Unit Trucks	Baseline	0.22	0.22	0.22
	Baseline+Proposed Option 1	0.27	0.22	0.22
	Baseline+Proposed Option 2	0.24	0.23	0.23
	Option 1 increase from Baseline	0.05	0.00	0.00
	Option 2 increase from Baseline	0.02	0.02	0.01
Motor Homes	Baseline	0.08	0.08	0.08
	Baseline+Proposed Option 1	0.07	0.04	0.04
	Baseline+Proposed Option 2	0.12	0.11	0.11
	Option 1 increase from Baseline	-0.01	-0.04	-0.04
	Option 2 increase from Baseline	0.04	0.04	0.03

* Negative values denote lower costs, i.e., savings in emission repair expenditures.

Table 7-53: Gasoline Emission Repair Costs, Average Cost per Mile during the first 10 Years of each MY Lifetime by MOVES Sourcetypes equipped with HHD8 Engines (*cents/mile* in 2017 dollars, Undiscounted)*

MOVES Sourcetype	Scenario	MY2027	MY2031	MY2035
Short-Haul Single Unit Trucks	Baseline	0.17	0.17	0.17
	Baseline+Proposed Option 1	0.17	0.10	0.12
	Baseline+Proposed Option 2	0.13	0.12	0.14
	Option 1 increase from Baseline	0.00	-0.07	-0.06
	Option 2 increase from Baseline	-0.05	-0.05	-0.03
Long-Haul Single Unit Trucks	Baseline	0.22	0.22	0.22
	Baseline+Proposed Option 1	0.27	0.22	0.22
	Baseline+Proposed Option 2	0.24	0.23	0.23
	Option 1 increase from Baseline	0.05	0.00	0.00
	Option 2 increase from Baseline	0.02	0.02	0.01
Motor Homes	Baseline	0.08	0.08	0.08
	Baseline+Proposed Option 1	0.07	0.04	0.04
	Baseline+Proposed Option 2	0.12	0.11	0.11
	Option 1 increase from Baseline	-0.01	-0.04	-0.04
	Option 2 increase from Baseline	0.04	0.04	0.03

* Negative values denote lower costs, i.e., savings in emission repair expenditures.

Table 7-54: CNG Emission Repair Costs, Average Cost per Mile during the first 10 Years of each MY Lifetime by MOVES Sourcetypes equipped with HHD8 Engines (*cents/mile* in 2017 dollars, Undiscounted)*

MOVES Sourcetype	Scenario	MY2027	MY2031	MY2035
Other Buses	Baseline	0.45	0.45	0.45
	Baseline+Proposed Option 1	0.25	0.14	0.14
	Baseline+Proposed Option 2	0.37	0.37	0.37
	Option 1 increase from Baseline	-0.20	-0.31	-0.31
	Option 2 increase from Baseline	-0.08	-0.08	-0.08
School Buses	Baseline	0.39	0.39	0.39
	Baseline+Proposed Option 1	0.27	0.14	0.14
	Baseline+Proposed Option 2	0.39	0.39	0.39
	Option 1 increase from Baseline	-0.12	-0.25	-0.25
	Option 2 increase from Baseline	0.00	0.00	0.00
Refuse Trucks	Baseline	0.44	0.44	0.44
	Baseline+Proposed Option 1	0.25	0.14	0.14
	Baseline+Proposed Option 2	0.36	0.36	0.36
	Option 1 increase from Baseline	-0.20	-0.30	-0.30
	Option 2 increase from Baseline	-0.08	-0.08	-0.08
Short-Haul Single Unit Trucks	Baseline	0.39	0.39	0.39
	Baseline+Proposed Option 1	0.24	0.14	0.14
	Baseline+Proposed Option 2	0.35	0.35	0.35
	Option 1 increase from Baseline	-0.15	-0.25	-0.25
	Option 2 increase from Baseline	-0.04	-0.04	-0.04
Long-Haul Single Unit Trucks	Baseline	0.43	0.43	0.43
	Baseline+Proposed Option 1	0.24	0.14	0.14
	Baseline+Proposed Option 2	0.34	0.34	0.34
	Option 1 increase from Baseline	-0.19	-0.29	-0.29
	Option 2 increase from Baseline	-0.08	-0.08	-0.08
Short-Haul Combination Trucks	Baseline	0.81	0.80	0.80
	Baseline+Proposed Option 1	0.43	0.23	0.23
	Baseline+Proposed Option 2	0.41	0.47	0.47
	Option 1 increase from Baseline	-0.37	-0.57	-0.57
	Option 2 increase from Baseline	-0.40	-0.33	-0.33

* Negative values denote lower costs, i.e., savings in emission repair expenditures.

Table 7-55: CNG Emission Repair Costs, Average Cost per Mile during the first 10 Years of each MY Lifetime by MOVES Sourcetypes equipped with Urban Bus Engines (*cents/mile* in 2017 dollars, Undiscounted) *

MOVES Sourcetype	Scenario	MY2027	MY2031	MY2035
Transit Buses	Baseline	0.34	0.34	0.34
	Baseline+Proposed Option 1	0.19	0.10	0.10
	Baseline+Proposed Option 2	0.28	0.28	0.28
	Option 1 increase from Baseline	-0.15	-0.23	-0.23
	Option 2 increase from Baseline	-0.06	-0.06	-0.06

* Negative values denote lower costs, i.e., savings in emission repair expenditures.

7.3 Program Costs

Using the cost elements outlined above, we have estimated the costs associated with the proposed criteria pollutant standards as presented in the following tables. Costs are broken into

two main categories: Technology Costs and Operating Costs. Technology costs are broken further into direct costs and the indirect costs elements (warranty costs, R&D costs, other indirect costs and profits) to arrive at total technology costs. Operating costs are broken into urea/DEF costs (diesel only), fuel savings (gasoline only) and repair costs. Section 7.3.1 present the total technology costs for each proposed option relative to the baseline case, broken down by class, showing diesel and gasoline separately as well as combined. Section 7.3.2 presents the operating costs, similarly grouped. Section 7.3.3 presents the total program costs relative to the baseline case for each proposed option. Costs are presented in 2017 dollars in undiscounted annual values along with present values at both 3 and 7 percent discount rates with values discounted to the 2019 calendar year.

As noted in the introductory text to this chapter, the costs presented here reflect our best estimate of the costs to society. Total program costs under the two proposed options are presented in terms of calendar year 2045 costs, present value costs, and annualized costs (see Table 7-98 and Table 7-99).^{MMMMMM}

We are not including an analysis of the costs of the Alternative (described in Sections III and IV) because we currently do not have sufficient information to conclude that the Alternative standards would be feasible in the MY2027 timeframe. Section III presents our current feasibility analysis for the Alternative.

7.3.1 **Total Technology Costs**

The series of tables shown here show direct manufacturing, warranty, R&D, profits, other indirect costs and total technology costs by fuel type, then by regulatory class for each of the proposed options. Values shown for a given calendar year are undiscounted values while discounted values are presented at both 3 and 7 percent discount rates. All values are shown in 2017 dollars.

^{MMMMMM} The costs presented in Table 7-98 and Table 7-99 are presented again in Table ES ,which summarizes the net benefits of the two proposed options.

Table 7-56: Technology Cost Impacts of the Proposed Option 1 Relative to the Baseline Case, Diesel, Millions of 2017 dollars *

Calendar Year	Direct Manufacturing Costs	Warranty Costs	R&D Costs	Other Indirect Costs	Profits	Total Technology Costs
2027	\$950	\$290	\$130	\$280	\$48	\$1,700
2028	\$920	\$280	\$130	\$270	\$46	\$1,600
2029	\$900	\$280	\$120	\$260	\$45	\$1,600
2030	\$880	\$280	\$44	\$260	\$44	\$1,500
2031	\$870	\$390	\$100	\$250	\$43	\$1,700
2032	\$850	\$390	\$100	\$250	\$42	\$1,600
2033	\$830	\$390	\$98	\$240	\$42	\$1,600
2034	\$820	\$380	\$41	\$240	\$41	\$1,500
2035	\$820	\$380	\$41	\$240	\$41	\$1,500
2036	\$810	\$380	\$41	\$240	\$41	\$1,500
2037	\$800	\$380	\$40	\$230	\$40	\$1,500
2038	\$800	\$380	\$40	\$230	\$40	\$1,500
2039	\$800	\$380	\$40	\$230	\$40	\$1,500
2040	\$800	\$380	\$40	\$230	\$40	\$1,500
2041	\$800	\$390	\$40	\$230	\$40	\$1,500
2042	\$800	\$390	\$40	\$230	\$40	\$1,500
2043	\$800	\$390	\$40	\$230	\$40	\$1,500
2044	\$800	\$390	\$40	\$230	\$40	\$1,500
2045	\$810	\$390	\$40	\$230	\$40	\$1,500
PV, 3%	\$12,000	\$5,100	\$970	\$3,500	\$600	\$22,000
PV, 7%	\$8,800	\$3,600	\$760	\$2,600	\$440	\$16,000

* Values show 2 significant digits. Note that the Information Collection Request costs addressed in Section XIII of the preamble would fall within the "Other" indirect costs shown here.

Table 7-57: Technology Cost Impacts of the Proposed Option 2 Relative to the Baseline Case, Diesel, Millions of 2017 dollars *

Calendar Year	Direct Manufacturing Costs	Warranty Costs	R&D Costs	Other Indirect Costs	Profits	Total Technology Costs
2027	\$950	\$200	\$170	\$280	\$48	\$1,600
2028	\$920	\$200	\$170	\$270	\$46	\$1,600
2029	\$900	\$200	\$160	\$260	\$45	\$1,600
2030	\$880	\$190	\$44	\$260	\$44	\$1,400
2031	\$870	\$190	\$43	\$250	\$43	\$1,400
2032	\$850	\$190	\$42	\$250	\$42	\$1,400
2033	\$830	\$190	\$42	\$240	\$42	\$1,300
2034	\$820	\$190	\$41	\$240	\$41	\$1,300
2035	\$820	\$190	\$41	\$240	\$41	\$1,300
2036	\$810	\$190	\$41	\$240	\$41	\$1,300
2037	\$800	\$190	\$40	\$230	\$40	\$1,300
2038	\$800	\$180	\$40	\$230	\$40	\$1,300
2039	\$800	\$190	\$40	\$230	\$40	\$1,300
2040	\$800	\$190	\$40	\$230	\$40	\$1,300
2041	\$800	\$190	\$40	\$230	\$40	\$1,300
2042	\$800	\$190	\$40	\$230	\$40	\$1,300
2043	\$800	\$190	\$40	\$230	\$40	\$1,300
2044	\$800	\$190	\$40	\$230	\$40	\$1,300
2045	\$810	\$190	\$40	\$230	\$40	\$1,300
PV, 3%	\$12,000	\$2,700	\$940	\$3,500	\$600	\$20,000
PV, 7%	\$8,800	\$2,000	\$750	\$2,600	\$440	\$15,000

* Values show 2 significant digits. Note that the Information Collection Request costs addressed in Section XIII of the preamble would fall within the "Other" indirect costs shown here.

Table 7-58: Technology Cost Impacts of the Proposed Option 1 Relative to the Baseline Case, Diesel by Regulatory Class, Millions of 2017 dollars, Present Values at 3% Discounting *

	Direct Manufacturing Costs	Warranty Costs	R&D Costs	Other Indirect Costs	Profits	Total Technology Costs
LHD	\$280	\$37	\$26	\$81	\$14	\$440
LHD45	\$1,700	\$230	\$150	\$500	\$86	\$2,700
MHD67	\$3,400	\$740	\$270	\$990	\$170	\$5,600
HHD8	\$6,600	\$4,100	\$520	\$1,900	\$330	\$13,000
Urban bus	\$100	\$56	\$7.6	\$29	\$5.0	\$200
Sum	\$12,000	\$5,100	\$970	\$3,500	\$600	\$22,000

* Values show 2 significant digits.

Table 7-59: Technology Cost Impacts of the Proposed Option 2 Relative to the Baseline Case, Diesel by Regulatory Class, Millions of 2017 dollars, Present Values at 3% Discounting *

	Direct Manufacturing Costs	Warranty Costs	R&D Costs	Other Indirect Costs	Profits	Total Technology Costs
LHD	\$280	\$11	\$28	\$81	\$14	\$420
LHD45	\$1,700	\$70	\$170	\$500	\$86	\$2,500
MHD67	\$3,400	\$300	\$270	\$990	\$170	\$5,100
HHD8	\$6,600	\$2,300	\$470	\$1,900	\$330	\$12,000
Urban bus	\$100	\$32	\$6.9	\$29	\$5.0	\$170
Sum	\$12,000	\$2,700	\$940	\$3,500	\$600	\$20,000

* Values show 2 significant digits.

Table 7-60: Technology Cost Impacts of the Proposed Option 1 Relative to the Baseline Case, Diesel by Regulatory Class, Millions of 2017 dollars, Present Values at 7% Discounting *

	Direct Manufacturing Costs	Warranty Costs	R&D Costs	Other Indirect Costs	Profits	Total Technology Costs
LHD	\$210	\$26	\$21	\$60	\$10	\$320
LHD45	\$1,300	\$160	\$120	\$360	\$63	\$2,000
MHD67	\$2,500	\$530	\$210	\$720	\$120	\$4,100
HHD8	\$4,800	\$2,900	\$410	\$1,400	\$240	\$9,700
Urban bus	\$73	\$39	\$5.9	\$21	\$3.7	\$140
Sum	\$8,800	\$3,600	\$760	\$2,600	\$440	\$16,000

* Values show 2 significant digits.

Table 7-61: Technology Cost Impacts of the Proposed Option 2 Relative to the Baseline Case, Diesel by Regulatory Class, Millions of 2017 dollars, Present Values at 7% Discounting *

	Direct Manufacturing Costs	Warranty Costs	R&D Costs	Other Indirect Costs	Profits	Total Technology Costs
LHD	\$210	\$8.4	\$23	\$60	\$10	\$310
LHD45	\$1,300	\$51	\$140	\$360	\$63	\$1,900
MHD67	\$2,500	\$220	\$220	\$720	\$120	\$3,800
HHD8	\$4,800	\$1,700	\$370	\$1,400	\$240	\$8,400
Urban bus	\$73	\$23	\$5.4	\$21	\$3.7	\$130
Sum	\$8,800	\$2,000	\$750	\$2,600	\$440	\$15,000

* Values show 2 significant digits.

**Table 7-62: Technology Cost Impacts of the Proposed Option 1 Relative to the Baseline Case, Gasoline,
Millions of 2017 dollars ***

Calendar Year	Direct Manufacturing Costs	Warranty Costs	R&D Costs	Other Indirect Costs	Profits	Total Technology Costs
2027	\$41	\$5.7	\$4.6	\$15	\$2.5	\$69
2028	\$40	\$5.6	\$4.5	\$14	\$2.4	\$67
2029	\$39	\$5.6	\$4.4	\$14	\$2.3	\$65
2030	\$38	\$5.5	\$1.9	\$14	\$2.3	\$62
2031	\$37	\$9.0	\$3.6	\$13	\$2.2	\$66
2032	\$37	\$8.9	\$3.6	\$13	\$2.2	\$65
2033	\$36	\$8.8	\$3.5	\$13	\$2.2	\$63
2034	\$36	\$8.8	\$1.8	\$13	\$2.1	\$61
2035	\$35	\$8.7	\$1.8	\$13	\$2.1	\$61
2036	\$35	\$8.7	\$1.8	\$13	\$2.1	\$60
2037	\$35	\$8.7	\$1.7	\$13	\$2.1	\$60
2038	\$35	\$8.7	\$1.7	\$12	\$2.1	\$60
2039	\$35	\$8.7	\$1.7	\$12	\$2.1	\$60
2040	\$35	\$8.7	\$1.7	\$12	\$2.1	\$60
2041	\$35	\$8.8	\$1.7	\$13	\$2.1	\$60
2042	\$35	\$8.8	\$1.7	\$13	\$2.1	\$60
2043	\$35	\$8.9	\$1.7	\$13	\$2.1	\$60
2044	\$35	\$8.9	\$1.7	\$13	\$2.1	\$60
2045	\$35	\$8.9	\$1.8	\$13	\$2.1	\$60
PV, 3%	\$520	\$110	\$38	\$190	\$31	\$890
PV, 7%	\$380	\$80	\$29	\$140	\$23	\$650

* Values show 2 significant digits. Note that the Information Collection Request costs addressed in Section XIII of the preamble would fall within the "Other" indirect costs shown here.

**Table 7-63: Technology Cost Impacts of the Proposed Option 2 Relative to the Baseline Case, Gasoline,
Millions of 2017 dollars ***

Calendar Year	Direct Manufacturing Costs	Warranty Costs	R&D Costs	Other Indirect Costs	Profits	Total Technology Costs
2027	\$41	\$5.7	\$7.1	\$15	\$2.5	\$71
2028	\$40	\$5.6	\$7.0	\$14	\$2.4	\$69
2029	\$39	\$5.6	\$6.9	\$14	\$2.3	\$68
2030	\$38	\$5.5	\$1.9	\$14	\$2.3	\$62
2031	\$37	\$5.4	\$1.9	\$13	\$2.2	\$61
2032	\$37	\$5.4	\$1.8	\$13	\$2.2	\$59
2033	\$36	\$5.3	\$1.8	\$13	\$2.2	\$58
2034	\$36	\$5.3	\$1.8	\$13	\$2.1	\$58
2035	\$35	\$5.2	\$1.8	\$13	\$2.1	\$57
2036	\$35	\$5.2	\$1.8	\$13	\$2.1	\$57
2037	\$35	\$5.2	\$1.7	\$13	\$2.1	\$56
2038	\$35	\$5.2	\$1.7	\$12	\$2.1	\$56
2039	\$35	\$5.2	\$1.7	\$12	\$2.1	\$56
2040	\$35	\$5.2	\$1.7	\$12	\$2.1	\$56
2041	\$35	\$5.3	\$1.7	\$13	\$2.1	\$56
2042	\$35	\$5.3	\$1.7	\$13	\$2.1	\$56
2043	\$35	\$5.3	\$1.7	\$13	\$2.1	\$57
2044	\$35	\$5.3	\$1.7	\$13	\$2.1	\$57
2045	\$35	\$5.3	\$1.8	\$13	\$2.1	\$57
PV, 3%	\$520	\$77	\$40	\$190	\$31	\$860
PV, 7%	\$380	\$56	\$32	\$140	\$23	\$630

* Values show 2 significant digits. Note that the Information Collection Request costs addressed in Section XIII of the preamble would fall within the "Other" indirect costs shown here.

**Table 7-64: Technology Cost Impacts of the Proposed Option 1 Relative to the Baseline Case, Gasoline by
Regulatory Class, Millions of 2017 dollars, Present Values at 3% Discounting ***

	Direct Manufacturing Costs	Warranty Costs	R&D Costs	Other Indirect Costs	Profits	Total Technology Costs
LHD45	\$340	\$74	\$24	\$120	\$20	\$580
MHD67	\$150	\$34	\$11	\$56	\$9.3	\$260
HHD8	\$29	\$6.3	\$2.1	\$10	\$1.7	\$49
Sum	\$520	\$110	\$38	\$190	\$31	\$890

* Values show 2 significant digits.

**Table 7-65: Technology Cost Impacts of the Proposed Option 2 Relative to the Baseline Case, Gasoline by
Regulatory Class, Millions of 2017 dollars, Present Values at 3% Discounting ***

	Direct Manufacturing Costs	Warranty Costs	R&D Costs	Other Indirect Costs	Profits	Total Technology Costs
LHD45	\$340	\$50	\$26	\$120	\$20	\$560
MHD67	\$150	\$23	\$12	\$56	\$9.3	\$250
HHD8	\$29	\$4.2	\$2.2	\$10	\$1.7	\$47
Sum	\$520	\$77	\$40	\$190	\$31	\$860

* Values show 2 significant digits.

Table 7-66: Technology Cost Impacts of the Proposed Option 1 Relative to the Baseline Case, Gasoline by Regulatory Class, Millions of 2017 dollars, Present Values at 7% Discounting *

	Direct Manufacturing Costs	Warranty Costs	R&D Costs	Other Indirect Costs	Profits	Total Technology Costs
LHD45	\$250	\$52	\$19	\$89	\$15	\$420
MHD67	\$110	\$24	\$8.6	\$41	\$6.8	\$190
HHD8	\$21	\$4.4	\$1.6	\$7.5	\$1.3	\$36
Sum	\$380	\$80	\$29	\$140	\$23	\$650

* Values show 2 significant digits.

Table 7-67: Technology Cost Impacts of the Proposed Option 2 Relative to the Baseline Case, Gasoline by Regulatory Class, Millions of 2017 dollars, Present Values at 7% Discounting *

	Direct Manufacturing Costs	Warranty Costs	R&D Costs	Other Indirect Costs	Profits	Total Technology Costs
LHD45	\$250	\$36	\$21	\$89	\$15	\$410
MHD67	\$110	\$16	\$10	\$41	\$6.8	\$190
HHD8	\$21	\$3.0	\$1.8	\$7.5	\$1.3	\$34
Sum	\$380	\$56	\$32	\$140	\$23	\$630

* Values show 2 significant digits.

Table 7-68: Technology Cost Impacts of the Proposed Option 1 Relative to the Baseline Case, CNG, Millions of 2017 dollars *

Calendar Year	Direct Manufacturing Costs	Warranty Costs	R&D Costs	Other Indirect Costs	Profits	Total Technology Costs
2027	\$0.30	\$4.9	\$0.89	\$0.087	\$0.015	\$6.2
2028	\$0.29	\$4.9	\$0.90	\$0.084	\$0.015	\$6.2
2029	\$0.28	\$4.9	\$0.90	\$0.083	\$0.014	\$6.2
2030	\$0.28	\$4.9	\$0.01	\$0.081	\$0.014	\$5.3
2031	\$0.27	\$7.0	\$0.79	\$0.079	\$0.014	\$8.1
2032	\$0.27	\$6.9	\$0.78	\$0.078	\$0.013	\$8.1
2033	\$0.26	\$6.9	\$0.77	\$0.076	\$0.013	\$8.0
2034	\$0.26	\$6.8	\$0.013	\$0.075	\$0.013	\$7.2
2035	\$0.26	\$6.8	\$0.013	\$0.075	\$0.013	\$7.2
2036	\$0.26	\$6.8	\$0.013	\$0.074	\$0.013	\$7.2
2037	\$0.25	\$6.8	\$0.013	\$0.074	\$0.013	\$7.2
2038	\$0.25	\$6.8	\$0.013	\$0.073	\$0.013	\$7.2
2039	\$0.25	\$6.9	\$0.013	\$0.073	\$0.013	\$7.2
2040	\$0.25	\$6.9	\$0.013	\$0.073	\$0.013	\$7.3
2041	\$0.25	\$7.0	\$0.013	\$0.073	\$0.013	\$7.3
2042	\$0.25	\$7.0	\$0.013	\$0.073	\$0.013	\$7.3
2043	\$0.25	\$7.0	\$0.013	\$0.074	\$0.013	\$7.4
2044	\$0.25	\$7.1	\$0.013	\$0.074	\$0.013	\$7.4
2045	\$0.25	\$7.1	\$0.013	\$0.074	\$0.013	\$7.4
PV, 3%	\$3.8	\$91	\$4.6	\$1.1	\$0.19	\$100
PV, 7%	\$2.8	\$65	\$4.0	\$0.80	\$0.14	\$72

* Values show 2 significant digits. Note that the Information Collection Request costs addressed in Section XIII of the preamble would fall within the "Other" indirect costs shown here.

Table 7-69: Technology Cost Impacts of the Proposed Option 2 Relative to the Baseline Case, CNG, Millions of 2017 dollars *

Calendar Year	Direct Manufacturing Costs	Warranty Costs	R&D Costs	Other Indirect Costs	Profits	Total Technology Costs
2027	\$0.30	\$3.5	\$1.2	\$0.087	\$0.015	\$5.0
2028	\$0.29	\$3.5	\$1.2	\$0.084	\$0.015	\$5.0
2029	\$0.28	\$3.5	\$1.2	\$0.083	\$0.014	\$5.0
2030	\$0.28	\$3.5	\$0.014	\$0.081	\$0.014	\$3.9
2031	\$0.27	\$3.5	\$0.014	\$0.079	\$0.014	\$3.9
2032	\$0.27	\$3.5	\$0.013	\$0.078	\$0.013	\$3.8
2033	\$0.26	\$3.4	\$0.013	\$0.076	\$0.013	\$3.8
2034	\$0.26	\$3.4	\$0.013	\$0.075	\$0.013	\$3.8
2035	\$0.26	\$3.4	\$0.013	\$0.075	\$0.013	\$3.8
2036	\$0.26	\$3.4	\$0.013	\$0.074	\$0.013	\$3.8
2037	\$0.25	\$3.4	\$0.013	\$0.074	\$0.013	\$3.8
2038	\$0.25	\$3.4	\$0.013	\$0.073	\$0.013	\$3.8
2039	\$0.25	\$3.4	\$0.013	\$0.073	\$0.013	\$3.8
2040	\$0.25	\$3.5	\$0.013	\$0.073	\$0.013	\$3.8
2041	\$0.25	\$3.5	\$0.013	\$0.073	\$0.013	\$3.8
2042	\$0.25	\$3.5	\$0.013	\$0.073	\$0.013	\$3.8
2043	\$0.25	\$3.5	\$0.013	\$0.074	\$0.013	\$3.9
2044	\$0.25	\$3.5	\$0.013	\$0.074	\$0.013	\$3.9
2045	\$0.25	\$3.6	\$0.013	\$0.074	\$0.013	\$3.9
PV, 3%	\$3.8	\$50	\$3.4	\$1.1	\$0.19	\$58
PV, 7%	\$2.8	\$36	\$3.1	\$0.80	\$0.14	\$43

* Values show 2 significant digits. Note that the Information Collection Request costs addressed in Section XIII of the preamble would fall within the "Other" indirect costs shown here.

Table 7-70: Technology Cost Impacts of the Proposed Option 1 Relative to the Baseline Case, CNG by Regulatory Class, Millions of 2017 dollars, Present Values at 3% Discounting *

	Direct Manufacturing Costs	Warranty Costs	R&D Costs	Other Indirect Costs	Profits	Total Technology Costs
HHD8	\$3.7	\$89	\$4.5	\$1.1	\$0.19	\$99
Urban bus	\$0.094	\$2.4	\$0.12	\$0.027	\$0.0047	\$2.6
Sum	\$3.8	\$91	\$4.6	\$1.1	\$0.19	\$100

* Values show 2 significant digits.

Table 7-71: Technology Cost Impacts of the Proposed Option 2 Relative to the Baseline Case, CNG by Regulatory Class, Millions of 2017 dollars, Present Values at 3% Discounting *

	Direct Manufacturing Costs	Warranty Costs	R&D Costs	Other Indirect Costs	Profits	Total Technology Costs
HHD8	\$3.7	\$48	\$3.3	\$1.1	\$0.19	\$57
Urban bus	\$0.094	\$1.3	\$0.088	\$0.027	\$0.0047	\$1.5
Sum	\$3.8	\$50	\$3.4	\$1.1	\$0.19	\$58

* Values show 2 significant digits.

Table 7-72: Technology Cost Impacts of the Proposed Option 1 Relative to the Baseline Case, CNG by Regulatory Class, Millions of 2017 dollars, Present Values at 7% Discounting *

	Direct Manufacturing Costs	Warranty Costs	R&D Costs	Other Indirect Costs	Profits	Total Technology Costs
HHD8	\$2.7	\$63	\$3.9	\$0.78	\$0.14	\$70
Urban bus	\$0.1	\$1.7	\$0.10	\$0.020	\$0.0034	\$1.9
Sum	\$2.8	\$65	\$4.0	\$0.80	\$0.14	\$72

* Values show 2 significant digits.

Table 7-73: Technology Cost Impacts of the Proposed Option 2 Relative to the Baseline Case, CNG by Regulatory Class, Millions of 2017 dollars, Present Values at 7% Discounting *

	Direct Manufacturing Costs	Warranty Costs	R&D Costs	Other Indirect Costs	Profits	Total Technology Costs
HHD8	\$2.7	\$35	\$3.1	\$0.78	\$0.14	\$42
Urban bus	\$0.068	\$0.93	\$0.081	\$0.020	\$0.0034	\$1.1
Sum	\$2.8	\$36	\$3.1	\$0.80	\$0.14	\$43

* Values show 2 significant digits.

Table 7-74: Technology Cost Impacts Relative to the Baseline Case, All Fuels by Proposed Option, Millions of 2017 dollars, Present Values at 3% Discounting *

	Direct Manufacturing Costs	Warranty Costs	R&D Costs	Other Indirect Costs	Profits	Total Technology Costs
Option 1 increase from Baseline	\$13,000	\$5,300	\$1,000	\$3,700	\$630	\$23,000
Option 2 increase from Baseline	\$13,000	\$2,800	\$980	\$3,700	\$630	\$21,000

* Values show 2 significant digits. Note that the Information Collection Request costs addressed in Section XIII of the preamble would fall within the "Other" indirect costs shown here.

Table 7-75: Technology Cost Impacts Relative to the Baseline Case, All Fuels by Proposed Option, Millions of 2017 dollars, Present Values at 7% Discounting *

	Direct Manufacturing Costs	Warranty Costs	R&D Costs	Other Indirect Costs	Profits	Total Technology Costs
Option 1 increase from Baseline	\$9,200	\$3,800	\$800	\$2,700	\$460	\$17,000
Option 2 increase from Baseline	\$9,200	\$2,100	\$790	\$2,700	\$460	\$15,000

* Values show 2 significant digits. Note that the Information Collection Request costs addressed in Section XIII of the preamble would fall within the "Other" indirect costs shown here.

7.3.2 Total Operating Costs

The series of tables shown here show emission repair costs, urea costs, pre-tax fuel costs and total operating costs by fuel type, then by regulatory class for each of the proposed options.

Values shown for a given calendar year are undiscounted values while discounted values are presented at both 3 and 7 percent discount rates. All values are shown in 2017 dollars.

Note that the emission repair and fuel costs are shown as negative costs, or savings. This is expected with respect to the fuel costs since the ORVR requirements are expected to reduce gasoline consumption due to the capture of previously evaporated emissions. With respect to the emission repair costs, we expect the baseline emission repair costs to increase year-over-year as vehicles age, and thus the proposed longer warranty and useful life periods result in the magnitude of the savings growing in the early years. However, eventually vehicles would begin to age beyond their longer warranty and useful life periods and, we estimate, incur higher costs than in the baseline because of the higher technology costs. This explains the lower magnitude of emission repair savings in the later years shown in the tables. The early implementation vehicles--MY2027 through MY2035--are aging into more costly emission-repair rates, which is beginning to offset the lower emission-repair rates of the MY2036 and later vehicles.

For Table 7-76 through Table 7-81, we note that, as discussed in Section 5.2.2.5, we did not include diesel-fueled, engine-certified LHD2b3 vehicles in the baseline emission inventory, but did include these vehicles in our emission inventory estimates for the proposed Options 1 and 2 control scenarios. We decided to include the engine-certified LHD2b3 vehicles in the emissions inventories of the control scenario to better estimate the projected emissions of heavy-duty vehicles in the control scenarios, even though it will conservatively underestimate the benefits of controlling these vehicles. As a result, the NO_x emission inventories may demonstrate an increase in emissions from source types containing diesel-fueled LHD2b3 vehicles for certain calendar years. We plan to update our baseline modeling to reflect any requirements for diesel-fueled, engine-certified LHD2b3 vehicles in the final rulemaking. In addition, the MOVES baseline emission rates for all LHD diesel (not just 2b3 vehicles) were incorrectly developed using a warranty period of 100K instead of 50K, and thus we underestimated the LHD diesel emissions impact of the longer warranty periods in the proposal and alternative scenarios. We will update the baseline warranty period for LHD diesel in the FRM analysis.

Table 7-76: Operating Cost Impacts of the Proposed Option 1 Relative to the Baseline Case, Diesel, Millions of 2017 dollars *

Calendar Year	Emission Repair Costs	Urea Costs	Pre-tax Fuel Costs	Total Operating Costs
2027	\$16	\$61	\$0.0	\$77
2028	-\$55	\$130	\$0.0	\$72
2029	-\$220	\$200	\$0.0	-\$21
2030	-\$250	\$270	\$0.0	\$20
2031	-\$230	\$370	\$0.0	\$140
2032	-\$230	\$460	\$0.0	\$230
2033	-\$230	\$530	\$0.0	\$290
2034	-\$430	\$590	\$0.0	\$160
2035	-\$470	\$650	\$0.0	\$180
2036	-\$420	\$720	\$0.0	\$300
2037	-\$400	\$800	\$0.0	\$400
2038	-\$420	\$890	\$0.0	\$470
2039	-\$450	\$940	\$0.0	\$490
2040	-\$480	\$990	\$0.0	\$500
2041	-\$470	\$1,000	\$0.0	\$560
2042	-\$470	\$1,100	\$0.0	\$610
2043	-\$460	\$1,100	\$0.0	\$660
2044	-\$450	\$1,200	\$0.0	\$710
2045	-\$440	\$1,200	\$0.0	\$760
PV, 3%	-\$4,600	\$9,100	\$0.0	\$4,400
PV, 7%	-\$3,100	\$5,800	\$0.0	\$2,700

* Values show 2 significant digits.

Table 7-77: Operating Cost Impacts of the Proposed Option 2 Relative to the Baseline Case, Diesel, Millions of 2017 dollars *

Calendar Year	Emission Repair Costs	Urea Costs	Pre-tax Fuel Costs	Total Operating Costs
2027	\$16	\$56	\$0.0	\$72
2028	-\$55	\$120	\$0.0	\$61
2029	-\$150	\$180	\$0.0	\$34
2030	-\$210	\$250	\$0.0	\$38
2031	-\$200	\$320	\$0.0	\$120
2032	-\$89	\$400	\$0.0	\$310
2033	-\$56	\$460	\$0.0	\$400
2034	-\$8.6	\$510	\$0.0	\$500
2035	\$47	\$560	\$0.0	\$610
2036	\$120	\$610	\$0.0	\$730
2037	\$210	\$650	\$0.0	\$860
2038	\$290	\$690	\$0.0	\$980
2039	\$370	\$730	\$0.0	\$1,100
2040	\$410	\$770	\$0.0	\$1,200
2041	\$450	\$810	\$0.0	\$1,300
2042	\$500	\$840	\$0.0	\$1,300
2043	\$530	\$870	\$0.0	\$1,400
2044	\$560	\$910	\$0.0	\$1,500
2045	\$580	\$940	\$0.0	\$1,500
PV, 3%	\$1,900	\$7,400	\$0.0	\$9,400
PV, 7%	\$910	\$4,800	\$0.0	\$5,700

* Values show 2 significant digits.

Table 7-78: Operating Cost Impacts of the Proposed Option 1 Relative to the Baseline Case, Diesel by Regulatory Class, Millions of 2017 dollars, Present Values at 3% Discounting *

	Emission Repair Costs	Urea Costs	Pre-tax Fuel Costs	Total Operating Costs
LHD	-\$70	\$10	\$0.0	-\$60
LHD45	-\$510	\$420	\$0.0	-\$85
MHD67	-\$620	\$950	\$0.0	\$330
HHD8	-\$3,400	\$7,600	\$0.0	\$4,200
Urban bus	-\$21	\$96	\$0.0	\$76
Sum	-\$4,600	\$9,100	\$0.0	\$4,400

* Values show 2 significant digits.

Table 7-79: Operating Cost Impacts of the Proposed Option 2 Relative to the Baseline Case, Diesel by Regulatory Class, Millions of 2017 dollars, Present Values at 3% Discounting *

	Emission Repair Costs	Urea Costs	Pre-tax Fuel Costs	Total Operating Costs
LHD	-\$32	-\$1.3	\$0.0	-\$33
LHD45	-\$330	\$340	\$0.0	\$9.4
MHD67	\$150	\$750	\$0.0	\$900
HHD8	\$2,100	\$6,200	\$0.0	\$8,400
Urban bus	\$21	\$80	\$0.0	\$100
Sum	-\$4,600	\$9,100	\$0.0	\$4,400

* Values show 2 significant digits.

Table 7-80: Operating Cost Impacts of the Proposed Option 1 Relative to the Baseline Case, Diesel by Regulatory Class, Millions of 2017 dollars, Present Values at 7% Discounting *

	Emission Repair Costs	Urea Costs	Pre-tax Fuel Costs	Total Operating Costs
LHD	-\$42	\$6.2	\$0.0	-\$36
LHD45	-\$310	\$270	\$0.0	-\$39
MHD67	-\$380	\$610	\$0.0	\$220
HHD8	-\$2,300	\$4,900	\$0.0	\$2,500
Urban bus	-\$12	\$61	\$0.0	\$48
Sum	-\$3,100	\$5,800	\$0.0	\$2,700

* Values show 2 significant digits.

Table 7-81: Operating Cost Impacts of the Proposed Option 2 Relative to the Baseline Case, Diesel by Regulatory Class, Millions of 2017 dollars, Present Values at 7% Discounting *

	Emission Repair Costs	Urea Costs	Pre-tax Fuel Costs	Total Operating Costs
LHD	-\$21	\$0	\$0.0	-\$21
LHD45	-\$220	\$220	\$0.0	\$3.4
MHD67	\$75	\$490	\$0.0	\$560
HHD8	\$1,100	\$4,000	\$0.0	\$5,100
Urban bus	\$12	\$51	\$0.0	\$63
Sum	\$910	\$4,800	\$0.0	\$5,700

* Values show 2 significant digits.

Table 7-82: Operating Cost Impacts of the Proposed Option 1 Relative to the Baseline Case, Gasoline, Millions of 2017 dollars

Calendar Year	Emission Repair Costs	Urea Costs	Pre-tax Fuel Costs	Total Operating Costs
2027	\$0.27	\$0.0	-\$0.80	-\$0.53
2028	\$0.34	\$0.0	-\$1.6	-\$1.3
2029	-\$0.65	\$0.0	-\$2.5	-\$3.2
2030	-\$2.1	\$0.0	-\$3.4	-\$5.5
2031	-\$4.0	\$0.0	-\$4.3	-\$8.4
2032	-\$5.2	\$0.0	-\$5.2	-\$10
2033	-\$4.9	\$0.0	-\$6.3	-\$11
2034	-\$4.1	\$0.0	-\$7.3	-\$11
2035	-\$3.0	\$0.0	-\$8.3	-\$11
2036	-\$3.5	\$0.0	-\$9.2	-\$13
2037	-\$5.7	\$0.0	-\$10	-\$16
2038	-\$7.6	\$0.0	-\$11	-\$19
2039	-\$6.5	\$0.0	-\$12	-\$18
2040	-\$4.9	\$0.0	-\$13	-\$18
2041	-\$4.6	\$0.0	-\$13	-\$18
2042	-\$4.4	\$0.0	-\$14	-\$18
2043	-\$4.3	\$0.0	-\$14	-\$19
2044	-\$4.3	\$0.0	-\$15	-\$19
2045	-\$4.2	\$0.0	-\$16	-\$20
PV, 3%	-\$52	\$0.0	-\$120	-\$170
PV, 7%	-\$34	\$0.0	-\$73	-\$110

* Values show 2 significant digits.

Table 7-83: Operating Cost Impacts of the Proposed Option 2 Relative to the Baseline Case, Gasoline, Millions of 2017 dollars

Calendar Year	Emission Repair Costs	Urea Costs	Pre-tax Fuel Costs	Total Operating Costs
2027	\$0.27	\$0.0	-\$0.79	-\$0.52
2028	\$0.34	\$0.0	-\$1.6	-\$1.3
2029	-\$0.65	\$0.0	-\$2.5	-\$3.1
2030	-\$2.4	\$0.0	-\$3.4	-\$5.8
2031	-\$4.6	\$0.0	-\$4.3	-\$8.8
2032	-\$6.5	\$0.0	-\$5.1	-\$12
2033	-\$7.5	\$0.0	-\$6.2	-\$14
2034	-\$7.7	\$0.0	-\$7.2	-\$15
2035	-\$7.3	\$0.0	-\$8.1	-\$15
2036	-\$6.0	\$0.0	-\$9.0	-\$15
2037	-\$4.4	\$0.0	-\$10	-\$14
2038	-\$2.8	\$0.0	-\$11	-\$13
2039	-\$1.1	\$0.0	-\$11	-\$13
2040	\$0.8	\$0.0	-\$12	-\$11
2041	\$1.4	\$0.0	-\$13	-\$11
2042	\$2.0	\$0.0	-\$13	-\$12
2043	\$2.4	\$0.0	-\$14	-\$12
2044	\$2.7	\$0.0	-\$15	-\$12
2045	\$3.0	\$0.0	-\$15	-\$12
PV, 3%	-\$32	\$0.0	-\$110	-\$140
PV, 7%	-\$25	\$0.0	-\$71	-\$97

* Values show 2 significant digits.

Table 7-84: Operating Cost Impacts of the Proposed Option 1 Relative to the Baseline Case, Gasoline by Regulatory Class, Millions of 2017 dollars, Present Values at 3% Discounting *

	Emission Repair Costs	Urea Costs	Pre-tax Fuel Costs	Total Operating Costs
LHD45	-\$37	\$0	-\$75	-\$110
MHD67	-\$11	\$0	-\$29	-\$40
HHD8	-\$4.3	\$0	-\$11	-\$15
Sum	-\$52	\$0	-\$120	-\$170

* Values show 2 significant digits.

Table 7-85: Operating Cost Impacts of the Proposed Option 2 Relative to the Baseline Case, Gasoline by Regulatory Class, Millions of 2017 dollars, Present Values at 3% Discounting *

	Emission Repair Costs	Urea Costs	Pre-tax Fuel Costs	Total Operating Costs
LHD45	-\$26	\$0.0	-\$74	-\$100
MHD67	-\$2.1	\$0.0	-\$28	-\$30
HHD8	-\$3.8	\$0.0	-\$10	-\$14
Sum	-\$32	\$0.0	-\$110	-\$140

* Values show 2 significant digits.

Table 7-86: Operating Cost Impacts of the Proposed Option 1 Relative to the Baseline Case, Gasoline by Regulatory Class, Millions of 2017 dollars, Present Values at 7% Discounting *

	Emission Repair Costs	Urea Costs	Pre-tax Fuel Costs	Total Operating Costs
LHD45	-\$24	\$0	-\$48	-\$72
MHD67	-\$7.1	\$0	-\$18	-\$26
HHD8	-\$2.8	\$0	-\$6.7	-\$9.6
Sum	-\$34	\$0	-\$73	-\$110

* Values show 2 significant digits.

Table 7-87: Operating Cost Impacts of the Proposed Option 2 Relative to the Baseline Case, Gasoline by Regulatory Class, Millions of 2017 dollars, Present Values at 7% Discounting *

	Emission Repair Costs	Urea Costs	Pre-tax Fuel Costs	Total Operating Costs
LHD45	-\$20	\$0.0	-\$47	-\$67
MHD67	-\$2.3	\$0.0	-\$18	-\$20
HHD8	-\$2.8	\$0.0	-\$6.5	-\$9.2
Sum	-\$25	\$0.0	-\$71	-\$97

* Values show 2 significant digits.

Table 7-88: Operating Cost Impacts of the Proposed Option 1 Relative to the Baseline Case, CNG, Millions of 2017 dollars

Calendar Year	Emission Repair Costs, Owner	Urea Costs	Fuel Costs	Total Operating Costs
2027	\$0.0035	\$0.0	\$0.0	\$0.0035
2028	-\$0.21	\$0.0	\$0.0	-\$0.21
2029	-\$0.66	\$0.0	\$0.0	-\$0.66
2030	-\$1.5	\$0.0	\$0.0	-\$1.5
2031	-\$2.8	\$0.0	\$0.0	-\$2.8
2032	-\$4.6	\$0.0	\$0.0	-\$4.6
2033	-\$6.5	\$0.0	\$0.0	-\$6.5
2034	-\$7.7	\$0.0	\$0.0	-\$7.7
2035	-\$8.4	\$0.0	\$0.0	-\$8.4
2036	-\$8.9	\$0.0	\$0.0	-\$8.9
2037	-\$10	\$0.0	\$0.0	-\$10
2038	-\$11	\$0.0	\$0.0	-\$11
2039	-\$13	\$0.0	\$0.0	-\$13
2040	-\$15	\$0.0	\$0.0	-\$15
2041	-\$16	\$0.0	\$0.0	-\$16
2042	-\$16	\$0.0	\$0.0	-\$16
2043	-\$16	\$0.0	\$0.0	-\$16
2044	-\$17	\$0.0	\$0.0	-\$17
2045	-\$17	\$0.0	\$0.0	-\$17
PV, 3%	-\$120	\$0.0	\$0.0	-\$120
PV, 7%	-\$71	\$0.0	\$0.0	-\$71

* Values show 2 significant digits.

Table 7-89: Operating Cost Impacts of the Proposed Option 2 Relative to the Baseline Case, CNG, Millions of 2017 dollars

Calendar Year	Emission Repair Costs, Owner	Urea Costs	Fuel Costs	Total Operating Costs
2027	\$0.0035	\$0.0	\$0.0	\$0.0035
2028	-\$0.21	\$0.0	\$0.0	-\$0.21
2029	-\$0.66	\$0.0	\$0.0	-\$0.66
2030	-\$1.5	\$0.0	\$0.0	-\$1.5
2031	-\$2.8	\$0.0	\$0.0	-\$2.8
2032	-\$3.9	\$0.0	\$0.0	-\$3.9
2033	-\$5.1	\$0.0	\$0.0	-\$5.1
2034	-\$5.9	\$0.0	\$0.0	-\$5.9
2035	-\$6.4	\$0.0	\$0.0	-\$6.4
2036	-\$6.4	\$0.0	\$0.0	-\$6.4
2037	-\$6.3	\$0.0	\$0.0	-\$6.3
2038	-\$6.1	\$0.0	\$0.0	-\$6.1
2039	-\$5.9	\$0.0	\$0.0	-\$5.9
2040	-\$5.9	\$0.0	\$0.0	-\$5.9
2041	-\$6.0	\$0.0	\$0.0	-\$6.0
2042	-\$5.7	\$0.0	\$0.0	-\$5.7
2043	-\$5.6	\$0.0	\$0.0	-\$5.6
2044	-\$5.6	\$0.0	\$0.0	-\$5.6
2045	-\$5.6	\$0.0	\$0.0	-\$5.6
PV, 3%	-\$60	\$0.0	\$0.0	-\$60
PV, 7%	-\$39	\$0.0	\$0.0	-\$39

* Values show 2 significant digits.

Table 7-90: Operating Cost Impacts of the Proposed Option 1 Relative to the Baseline Case, CNG by Regulatory Class, Millions of 2017 dollars, Present Values at 3% Discounting *

	Emission Repair Costs	Urea Costs	Pre-tax Fuel Costs	Total Operating Costs
HHD8	-\$110	\$0.0	\$0.0	-\$110
Urban bus	-\$2.8	\$0.0	\$0.0	-\$2.8
Sum	-\$120	\$0.0	\$0.0	-\$120

* Values show 2 significant digits.

Table 7-91: Operating Cost Impacts of the Proposed Option 2 Relative to the Baseline Case, CNG by Regulatory Class, Millions of 2017 dollars, Present Values at 3% Discounting *

	Emission Repair Costs	Urea Costs	Pre-tax Fuel Costs	Total Operating Costs
HHD8	-\$59	\$0.0	\$0.0	-\$59
Urban bus	-\$0.89	\$0.0	\$0.0	-\$0.89
Sum	-\$60	\$0.0	\$0.0	-\$60

* Values show 2 significant digits.

Table 7-92: Operating Cost Impacts of the Proposed Option 1 Relative to the Baseline Case, CNG by Regulatory Class, Millions of 2017 dollars, Present Values at 7% Discounting *

	Emission Repair Costs	Urea Costs	Pre-tax Fuel Costs	Total Operating Costs
HHD8	-\$70	\$0	\$0	-\$70
Urban bus	-\$1.7	\$0	\$0	-\$1.7
Sum	-\$71	\$0	\$0	-\$71

* Values show 2 significant digits.

Table 7-93: Operating Cost Impacts of the Proposed Option 2 Relative to the Baseline Case, CNG by Regulatory Class, Millions of 2017 dollars, Present Values at 7% Discounting *

	Emission Repair Costs	Urea Costs	Pre-tax Fuel Costs	Total Operating Costs
HHD8	-\$39	\$0.0	\$0.0	-\$39
Urban bus	-\$0.57	\$0.0	\$0.0	-\$0.57
Sum	-\$39	\$0.0	\$0.0	-\$39

* Values show 2 significant digits.

Table 7-94: Operating Cost Impacts Relative to the Baseline Case, All Fuels by Proposed Option, Millions of 2017 dollars, Present Values at 3% Discounting *

	Emission Repair Costs	Urea Costs	Pre-tax Fuel Costs	Total Operating Costs
Option 1 increase from Baseline	-\$4,800	\$9,100	-\$120	\$4,200
Option 2 increase from Baseline	\$1,800	\$7,400	-\$110	\$9,200

* Values show 2 significant digits.

Table 7-95: Operating Cost Impacts Relative to the Baseline Case, All Fuels by Proposed Option, Millions of 2017 dollars, Present Values at 7% Discounting *

	Emission Repair Costs	Urea Costs	Pre-tax Fuel Costs	Total Operating Costs
Option 1 increase from Baseline	-\$3,200	\$5,800	-\$73	\$2,600
Option 2 increase from Baseline	\$840	\$4,800	-\$71	\$5,500

* Values show 2 significant digits.

Note that the ORVR requirements would result in previously evaporated gasoline being used by in the engines of gasoline vehicles. We have estimated the cost savings that owner/operators would experience and present those in Section 7.2.2. In this section, we also show the pre-tax fuel savings that are ultimately part of the benefit-cost analysis presented in Chapter 9. Table 7-96 and Table 7-97 show the impacts on fuel tax revenues that would be expected from these changes under the proposed Options 1 and 2, respectively.

**Table 7-96: Fuel Cost and Transfer Impacts of the Proposed Option 1 Relative to the Baseline Case, Gasoline,
Millions of 2017 dollars**

Calendar Year	Retail Fuel Costs	Pre-tax Fuel Costs	Tax Revenues
2027	-\$0.95	-\$0.80	-\$0.15
2028	-\$1.9	-\$1.6	-\$0.31
2029	-\$3.0	-\$2.5	-\$0.47
2030	-\$4.0	-\$3.4	-\$0.62
2031	-\$5.1	-\$4.3	-\$0.77
2032	-\$6.1	-\$5.2	-\$0.92
2033	-\$7.4	-\$6.3	-\$1.1
2034	-\$8.6	-\$7.3	-\$1.2
2035	-\$9.7	-\$8.3	-\$1.4
2036	-\$11	-\$9.2	-\$1.5
2037	-\$12	-\$10	-\$1.7
2038	-\$13	-\$11	-\$1.8
2039	-\$14	-\$12	-\$1.9
2040	-\$15	-\$13	-\$2.0
2041	-\$15	-\$13	-\$2.1
2042	-\$16	-\$14	-\$2.1
2043	-\$17	-\$14	-\$2.2
2044	-\$17	-\$15	-\$2.3
2045	-\$18	-\$16	-\$2.3
PV, 3%	-\$130	-\$120	-\$19
PV, 7%	-\$85	-\$73	-\$12

**Table 7-97: Fuel Cost and Transfer Impacts of Proposed Option 2 Relative to the Baseline Case, Gasoline,
Millions of 2017 dollars**

Calendar Year	Retail Fuel Costs	Pre-tax Fuel Costs	Tax Revenues
2027	-\$0.94	-\$0.79	-\$0.15
2028	-\$1.9	-\$1.6	-\$0.30
2029	-\$2.9	-\$2.5	-\$0.46
2030	-\$4.0	-\$3.4	-\$0.62
2031	-\$5.0	-\$4.3	-\$0.76
2032	-\$6.0	-\$5.1	-\$0.90
2033	-\$7.2	-\$6.2	-\$1.1
2034	-\$8.4	-\$7.2	-\$1.2
2035	-\$9.5	-\$8.1	-\$1.4
2036	-\$11	-\$9.0	-\$1.5
2037	-\$12	-\$10	-\$1.6
2038	-\$12	-\$11	-\$1.7
2039	-\$13	-\$11	-\$1.8
2040	-\$14	-\$12	-\$1.9
2041	-\$15	-\$13	-\$2.0
2042	-\$16	-\$13	-\$2.1
2043	-\$16	-\$14	-\$2.1
2044	-\$17	-\$15	-\$2.2
2045	-\$17	-\$15	-\$2.2
PV, 3%	-\$130	-\$110	-\$18
PV, 7%	-\$83	-\$71	-\$12

7.3.3 **Total Program Costs**

The series of tables shown here present technology costs, operating costs and the sum of the two for each proposed option. Values shown for a given calendar year are undiscounted values while discounted values are presented at both 3 and 7 percent discount rates. All values are shown in 2017 dollars.

Table 7-98: Total Technology & Operating Cost Impacts of the Proposed Option 1 Relative to the Baseline Case, All Regulatory Classes and All Fuels, Millions of 2017 dollars

Calendar Year	Total Technology Costs	Total Operating Costs	Sum
2027	\$1,800	\$77	\$1,800
2028	\$1,700	\$71	\$1,800
2029	\$1,700	-\$25	\$1,700
2030	\$1,600	\$13	\$1,600
2031	\$1,700	\$120	\$1,900
2032	\$1,700	\$210	\$1,900
2033	\$1,700	\$280	\$1,900
2034	\$1,600	\$140	\$1,700
2035	\$1,600	\$160	\$1,700
2036	\$1,600	\$280	\$1,900
2037	\$1,600	\$380	\$1,900
2038	\$1,600	\$440	\$2,000
2039	\$1,600	\$450	\$2,000
2040	\$1,600	\$470	\$2,000
2041	\$1,600	\$520	\$2,100
2042	\$1,600	\$570	\$2,100
2043	\$1,600	\$620	\$2,200
2044	\$1,600	\$670	\$2,200
2045	\$1,600	\$720	\$2,300
PV, 3%	\$23,000	\$4,200	\$27,000
PV, 7%	\$17,000	\$2,600	\$19,000
Annualized, 3%	\$1,600	\$290	\$1,900
Annualized, 7%	\$1,600	\$250	\$1,900

* Values show 2 significant digits.

Table 7-99: Total Technology & Operating Cost Impacts of Proposed Option 2 Relative to the Baseline Case, All Regulatory Classes and All Fuels, Millions of 2017 dollars

Calendar Year	Total Technology Costs	Total Operating Costs	Sum
2027	\$1,700	\$72	\$1,800
2028	\$1,700	\$60	\$1,700
2029	\$1,600	\$31	\$1,700
2030	\$1,500	\$31	\$1,500
2031	\$1,500	\$110	\$1,600
2032	\$1,400	\$300	\$1,700
2033	\$1,400	\$380	\$1,800
2034	\$1,400	\$480	\$1,900
2035	\$1,400	\$580	\$2,000
2036	\$1,400	\$710	\$2,100
2037	\$1,400	\$840	\$2,200
2038	\$1,400	\$960	\$2,300
2039	\$1,400	\$1,100	\$2,400
2040	\$1,400	\$1,200	\$2,500
2041	\$1,400	\$1,200	\$2,600
2042	\$1,400	\$1,300	\$2,700
2043	\$1,400	\$1,400	\$2,800
2044	\$1,400	\$1,400	\$2,800
2045	\$1,400	\$1,500	\$2,900
PV, 3%	\$21,000	\$9,200	\$30,000
PV, 7%	\$15,000	\$5,500	\$21,000
Annualized, 3%	\$1,400	\$640	\$2,100
Annualized, 7%	\$1,500	\$540	\$2,000

* Values show 2 significant digits.

Chapter 8 Estimated Benefits

8.1 Overview

This chapter describes the methods used to estimate health benefits from reducing concentrations of ozone and PM_{2.5}. For the proposed rulemaking, we have quantified and monetized health impacts in 2045, representing projected impacts associated with a year when the program would be fully implemented and when most of the regulated fleet would have turned over. There are also benefits associated with the standards that, if quantified and monetized, would increase the total monetized benefits. These unquantified benefits are discussed in Section 8.8 of this chapter. Overall, we estimate that the proposed program would lead to a substantial decrease in adverse PM_{2.5}- and ozone-related health impacts in 2045.

We adopt an updated analysis approach that was recently used to quantify the benefits of changes in PM_{2.5} and ozone in the final Revised Cross-State Air Pollution Rule (CSAPR) Update RIA.^{377,NNNNNN} While the steps to performing a criteria pollutant benefits analysis remain unchanged from past mobile source rulemakings (e.g., Tier 3 Motor Vehicle Emission and Fuel Standards Final Rule)³⁷⁸, the final CSAPR RIA updated the suite of quantified health endpoints included in the benefits analysis, as well as the data used to quantify each health endpoint, to reflect more recent scientific evidence. These updates were based on information drawn from the recent PM_{2.5} and ozone Integrated Science Assessments (ISAs), which were reviewed by the Clean Air Science Advisory Committee (CASAC) and the public,^{379,380} and are summarized in a technical support document (TSD) originally published for the final Revised CSAPR Update titled *Estimating PM_{2.5}- and Ozone-Attributable Health Benefits*.^{381,000000}

8.2 Updates to EPA's Human Health Benefits Methods

When the RIA for the Final Revised CSAPR Update was published in March 2021, the Agency adopted an updated approach for estimating benefits that incorporated an array of science-policy and technical changes since the previous reviews of the PM_{2.5} standards in 2012 and the ozone standards in 2015. As part of this process, the Agency carefully considered: (1) the extent to which the science supports the existence of a causal relationship between that pollutant and the adverse effect; (2) whether suitable epidemiologic studies exist to support quantifying health impacts; and (3) whether robust economic approaches are available for estimating the value of the impact of reducing human exposure to the pollutant. The Estimating PM_{2.5}- and Ozone-Attributable Health Benefits TSD provides a full discussion of the Agency's updated approach for quantifying the number and value of estimated air pollution-related impacts. Below, we summarize the rationale for selecting health endpoints to quantify; the demographic, health

NNNNNN On March 15, 2021, EPA finalized the Revised Cross-State Air Pollution Rule Update for the 2008 ozone National Ambient Air Quality Standards (NAAQS). Starting in the 2021 ozone season, the rule will require additional emissions reductions of nitrogen oxides (NO_x) from power plants in 12 states.
<https://www.epa.gov/csapr/revised-cross-state-air-pollution-rule-update>.

000000 On June 10, 2021, EPA announced that it will reconsider the previous administration's decision to retain the PM NAAQS. To the extent that new health information is introduced in the reconsideration, the Agency may update its benefits methods in future analyses.

and economic data used; modeling assumptions; and our techniques for quantifying uncertainty.^{PPPPPP} EPA followed a five-step approach:

- Establish criteria for identifying studies and risk estimates most appropriate to inform a PM_{2.5} and O₃ benefit analysis for an RIA. Study criteria, such as study design, location, population characteristics, and other attributes, were used to identify the most suitable estimates. This step precedes health endpoint identification to ensure impartial health endpoint identification and prevent identification of non-quantifiable endpoints.
- Identify pollutant-attributable health effects for which the ISA reports strong evidence and that may be quantified in a benefits assessment. EPA considered new evidence reported in the recent PM and ozone ISAs and clinically significant outcomes (e.g., premature mortality and hospital admissions) for which endpoint-specific baseline incidence data is available. While ISAs form causal determinations for broad endpoint categories (e.g., respiratory effects), which are generally preferred over specific health endpoints (e.g., hay fever symptoms) for comprehensive benefits assessments, they do not make causal determinations for each specific health endpoint. Instead, the ISAs provide information on the strength and consistency of the evidence supporting more specific endpoints within each broad category. The strength and consistency of evidence supporting relationships with specific health endpoints, together with the broad category causality determinations, are used when identifying specific health endpoints for inclusion in benefits assessments. New ISA evidence was considered sufficient for inclusion in the benefits assessment if the ISA determined the broad health endpoint category was causally related to pollutant exposure, the ISA determined that the specific health endpoint is a biologically plausible health effect of exposure, and the ISA found strong and consistent support relating the specific health endpoint with pollutant exposure.³⁸²
- Collect baseline incidence and prevalence estimates and demographic information. EPA develops either daily or annual baseline incidence and prevalence rates at the most geographically- and age-specific levels feasible for each health endpoint assessed. EPA uses population projections based on economic forecasting models developed by Woods and Poole, Inc.³⁸³ The Woods and Poole database contains county-level projections of population by age, sex, and race out to 2050, relative to a baseline using the 2010 Decennial Census.
- Develop economic unit values. To directly compare benefits estimates associated with a rulemaking to cost estimates, the number of instances of each air pollution-attributable health impact must be converted to a monetary value. This requires a valuation estimate for each unique health endpoint, and potentially also discounting if the benefits are expected to accrue over more than a single year. EPA develops valuation estimates at the most age-refined level feasible for each health endpoint assessed.
- Characterize uncertainty associated with quantified benefits estimates. Building on EPA's current methods for characterizing uncertainty, these approaches will include,

^{PPPPPP} Updated information has been incorporated into BenMAP-CE version 1.5.8 <https://www.epa.gov/benmap>.

among others, reporting confidence intervals calculated from risk estimates and separate quantification using multiple studies and risk estimates for particularly influential endpoints (e.g., mortality <https://www.epa.gov/benmap> risk), and approaches for aggregating and representing the results of multiple studies evaluating a particular health endpoint. QQQQQQ

Since publication of the Final Revised CSAPR Update and the accompanying Estimating PM_{2.5}- and Ozone-Attributable Health Benefits TSD, the Agency has made two additional, minor updates to its benefits approach described below.

Use ozone metrics and ozone seasons consistent with underlying health studies. Often, time and resource limitations constrain an analysis to the use of one ozone metric and/or one ozone seasonal definition. For example, the Final Revised CSAPR Update converted all ozone risk estimates into a standard maximum daily 8-hour average (MDA8) metric and applied those risk estimates to a standard May-September ozone warm season. Both approaches to standardization introduce some uncertainty into the analysis due to the potential for metric and seasonal mismatch with the underlying health studies, though we expect this mismatch only has a limited effect on the magnitude of related health incidence. For the benefits analysis of the proposed program, we rely on full-form photochemical air quality modeling concentration surfaces derived using the Community Multi-scale Air Quality Model (CMAQ).^{RRRRRR} Having run the model, we are able to create ozone concentration surfaces with exposure metrics and seasons that match as best as possible the same metric and season used by each study. See draft RIA Chapter 8.2.1 below and Sections 6.5.12 and 6.5.13 of the TSD for more a more detailed discussion.

Use updated income growth adjustment factors. As discussed in Sections 5.4 and 6.4.3 of the TSD, evidence and theory suggest that one's willingness-to-pay (WTP) for health and environmental improvements should increase as real income increases. To account for this, we adjust WTP-based valuation estimates, such as the Value of a Statistical Life (VSL), to account for the growth in income over time. This adjustment is a combination of data on income growth and estimated income elasticity of demand, which measures the responsiveness of the quantity demanded of a good to the change in the income of the people demanding the good. In previous analyses, projections of income growth were capped at 2026. For the benefits analysis of the proposed program, we have estimated income growth adjustment factors out to 2045 using future changes in annual income based on data presented in the Annual Energy Outlook (AEO) 2020, a report prepared by the U.S. Energy Information Administration (EIA).³⁸⁴

Estimating the health benefits of reductions in PM_{2.5} and O₃ exposure begins with estimating the change in exposure for each individual and then estimating the change in each individual's risks for those health outcomes affected by exposure. The benefit of the reduction in each health risk is based on the exposed individual's WTP for the risk change, assuming that each outcome

QQQQQ We consider study quality, inter-study heterogeneity, and redundancy where epidemiologic risk estimates are combined or aggregated.

RRRRRR As noted in Section VII, due to resource constraints we only conducted air quality modeling for the proposed Option 1. We have also used year-over-year Option 2 NO_x emissions reductions to scale the total benefits associated with Option 1 to derive a best estimate of criteria pollutant benefits associated with Option 2 (see draft RIA Chapter 8.7 for details).

is independent of one another. The greater the magnitude of the risk reduction from a given change in concentration, the greater the individual's WTP, all else equal. The social benefit of the change in health risks equals the sum of the individual WTP estimates across all of the affected individuals.^{SSSSS} We conduct this analysis by adapting primary research - specifically, air pollution epidemiology studies and economic value studies - from similar contexts. This approach is sometimes referred to as "benefits transfer." Below we describe the procedure we follow for quantifying and monetizing the health benefits associated with reduced human exposure to PM_{2.5} and ozone.

8.3 Health Impact Assessment for PM_{2.5} and Ozone

There are four distinct steps the Agency follows when conducting a health impacts assessment, each of which are described in this section: (1) prepare air quality modeling data for health impacts analysis; (2) select air pollution health endpoints to quantify; (3) calculate counts of air pollution effects using a health impact function; (4) specify the health impact function with concentration-response parameters drawn from the epidemiological literature.

8.3.1 Preparing Air Quality Modeling Data for Health Impacts Analysis

In draft RIA Chapter 5, we present the emissions that would be reduced if the proposed Options 1 or 2 were in place, including NO_x, direct PM, and VOCs, all of which contribute to ambient concentrations of PM_{2.5} and ozone. These reduced emissions would benefit public health and the environment since exposure to ozone and PM_{2.5} is linked to adverse public health and environmental effects.^{TTTTT} In draft RIA Chapter 6, we summarize the air quality modeling methods and results for the proposed Option 1.^{UUUUU} These air quality results, measured in terms of ambient concentrations of PM_{2.5} and ozone, are in turn associated with human populations to estimate changes in health effects. This section describes how the CMAQ modeling output was converted into a format suitable for the health impacts analysis.

The first step was to extract 2016 base year predicted hourly, surface-layer PM_{2.5} and ozone concentrations for each grid cell directly from the standard CMAQ output files (at a 12-km by 12-km resolution). For ozone, we generated predicted ozone concentration surfaces for each of three different warm seasons defined by the underlying health studies used in the analysis: April-

^{SSSSS} This RIA also reports the change in the sum of the risk, or the change in the total incidence, of a health outcome across the population. If the benefit per unit of risk is invariant across individuals, the total expected change in the incidence of the health outcome across the population can be multiplied by the benefit per unit of risk to estimate the social benefit of the total expected change in the incidence of the health outcome.

^{TTTTT} We note that detailed county-level emission inventories were generated for the air quality modeling that supports the benefits analysis. However, national-scale emission inventories, which utilize national average values for various input variables, were developed to demonstrate the emission impacts of the proposed program over time. The national-scale approach is simpler but coarser compared to the approach used to develop the detailed inventories needed for air quality modeling. For this reason, the modeled changes in emissions used to support the air quality and benefits analyses are slightly smaller relative to the national-scale inventories used to represent the emissions impacts of the proposed program. We do not expect the magnitude of the differences to materially impact our cost-benefit conclusions. See draft RIA Chapter 5.4 for more details.

^{UUUUU} As noted in Chapter 5.4 of the draft RIA, while we refer to air quality modeling for the proposed Option 1, there are differences between the proposed Option 1 standards, emission warranty, and useful life provisions presented in Sections III and IV of the preamble and those included in the control scenario modeled for the air quality analysis. Estimates of health benefits are based on our air quality analysis, and thus differences between proposed Option 1 and modeling are not reflected in the benefits analysis.

September, May-September, and June-August. These hourly model predictions were then combined with monitored observations obtained from the Agency's Air Quality System (AQS) to interpolate hourly ozone concentrations to 12-km by 12-km grid cells for the contiguous 48 states to create gridded 2016 surfaces informed by observational data.^{vvvvvv,wwwwww} We then converted these warm-season hourly ozone concentrations to an ozone metric of interest, such as the daily maximum 8-hour average concentration or the daily maximum 1-hour average concentration, again consistent with the underlying health studies used in the analysis. Gridded fields of relative response factors (RRFs) were created for each ozone metric and warm season definition of interest by dividing unadjusted future year (2045) CMAQ concentrations by unadjusted 2016 base year CMAQ concentrations. Separate 12-km gridded RRFs were created for the future year base case and policy cases for each metric/season combination. Then final future year air quality surfaces were created by multiplying each of the RRF surfaces by the 2016 eVNA surface. These surfaces then served as inputs to the health impact functions of the benefits analysis, contained within the Environmental Benefits Mapping and Analysis Program – Community Edition (BenMAP-CE).

For PM_{2.5}, we also used the model predictions in conjunction with observed monitor data. CMAQ generates predictions of hourly PM species concentrations for every grid. The species include a primary coarse fraction (corresponding to PM in the 2.5 to 10 micron size range), a primary fine fraction (corresponding to PM less than 2.5 microns in diameter), and several secondary particles (e.g., sulfates, nitrates, and organics). PM_{2.5} is calculated as the sum of the primary fine fraction and all of the secondarily formed particles. A gridded field of PM_{2.5} concentrations was created by interpolating Federal Reference Monitor ambient data and Interagency Monitoring of Protected Visual Environments (IMPROVE) ambient data. Gridded fields of PM_{2.5} species concentrations were created by interpolating EPA Chemical Speciation Network (CSN) ambient data and IMPROVE data. The ambient data were interpolated to the CMAQ 12-km grid. Future-year estimates of PM_{2.5} were calculated using gridded RRFs applied to gridded 2016 ambient PM_{2.5} and PM_{2.5} species concentrations.

The procedures for determining the RRFs are similar to those in EPA's Modeling Guidance for Demonstrating Air Quality Goals for Ozone, PM_{2.5}, and Regional Haze.³⁸⁵ The guidance recommends that model predictions be used in a relative sense to estimate changes expected to occur in each major PM_{2.5} species. The procedure for calculating future-year PM_{2.5} design values is called the "Speciated Modeled Attainment Test (SMAT)." EPA used this procedure to estimate the ambient impacts of the proposed Option 1.

Table 8-1 provides ozone and PM_{2.5} metrics for those grid cells in the modeled domain that enter the health impact functions for health benefits endpoints. The population-weighted average reflects the baseline levels and predicted changes for more populated areas of the nation. This measure better reflects the potential benefits through exposure changes to these populations.

^{vvvvvv} The 12-km grid squares contain the population data used in the health benefits analysis model, BenMAP-CE.
^{wwwwww} This approach is a generalization of planar interpolation that is technically referred to as enhanced Voronoi Neighbor Averaging (eVNA) spatial interpolation. See the BenMAP-CE manual for technical details, available for download at <http://www.epa.gov/benmap>.

Table 8-1: Summary of CMAQ-Derived Population-Weighted Ozone and PM_{2.5} Air Quality Metrics for Health Benefits Endpoints Associated with Proposed Option 1

Statistic ^a	2045	
	Baseline	Change ^b
Ozone Metric: National Population-Weighted Average (ppb) ^c		
Daily Maximum 8-Hour Average Concentration – May-September	39	0.69
Daily Maximum 8-Hour Average Concentration – April-September	39	0.64
Daily Maximum 8-Hour Average Concentration – June-August	38	0.76
Daily Maximum 1-Hour Average Concentration – April-September	44	0.80
PM _{2.5} Metric: National Population-Weighted Average (µg/m ³) ^c		
Annual Average Concentration	7.3	0.034

^a Ozone and PM_{2.5} metrics were calculated at the CMAQ grid-cell level for use in health effects estimates. Ozone metrics were calculated over relevant time periods during daylight hours of each “ozone season.” Note that the national, population-weighted PM_{2.5} and ozone air quality metrics presented in this table represent an average for the entire, gridded U.S. CMAQ domain. These are different than the population-weighted PM_{2.5} and ozone design value metrics presented in draft RIA Chapter 6, which represent the average for areas with a current air quality monitor.

^b The change is defined as the baseline value minus the control-case value.

^c Calculated by summing the product of the projected CMAQ grid-cell population and the estimated CMAQ grid concentration and then dividing by the total population.

8.3.2 **Selecting Air Pollution Health Endpoints to Quantify**

As a first step in quantifying ozone and PM_{2.5}-related human health impacts, the Agency consults the Integrated Science Assessment for Ozone and Related Photochemical Oxidants (Ozone ISA) and the Integrated Science Assessment for Particulate Matter (PM ISA). These two documents synthesize 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 short-term (i.e., hours to less than one month) or long-term (i.e., one month to years) 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. The Agency estimates the incidence of air pollution effects for those health endpoints above where the ISA classified as either causal or likely-to-be-causal.

In brief, the ISA for ozone found short-term exposures to ozone to be causally related to respiratory effects, a “likely to be causal” relationship with metabolic effects and a “suggestive of, but not sufficient to infer, a causal relationship” for central nervous system effects, cardiovascular effects, and total mortality. The ISA reported that long-term exposures to ozone are “likely to be causal” for respiratory effects including respiratory mortality, and a “suggestive of, but not sufficient to infer, a causal relationship” for cardiovascular effects, reproductive effects, central nervous system effects, metabolic effects, and total mortality. The PM ISA found short-term exposure to PM_{2.5} to be causally related to cardiovascular effects and mortality (i.e., premature death), respiratory effects as likely-to-be-causally related, and a suggestive relationship for metabolic effects and nervous system effects. The ISA identified cardiovascular

effects and total mortality as being causally related to long-term exposure to PM_{2.5}. A likely-to-be-causal relationship was determined between long-term PM_{2.5} exposures and respiratory effects, nervous system effects, and cancer effects and the evidence was suggestive of a causal relationship for male and female reproduction and fertility effects, pregnancy and birth outcomes, and metabolic effects.

Table 8-2 reports the effects we quantified and those we did not quantify in this RIA. The list of benefit categories not quantified is not exhaustive. And, among the effects quantified, it might not have been possible to quantify completely either the full range of human health impacts or economic values. The table below omits health effects associated with NO₂ exposure, and any welfare effects such as acidification and nutrient enrichment; these effects are described in the Ozone and PM NAAQS RIAs and summarized later in this chapter.^{386,387}

Table 8-2: 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 65-99 or age 30-99)	✓	✓	PM ISA
	Infant mortality (age <1)	✓	✓	PM ISA
Nonfatal morbidity from exposure to PM _{2.5}	Heart attacks (age > 18)	✓	✓ ¹	PM ISA
	Hospital admissions—cardiovascular (ages 65-99)	✓	✓	PM ISA
	Emergency department visits—cardiovascular (age 0-99)	✓	✓	PM ISA
	Hospital admissions—respiratory (ages 0-18 and 65-99)	✓	✓	PM ISA
	Emergency room visits—respiratory (all ages)	✓	✓	PM ISA
	Cardiac arrest (ages 0-99; excludes initial hospital and/or emergency department visits)	✓	✓ ¹	PM ISA
	Stroke (ages 65-99)	✓	✓ ¹	PM ISA
	Asthma onset (ages 0-17)	✓	✓	PM ISA
	Asthma symptoms/exacerbation (6-17)	✓	✓	PM ISA
	Lung cancer (ages 30-99)	✓	✓	PM ISA
	Allergic rhinitis (hay fever) symptoms (ages 3-17)	✓	✓	PM ISA
	Lost work days (age 18-65)	✓	✓	PM ISA
	Minor restricted-activity days (age 18-65)	✓	✓	PM ISA
	Hospital admissions—Alzheimer’s disease (ages 65-99)	✓	✓	PM ISA
	Hospital admissions—Parkinson’s disease (ages 65-99)	✓	✓	PM ISA
	Other cardiovascular effects (e.g., other ages)	—	—	PM ISA ²
	Other respiratory effects (e.g., pulmonary function, non-asthma ER visits, non-bronchitis chronic diseases, other ages and populations)	—	—	PM ISA ²
	Other nervous system effects (e.g., autism, cognitive decline, dementia)	—	—	PM ISA ²
	Metabolic effects (e.g., diabetes)	—	—	PM ISA ²
	Reproductive and developmental effects (e.g., low birth weight, pre-term births, etc.)	—	—	PM ISA ²
	Cancer, mutagenicity, and genotoxicity effects	—	—	PM ISA ²
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 ²
	Metabolic effects (e.g., diabetes)	—	—	Ozone ISA ²
	Other respiratory effects (e.g., premature aging of lungs)	—	—	Ozone ISA ²
	Cardiovascular and nervous system effects	—	—	Ozone ISA ²
	Reproductive and developmental effects	—	—	Ozone ISA ²

¹Valuation estimate excludes initial hospital and/or emergency department visits.

² Not quantified due to data availability limitations and/or because current evidence is only suggestive of causality.

8.3.3 Calculating Counts of Air Pollution Effects Using the Health Impact Function

We use BenMAP-CE to quantify individual risk and counts of estimated premature deaths and illnesses attributable to photochemical modeled changes in warm season average ozone concentrations and annual mean PM_{2.5} for the year 2045 using a health impact function.³⁸⁸ A health impact function combines information regarding the: concentration-response relationship between air quality changes and the risk of a given adverse outcome; population exposed to the air quality change; baseline rate of death or disease in that population; and, air pollution concentration to which the population is exposed.

The following provides an example of a health impact function, in this case for PM_{2.5} mortality risk. We estimate counts of PM_{2.5}-related total deaths (y_{ij}) during each year i ($i=1, \dots, I$ where I is the total number of years analyzed) among adults aged 30 and older (a) in each county in the contiguous U.S. j ($j=1, \dots, J$ where J is the total number of counties) as

$$y_{ij} = \sum_a y_{ija}$$
$$y_{ija} = mo_{ija} \times (e^{\beta \cdot \Delta C_{ij} - 1}) \times P_{ija}, \quad \text{Eq[1]}$$

where mo_{ija} is the baseline all-cause mortality rate for adults aged $a=30-99$ in county j in year i stratified in 10-year age groups, β is the risk coefficient for all-cause mortality for adults associated with annual average PM_{2.5} exposure, C_{ij} is the annual mean PM_{2.5} concentration in county j in year i , and P_{ija} is the number of county adult residents aged $a=30-99$ in county j in year i stratified into 5-year age groups.^{xxxxxx}

The BenMAP-CE tool is pre-loaded with projected population from the Woods & Poole company; cause-specific and age-stratified death rates from the Centers for Disease Control and Prevention, projected to future years; recent-year baseline rates of hospital admissions, emergency department visits and other morbidity outcomes from the Healthcare Cost and Utilization Program and other sources; concentration-response parameters from the published epidemiologic literature cited in the ISAs for fine particles and ground-level ozone; and, cost of illness or WTP unit values for each endpoint.

8.3.4 Quantifying Ozone-Attributable Premature Mortality

In 2008, the National Academies of Science (NAS) issued a series of recommendations to EPA regarding the procedure for quantifying and valuing ozone-related mortality due to short-term exposures.³⁸⁹ Chief among these was that "...short-term exposure to ambient ozone is likely to contribute to premature deaths" and the committee recommended that "ozone-related mortality be included in future estimates of the health benefits of reducing ozone exposures..." The NAS also recommended that "...the greatest emphasis be placed on the multicity and [National Mortality and Morbidity Air Pollution Studies (NMMAPS)] ...studies without exclusion of the meta-analyses."

^{xxxxxx} In this illustrative example, the air quality is resolved at the county level. For this RIA, we simulate air quality concentrations at 12km by 12km grids. The BenMAP-CE tool assigns the rates of baseline death and disease stored at the county level to the 12km by 12km grid cells using an area-weighted algorithm. This approach is described in greater detail in the appendices to the BenMAP-CE user manual.

Prior to the 2015 Ozone NAAQS RIA, the Agency estimated ozone-attributable premature deaths using an NMMAPS-based analysis of total mortality, two multi-city studies of cardiopulmonary and total mortality and effect estimates from three meta-analyses of non-accidental mortality.^{390,391,392,393,394,395} Beginning with the 2015 Ozone NAAQS RIA, the Agency began quantifying ozone-attributable premature deaths using two newer multi-city studies of non-accidental mortality and one long-term cohort study of respiratory mortality.^{396,397,398} The 2020 Ozone ISA included changes to the causality relationship determinations between short-term exposures and total mortality, as well as including more recent epidemiologic analyses of long-term exposure effects on respiratory mortality.³⁹⁹ In the final 2021 CSAPR RIA, mortality from long-term exposures was estimated using the Turner et al. (2016) study extending and expanding the analysis of the American Cancer Society cohort (ACS). Mortality for short-term exposures was estimated using the risk estimate parameters from Zanobetti et al. (2008) and Katsouyanni et al. (2009) were pooled using a consistent ozone season (May-Sept) and ozone metric (maximum daily 8-hour average).^{400,401,402}

In this RIA, ozone-attributable respiratory deaths are also estimated using the risk estimate parameters described in the final 2021 CSAPR RIA. However, instead of pooling results derived from different ozone air quality surfaces, we have chosen to use only the risk estimates derived from the Katsouyanni et al. (2009) study because the study includes more cities across the United States. Furthermore, this analysis uses modeled ozone concentration data that matches the ozone metric (maximum daily 1-hour average) and season (April-September) used by Katsouyanni et al. (2009) rather than using a default ozone season (May-Sept) and metric (maximum daily 8-hour average) used in the CSAPR RIA.

8.3.5 Quantifying PM_{2.5}-Attributable Premature Mortality

When quantifying PM-attributable cases of adult mortality, we use risk estimates from two epidemiology studies examining two large population cohorts: the American Cancer Society cohort and the Medicare cohort.^{403,404} The 2019 PM ISA concluded that the analyses of the ACS and Medicare cohorts provide strong evidence of an association between long-term PM_{2.5} exposure and premature mortality with support from additional cohort studies. Both the ACS and Medicare cohort studies have separate and distinct attributes that make them well-suited to being used in a PM benefits assessment, so we present PM_{2.5} related effects derived using relative risk estimates from both cohorts.

The PM ISA, which was reviewed by the Clean Air Scientific Advisory Committee of EPA's Science Advisory Board (SAB-CASAC), concluded that there is a causal relationship between mortality and both long-term and short-term exposure to PM_{2.5} based on the entire body of scientific evidence.⁴⁰⁵ 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 setting of the 2020 PM NAAQS, 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".⁴⁰⁶ Consistent with this evidence, the Agency historically has estimated health impacts above and below the prevailing NAAQS.^{407,408,409,410,411,412,413,414,415,416,417,418,419,420,421}

Following this approach, we report the estimated PM_{2.5}-related benefits (in terms of both health impacts and monetized values) calculated using a log-linear concentration-response function that quantifies risk from the full range of simulated PM_{2.5} exposures.^{422,423} When setting the 2020 PM NAAQS, the EPA noted that:

“...an important consideration in characterizing the potential for additional public health improvements associated with changes in PM_{2.5} exposure is whether concentration- response relationships are linear across the range of concentrations or if nonlinear relationships exist along any part of this range. Several recent studies examine this issue, and continue to provide evidence of linear, no-threshold relationships between long-term PM_{2.5} exposures and all-cause and cause-specific mortality.⁴²⁴ However, interpreting the shapes of these relationships, particularly at PM_{2.5} concentrations near the lower end of the air quality distribution, can be complicated by relatively low data density in the lower concentration range, the possible influence of exposure measurement error, and variability among individuals with respect to air pollution health effects [85 FR 82696].⁴²⁵

Hence, we are most confident in the size of the risks estimated from simulated PM_{2.5} concentrations that coincide with the bulk of the observed PM concentrations in the epidemiological studies that are used to estimate the benefits. Likewise, we are less confident in the risk we estimate from simulated PM_{2.5} concentrations that fall below the bulk of the observed data in these studies.

To give readers insight to the level of uncertainty in the estimated PM_{2.5} mortality benefits at lower ambient concentrations, we report the estimated PM benefits as a distribution, identifying points along this distribution corresponding to the Lowest Reported Levels (LRLs) of each long-term exposure mortality study and the PM NAAQS (see Figure 8-2 below). In addition to adult mortality discussed above, we use risk estimates from a multi-city study to estimate PM-related infant mortality.⁴²⁶

8.4 Economic Valuation Methodology for Health Benefits

We next quantify the economic value of the ozone and PM_{2.5}-related deaths and illnesses estimated above. Changes in ambient concentrations of air pollution generally yield small changes in the risk of future adverse health effects for a large number of people. Therefore, the appropriate economic measure is WTP for changes in risk of a health effect. For some health effects, such as hospital admissions, WTP estimates are not generally available, so we use the cost of treating or mitigating the effect. These cost-of-illness (COI) estimates are typically a lower bound estimate of the true value of reducing the risk of a health effect because they reflect the direct expenditures related to treatment, but not the value of avoided pain and suffering. The unit values applied in this analysis are provided in Table 21 of the Estimating PM_{2.5}- and Ozone-Attributable Health Benefits TSD.

The estimated value of avoided premature deaths (PM_{2.5} plus ozone) account for between 84 percent or 94 percent of total monetized benefits depending on the studies used. The value for the projected reduction in the risk of premature mortality 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 VSL approach in calculating estimates of mortality benefits, because we believe this calculation provides the most reasonable single estimate of an individual's willingness to trade off money

for changes in the risk of death.⁴²⁷ The VSL approach is a summary measure for the value of small changes in the risk of death experienced by a large number of people.

EPA continues work to update its guidance on valuing mortality risk reductions, and the Agency consulted several times with the SAB-EEAC on this issue. Until updated guidance is available, the Agency determined that a single, peer-reviewed estimate applied consistently, best reflects the SAB-EEAC advice it has received. Therefore, EPA applies the VSL that was vetted and endorsed by the SAB in the Guidelines for Preparing Economic Analyses while the Agency continues its efforts to update its guidance on this issue.⁴²⁸ This approach calculates a mean value across VSL estimates derived from 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 2017\$ after adjusting for income growth is \$11 million for 2045.

The Agency 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 update its mortality risk valuation estimates. In 2016, the Agency proposed new meta-analytic approaches for updating its estimates, which were subsequently reviewed by the SAB-EEAC.⁴²⁹ EPA is taking the SAB's formal recommendations under advisement.

In valuing PM_{2.5}-related premature mortality, we discount the value of premature mortality occurring in future years using rates of 3 percent and 7 percent.⁴³⁰ We assume that there is a multi-year "cessation" lag between changes in PM exposures and the total realization of changes in health effects. Although the structure of the lag is uncertain, EPA follows the advice of the SAB-Health Effects Subcommittee (HES) to use a segmented lag structure that assumes 30 percent of premature deaths are reduced in the first year, 50 percent over years 2 to 5, and 20 percent over the years 6 to 20 after the reduction in PM_{2.5}.⁴³¹ Changes in the cessation lag assumptions do not change the total number of estimated deaths but rather the timing of those deaths.

Because short-term ozone-related premature mortality occurs within the analysis year, the estimated ozone-related benefits are identical for all discount rates. When valuing changes in ozone-attributable deaths using the Turner et al. (2016) study, we follow advice provided by the SAB-HES, which found that "...there is no evidence in the literature to support a different cessation lag between ozone and particulate matter. The HES therefore recommends using the same cessation lag structure and assumptions as for particulate matter when utilizing cohort mortality evidence for ozone".⁴³²

These estimated health benefits do not account for the influence of future changes in the climate on ambient concentrations of pollutants.⁴³³ For example, recent research suggests that future changes to climate may create conditions more conducive to forming ozone; the influence of changes in the climate on PM_{2.5} concentrations are less clear.⁴³⁴ The estimated health benefits also do not consider the potential for climate-induced changes in temperature to modify the relationship between ozone and the risk of premature death.^{435,436,437}

8.5 Characterizing Uncertainty in the Estimated Benefits

This analysis includes many data sources as inputs that are each subject to uncertainty. Input parameters include projected emission inventories, air quality data from models (with their associated parameters and inputs), population data, population estimates, health effect estimates from epidemiology studies, economic data, and assumptions regarding the future state of the world (i.e., regulations, technology, and human behavior). When compounded, even small uncertainties can greatly influence the size of the total quantified benefits.

Our estimate of the total monetized PM_{2.5} and ozone-attributable benefits is based on EPA's interpretation of the best available scientific literature and methods and supported by the SAB-HES and the National Academies of Science.⁴³⁸ Below are key assumptions underlying the estimates for PM_{2.5}-related premature mortality, followed by key uncertainties associated with estimating the number and value of ozone-related premature deaths. Chapter 6 of the Estimating PM_{2.5}- and Ozone-Attributable Health Benefits TSD presents a thorough quantitative and qualitative analysis of the sources of uncertainty present in the health benefits analysis.

We assume that all fine particles, regardless of their chemical composition, are equally potent in causing premature mortality. Support for this assumption comes from the 2019 PM ISA, which concluded that “many PM_{2.5} components and sources are associated with many health effects and that the evidence does not indicate that any one source or component is consistently more strongly related with health effects than PM_{2.5} mass”.⁴³⁹

As noted above, we assume that the health impact function for fine particles is log-linear without a threshold. Thus, the estimates include health benefits from reducing fine particles in areas with different concentrations of PM_{2.5}, including both areas with projected annual mean concentrations that are above the level of the fine particle standard and areas with projected concentrations below the level of the standard.

Also, as noted above, 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.⁴⁴⁰

In general, we are more confident in the magnitude of the risks we estimate from simulated PM_{2.5} concentrations that coincide with the bulk of the observed PM concentrations in the epidemiological studies that are used to estimate the benefits. Likewise, we are less confident in the risk we estimate from simulated PM_{2.5} concentrations that fall below the bulk of the observed data in these studies. There are uncertainties inherent in identifying any particular point at which our confidence in reported associations decreases appreciably, and the scientific evidence provides no clear dividing line. This relationship between the air quality data and our confidence in the estimated risk is represented below in Figure 8-1.

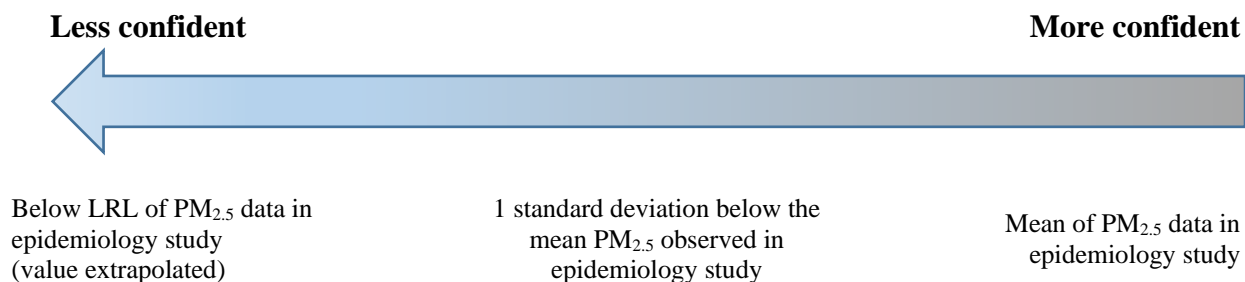


Figure 8-1: Stylized Relationship between the PM_{2.5} Concentrations Considered in Epidemiology Studies and our Confidence in the Estimated PM-related Premature Deaths

In this analysis, we plot estimated PM-related deaths according to where they occur along the distribution of baseline PM_{2.5} annual mean concentrations (Figure 8-2). Displaying the data in such a way allows readers to visualize the portion of population exposed to annual mean PM_{2.5} levels at or above different concentrations, which provides some insight into the level of uncertainty in the estimated PM_{2.5} mortality benefits. EPA does not view the level of the PM NAAQS or the lowest concentration levels reported in the mortality studies as concentration thresholds below which we would not quantify health benefits of air quality improvements.^{YYYYYY} Rather, the PM_{2.5}-attributable benefits estimates reported in this draft RIA are the most appropriate estimates because they reflect the full range of air quality concentrations associated with the emission reduction program being evaluated. The 2019 PM ISA concluded that the scientific evidence collectively is sufficient to conclude that there is a causal relationship between long-term PM_{2.5} exposures and mortality and that overall the studies support the use of a no-threshold log-linear model to estimate mortality attributed to long-term PM_{2.5} exposure.

Figure 8-2 compares the percentage of the population and PM-related deaths to the annual mean PM_{2.5} concentrations in the baseline for the year 2045. The figure identifies the LRL for each of the major cohort studies and the annual mean PM_{2.5} NAAQS of 12 µg/m³. For Turner et al. (2016), the LRL is 2.8 µg/m³ and for Di et al. (2017), the LRL is 0.02 µg/m³.^{ZZZZZZ} As PM-related mortality quantified using risk estimates from the Di et al. (2017) and Turner et al. (2016) are within 5 percent of one another, in the interest of clarity and simplicity, we present the results estimated using the risk estimate from Turner et al. (2016) alone in Figure 8-2. Additional information on low concentration exposures in Turner et al. (2016) and Di et al. (2017) can be found in section 6.1.2.1 of the Estimating PM_{2.5}- and Ozone-Attributable Health Benefits TSD. The air quality modeling predicts PM_{2.5} concentrations to be at or below the level of the annual PM_{2.5} NAAQS (12 µg/m³) in most locations in 2045. As noted in draft RIA Chapter 6.3.2, we are more confident in the projected changes in annual mean PM_{2.5} concentrations than we are in the projected absolute PM_{2.5} concentrations in 2045.

^{YYYYYY} For a summary of the scientific review statements regarding the lack of a threshold in the PM_{2.5}-mortality relationship, see the TSD entitled *Summary of Expert Opinions on the Existence of a Threshold in the Concentration-Response Function for PM_{2.5}-related Mortality* (U.S. EPA, 2010).

^{ZZZZZZ} Turner et al. (2016) estimated PM_{2.5} exposures using both a hierarchical Bayesian space-time model (HBM) and a land use regression model with Bayesian Maximum Entropy kriging of residuals (LURBME). As such, two LRLs are reported in the paper, 2.8 µg/m³ and 1.4 µg/m³. As the HBM risk estimate was used in the final 2021 CSAPR RIA, the HBM LRL is presented here.

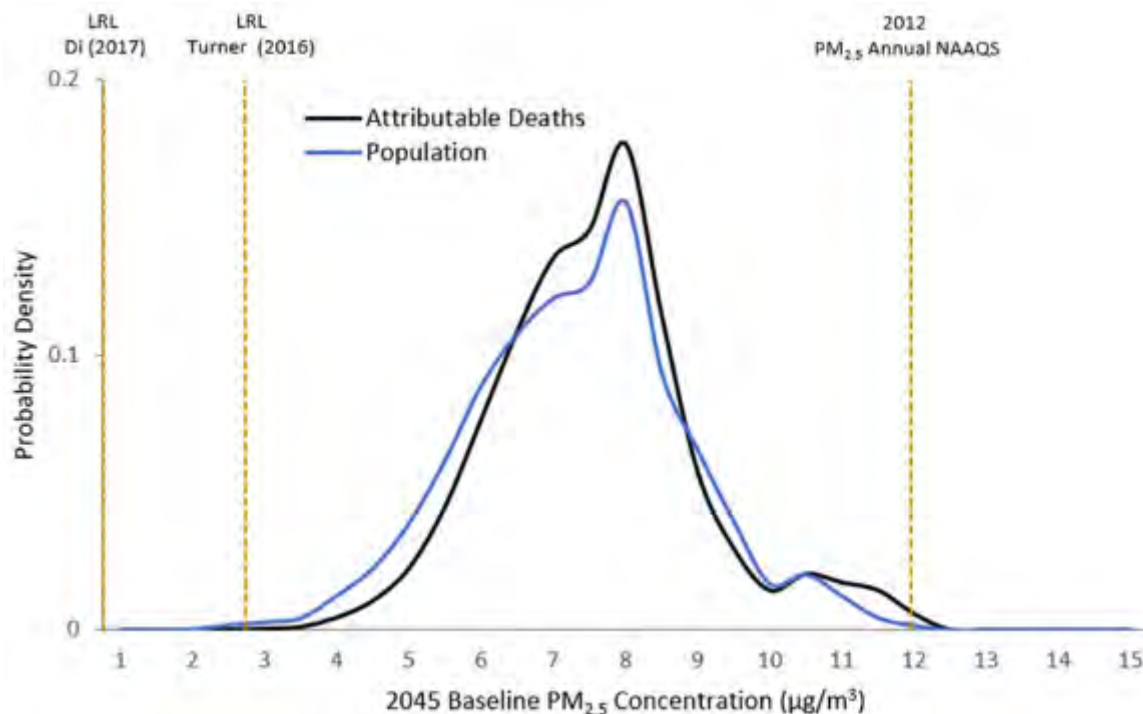


Figure 8-2: Estimated Percentage of PM_{2.5}-Related Deaths (Turner et al. 2016) and Number of Individuals Exposed (30+) by Annual Mean PM_{2.5} Level in 2045

The estimated number and value of avoided ozone-attributable deaths are also subject to uncertainty. When estimating the economic value of avoided premature mortality from long-term exposure to ozone, we use a 20-year segment lag (as used for PM_{2.5}) as there is no alternative empirical estimate of the cessation lag for long-term exposure to ozone. The 20-year segmented lag accounts for the onset of cardiovascular-related mortality, an outcome which is not relevant to the long-term respiratory mortality estimated here. We use a log-linear impact function without a threshold in modeling short-term ozone-related mortality. However, we acknowledge reduced confidence in specifying the shape of the concentration-response relationship in the range of ≤ 40 ppb and below.⁴⁴¹ Thus, the estimates include health benefits from reducing ozone in areas with varied concentrations of ozone down to the lowest modeled concentrations.

8.6 Estimated Number and Economic Value of Health Benefits

Below we report the estimated number of reduced premature deaths and illnesses in 2045 from proposed Option 1 relative to the baseline along with the 95 percent confidence interval (Table 8-3 and Table 8-4). The number of reduced estimated deaths and illnesses are calculated from the sum of individual reduced mortality and illness risk across the population. Table 8-5 reports the estimated individual economic value of avoided premature deaths and illnesses relative to the baseline along with the 95 percent confidence interval.

Table 8-6 reports total benefits associated with proposed Option 1 in 2045, 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.^{AAAAAAA}

^{AAAAAAA} EPA continues to refine its approach for estimating and reporting PM-related effects at lower concentrations. The Agency acknowledges the additional uncertainty associated with effects estimated at these lower levels and seeks to develop quantitative approaches for reflecting this uncertainty in the estimated PM benefits.

Table 8-3: Estimated Avoided PM_{2.5} Mortality and Illnesses in 2045 for Proposed Option 1 (95% Confidence Interval) ^{a,b}

		Proposed Option 1
Avoided premature mortality		
	Turner et al. (2016) – Ages 30+	740 (500 to 980)
	Di et al. (2017) – Ages 65+	800 (780 to 830)
	Woodruff et al. (2008) – Ages < 1	4.1 (-2.6 to 11)
Non-fatal heart attacks among adults		
Short-term exposure	Peters et al. (2001)	790 (180 to 1,400)
	Pooled estimate	85 (31 to 230)
Morbidity effects		
Long-term exposure	Asthma onset	1,600 (1,500 to 1,600)
	Allergic rhinitis symptoms	10,000 (2,500 to 18,000)
	Stroke	41 (11 to 70)
	Lung cancer	52 (16 to 86)
	Hospital Admissions - Alzheimer's disease	400 (300 to 500)
	Hospital Admissions - Parkinson's disease	43 (22 to 63)
Short-term exposure	Hospital admissions-cardiovascular	110 (76 to 130)
	ED visits- cardiovascular	210 (-82 to 500)
	Hospital admissions - respiratory	68 (23 to 110)
	ED visits - respiratory	400 (78 to 830)
	Asthma symptoms	210,000 (-100,000 to 520,000)
	Minor restricted-activity days	460,000 (370,000 to 550,000)
	Cardiac arrest	10 (-4.2 to 24)
	Lost work days	78,000 (66,000 to 90,000)

^a Values rounded to two significant figures.

^b PM_{2.5} exposure metrics are not presented here because all PM health endpoints are based on studies that used daily 24-hour average concentrations. Annual exposures are estimated using daily 24-hour average concentrations.

Table 8-4: Estimated Avoided Ozone Mortality and Illnesses in 2045 for the Proposed Option 1 (95% Confidence Interval)^a

		Metric and Season^b	Proposed Option 1
Avoided premature mortality			
Long-term exposure	Turner et al. (2016)	MDA8 April-September	2,100 (1,400 to 2,700)
Short-term exposure	Katsouyanni et al (2009)	MDA1 April-September	120 (-69 to 300)
Morbidity effects			
Long-term exposure	Asthma onset ^c	MDA8 June-August	16,000 (14,000 to 18,000)
Short-term exposure	Allergic rhinitis symptoms	MDA8 May-September	88,000 (47,000 to 130,000)
	Hospital admissions - respiratory	MDA1 April-September	350 (-91 to 770)
	ED visits - respiratory	MDA8 May-September	5,100 (1,400 to 11,000)
	Asthma symptoms - Cough ^d	MDA8 May-September	920,000 (-50,000 to 1,800,000)
	Asthma symptoms - Chest Tightness ^d	MDA8 May-September	770,000 (85,000 to 1,400,000)
	Asthma symptoms - Shortness of Breath ^d	MDA8 May-September	390,000 (-330,000 to 1,100,000)
	Asthma symptoms - Wheeze ^d	MDA8 May-September	730,000 (-57,000 to 1,500,000)
	Minor restricted-activity days ^d	MDA1 May-September	1,600,000 (650,000 to 2,600,000)
	School absence days	MDA8 May-September	1,100,000 (-150,000 to 2,200,000)

^a Values rounded to two significant figures.

^b MDA8 – maximum daily 8-hour average; MDA1 – maximum daily 1-hour average. Studies of ozone vary with regards to season, limiting analyses to various definitions of summer (e.g., April-September, May-September or June-August). These differences can reflect state-specific ozone seasons, EPA-defined seasons or another seasonal definition chosen by the study author. The paucity of ozone monitoring data in winter months complicates the development of full year projected ozone surfaces and limits our analysis to only warm seasons.

^c The underlying metric associated with this risk estimate is daily 8-hour average from 10am – 6pm (AVG8); however, we ran the study with a risk estimate converted to MDA8.

^d Applied risk estimate derived from full year exposures to estimates of ozone across a May-September ozone season. When risk estimates based on full-year, long-term ozone exposures are applied to warm season air quality projections, the resulting benefits assessment may underestimate impacts, due to a shorter timespan for impacts to accrue.

Table 8-5: Estimated Economic Value of PM_{2.5}- and Ozone-Attributable Premature Mortality and Illnesses in 2045 for Proposed Option 1 (95% Confidence Interval; millions of 2017\$)^a

			3% Discount Rate	7% Discount Rate
Avoided premature mortality				
PM _{2.5}	Long-term exposure	Turner et al. (2016)	\$8,100 (\$710 to \$22,000)	\$7,300 (\$640 to \$20,000)
		Di et al. (2017)	\$8,800 (\$790 to \$23,000)	\$7,900 (\$710 to \$21,000)
	Short-term exposure	Woodruff et al (2008)	\$50 (-\$28 to \$200)	
Ozone	Long-term exposure	Turner et al. (2016)	\$23,000 (\$2,000 to \$61,000)	\$20,000 (\$1,800 to \$55,000)
	Short-term exposure	Katsouyanni et al (2009)	\$1,500 (-\$720 to \$5,700)	
PM _{2.5} - related non-fatal heart attacks among adults				
Short-term exposure		Peters et al. (2001)	\$62 (\$14 to \$110)	\$60 (\$14 to \$100)
		Pooled estimate	\$6.7 (\$2.4 to \$18)	\$6.4 (\$2.3 to \$17)
Morbidity effects				
Long-term exposure		Asthma onset (PM _{2.5} & O ₃)	\$820 (\$720 to \$940)	\$520 (\$440 to \$580)
		Allergic rhinitis symptoms (PM _{2.5} & O ₃)	\$61 (\$31 to \$91)	
		Stroke (PM _{2.5})	\$1.4 (\$0.37 to \$2.5)	
		Lung cancer (PM _{2.5})	\$1.4 (\$0.43 to \$2.4)	\$1.1 (\$0.33 to \$1.8)
		Hospital Admissions - Alzheimer’s disease (PM _{2.5})	\$5.0 (\$3.8 to \$6.3)	
		Hospital Admissions - Parkinson’s disease (PM _{2.5})	\$0.57 (\$0.29 to \$0.84)	
Short-term exposure		Hospital admissions - cardiovascular (PM _{2.5})	\$1.7 (\$1.2 to \$2.1)	
		ED visits - cardiovascular (PM _{2.5})	\$0.25 (-\$0.098 to \$0.59)	
		Hospital admissions - respiratory (PM _{2.5} & O ₃)	\$14 (-\$3.2 to \$30)	
		ED visits - respiratory (PM _{2.5} & O ₃)	\$5.0 (\$1.4 to \$10)	
		Asthma symptoms (PM _{2.5} & O ₃)	\$650 (-\$79 to \$1,400)	
		Minor restricted-activity days (PM _{2.5} & O ₃)	\$170 (\$67 to \$300)	
		Cardiac arrest (PM _{2.5})	\$0.38 (-\$0.16 to \$0.87)	\$0.38 (-\$0.15 to \$0.86)
		Lost work days (PM _{2.5})	\$14 (\$12 to \$16)	
		School absence days (O ₃)	\$120 (-\$16 to \$240)	

^a Values rounded to two significant figures.

Table 8-6: Total Ozone and PM_{2.5}-Attributable Benefits in 2045 for Proposed Option 1 (95% Confidence Interval; billions of 2017\$)^{a,b}

	Total Annual Benefits in 2045	
3% Discount Rate	\$12 (\$0.72 to \$31) ^c	and \$33 (\$3.5 to \$87) ^d
7% Discount Rate	\$10 (\$0.37 to \$28) ^c	and \$30 (\$3.0 to \$78) ^d

^a The benefits associated with the standards presented here do not include the full complement of health, environmental, and climate-related benefits that, if quantified and monetized, would increase the total monetized benefits.

^b Values rounded to two significant figures. The two benefits estimates separated by the word “and” signify that they are two separate estimates. The estimates do not represent lower- and upper-bound estimates though they do reflect a grouping of estimates that yield more and less conservative benefit totals. They should not be summed.

^c Sum of benefits using the Katsouyanni et al. (2009) short-term exposure ozone respiratory mortality risk estimate and the Turner et al. (2016) long-term exposure PM_{2.5} all-cause risk estimate.

^d Sum of benefits using the Turner et al. (2016) long-term exposure ozone respiratory mortality risk estimate and the Di et al. (2017) long-term exposure PM_{2.5} all-cause risk estimate.

8.7 Present Value of Total Benefits of Proposed Option 1 and 2

The full-scale benefits analysis for proposed Option 1 presented earlier in this Chapter reflects spatially and temporally allocated emissions inventories generated using SMOKE/MOVES (see draft RIA Chapter 5), photochemical air quality modeling using CMAQ (see draft RIA Chapter 6), and PM_{2.5} and ozone benefits generated using BenMAP-CE, all for conditions projected to occur in calendar year 2045. As we presented in draft RIA Chapter 5 and Chapter 7, national estimates of year-over-year emissions and program costs were generated for both Option 1 and Option 2 from proposed implementation to a year when the program would be fully phased-in and the vehicle fleet would be approaching full turnover (2027-2045). The time and resources required to conduct air quality modeling to support a full-scale benefits analysis for Option 2 in 2045 and for all Option 1 and Option 2 analysis years from 2027 to 2044 precluded the Agency from conducting benefits analyses comparable to the calendar year 2045 Option 1 benefits analysis. Instead, we have used a reduced-form approach to scale total Option 1 benefits in 2045 back to 2027 (including interim years) using projected reductions in year-over-year NO_x emissions so that we can estimate the present value of the stream of estimated benefits for Option 1. We have also used year-over-year Option 2 NO_x emissions reductions to scale the total benefits associated with Option 1 to derive a best estimate of criteria pollutant benefits associated with Option 2.

This approach is similar to the Agency’s method for estimating “benefits-per-ton” values over time.⁴⁴² For interim analysis years without air quality modeling, we input the proposed program’s 2045 air quality data into BenMAP-CE to generate benefits that occur in earlier analysis years. This approach allows us to calculate the benefits for interim years by adjusting for changes in population, baseline mortality incidence, and income growth over time. Table 8-7

displays the data used to generate benefits that reflect input data for years 2027, 2030, 2035, 2040, and 2045.^{BBBBBBB}

Table 8-7: Benefits Inputs that Change Over Time used to Calculate Year-over-Year Estimates

Analysis Year	Air Quality Modeling & Emissions Year	Population Year	Baseline Mortality Incidence Year	Income Growth Year	Currency Year
2027	2045	2027	2025	2027	2017
2030		2030	2030	2030	
2035		2035	2035	2035	
2040		2040	2040	2040	
2045		2045	2045	2045	

We next calculate the total monetized benefits estimated for each of the analysis years and divide them by the estimated tons of NO_x emissions projected to be controlled by the proposed Option 1 in 2045 (see draft RIA Chapter 5, Table 5-21) to generate “benefit-per-ton” values that reflect benefits inputs consistent with the analysis year.^{CCCCCCC} Because NO_x is the dominating pollutant controlled by the proposed program, we make a simplifying assumption that total PM and ozone benefits can be scaled by NO_x emissions, even though emissions of other pollutants are controlled in smaller amounts by the proposed Options (see draft RIA Chapter 5, Table 5-21). By using the 2045 air quality modeling surfaces for the earlier analysis years, we also assume that the spatial distribution of NO_x emissions reductions does not change over time. While there may be localized differences in the rate of fleet turnover due to state or local incentive programs, we do not currently have sufficient data to incorporate those differences into our analyses and believe that they would generally even out over time (as noted in draft RIA Chapter 5, we use MOVES default vehicle activity data, including data on age of the fleet or turnover).

To estimate total benefits for the interim years, we multiply the benefit-per-ton values estimated for each earlier analysis year by the NO_x emissions projected to be controlled in that same year (2027, 2030, 2035, and 2040; see draft RIA Chapter 5, Table 5-33). For intervening years between the analysis years, we linearly interpolate total benefits.

Table 8-8 and Table 8-9 present the undiscounted stream of scaled annual total benefits of the proposed Option 1 between 2027 and 2045. We also estimate the present value and annualized value of the stream of benefits in these tables. Table 8-8 presents total benefits as the sum of short-term ozone respiratory mortality benefits for all ages, long-term PM_{2.5} all-cause mortality benefits for ages 30 and above, and all monetized avoided illnesses.^{443,444} Table 8-9 presents total benefits as the sum of long-term ozone respiratory mortality benefits for ages 30 and above, long-term PM_{2.5} all-cause mortality benefits for ages 65 and above, and all monetized avoided illnesses.^{445,446} The present value of benefits in both tables is discounted back to year 2027 using both a 3 percent and 7 percent discount rate.

^{BBBBBBB} Interim analysis years chosen for computational efficiency at reasonable intervals.

^{CCCCCCC} Note that these “benefit-per-ton” values are internally consistent with the air quality modeling conducted for Option 1 in 2045. They are appropriate for scaling benefits of the proposed program, but should not be used outside of the context of this rulemaking analysis.

To generate the undiscounted stream of total benefits associated with the proposed Option 2, and to estimate the present value of those benefits, we also employed a reduced-form scaling approach.^{DDDDDD} Beginning with the stream of total benefits associated with the proposed Option 1, we scaled annual benefits by the ratio of year-over-year NO_x emission reductions projected to occur from proposed Option 2 compared to year-over-year NO_x emission reductions associated with proposed Option 1 (see draft RIA Chapter 5, Table 5-33). The stream of total benefits for proposed Option 2, along with associated present and annualized values, are also presented in Table 8-8 and Table 8-9.

Table 8-8: Undiscounted Stream and Present Value of Human Health Benefits from 2027 through 2045: Monetized Benefits Quantified as Sum of Short-Term Ozone Respiratory Mortality Ages 0-99, and Long-Term PM_{2.5} All-Cause Mortality Ages 30+ (Discounted at 3% and 7%; billions of 2017\$)^{a b}

	Proposed Option 1		Proposed Option 2	
	3%	7%	3%	7%
2027	\$0.57	\$0.51	\$0.52	\$0.47
2028	\$1.2	\$1.1	\$1.1	\$0.98
2029	\$1.8	\$1.7	\$1.7	\$1.5
2030	\$2.5	\$2.3	\$2.3	\$2.1
2031	\$3.4	\$3.1	\$3.1	\$2.7
2032	\$4.3	\$3.9	\$3.8	\$3.4
2033	\$5.0	\$4.5	\$4.3	\$3.9
2034	\$5.6	\$5.0	\$4.9	\$4.4
2035	\$6.3	\$5.7	\$5.4	\$4.8
2036	\$6.9	\$6.2	\$5.8	\$5.3
2037	\$7.8	\$7.0	\$6.3	\$5.7
2038	\$8.6	\$7.7	\$6.7	\$6.0
2039	\$9.1	\$8.2	\$7.1	\$6.4
2040	\$9.6	\$8.6	\$7.5	\$6.7
2041	\$10	\$9.0	\$7.8	\$7.1
2042	\$10	\$9.4	\$8.2	\$7.4
2043	\$11	\$9.8	\$8.5	\$7.6
2044	\$11	\$10	\$8.8	\$7.9
2045 ^c	\$12	\$10	\$9.1	\$8.2
Present Value	\$87	\$50	\$71	\$41
Annualized Value	\$6.1	\$4.9	\$5.0	\$4.0

^a The benefits associated with the standards presented here do not include the full complement of health, environmental, and climate-related benefits that, if quantified and monetized, would increase the total monetized benefits.

^b Benefits calculated as value of avoided: PM_{2.5}-attributable deaths (quantified using a concentration-response relationship from the Turner et al. 2016 study); Ozone-attributable deaths (quantified using a concentration-response relationship from the Katsouyanni et al. 2009 study); and PM_{2.5} and ozone-related morbidity effects.

^c Year in which PM_{2.5} and ozone air quality associated with Option 1 was simulated (2045).

^{DDDDDD} We are not including an analysis of benefits of the Alternative (described in Preamble Sections III and IV) because we currently do not have sufficient information to conclude that the Alternative standards would be feasible in the MY2027 timeframe. Preamble Section III presents our current feasibility analysis for the Alternative.

Table 8-9: Undiscounted Stream and Present Value of Human Health Benefits from 2027 through 2045: Monetized Benefits Quantified as Sum of Long-Term Ozone Respiratory Mortality Ages 30+, and Long-Term PM_{2.5} All-Cause Mortality Ages 65+ (Discounted at 3% and 7%; billions of 2017\$)^{a,b}

	Proposed Option 1		Proposed Option 2	
	3%	7%	3%	7%
2027	\$1.6	\$1.4	\$1.4	\$1.3
2028	\$3.3	\$2.9	\$3.0	\$2.7
2029	\$5.1	\$4.6	\$4.7	\$4.2
2030	\$7.0	\$6.3	\$6.4	\$5.8
2031	\$9.6	\$8.6	\$8.5	\$7.6
2032	\$12	\$11	\$11	\$9.5
2033	\$14	\$13	\$12	\$11
2034	\$16	\$14	\$14	\$12
2035	\$18	\$16	\$15	\$14
2036	\$20	\$18	\$17	\$15
2037	\$22	\$20	\$18	\$16
2038	\$24	\$22	\$19	\$17
2039	\$26	\$23	\$20	\$18
2040	\$28	\$25	\$21	\$19
2041	\$29	\$26	\$23	\$20
2042	\$30	\$27	\$24	\$21
2043	\$31	\$28	\$24	\$22
2044	\$32	\$29	\$25	\$23
2045 ^c	\$33	\$30	\$26	\$23
Present Value	\$250	\$140	\$200	\$120
Annualized Value	\$17	\$14	\$14	\$11

^a The benefits associated with the standards presented here do not include the full complement of health, environmental, and climate-related benefits that, if quantified and monetized, would increase the total monetized benefits.

^b Benefits calculated as value of avoided: PM_{2.5}-attributable deaths (quantified using a concentration-response relationship from the Di et al. 2017 study); Ozone-attributable deaths (quantified using a concentration-response relationship from the Turner et al. 2016 study); and PM_{2.5} and ozone-related morbidity effects.

^c Year in which PM_{2.5} and ozone air quality for Option 1 was simulated (2045).

8.8 Unquantified Benefits

In addition to the PM_{2.5} and ozone-related health impacts we are unable to quantify or monetize in Table 8-2, there are additional benefits associated with reductions in exposure to ambient concentrations of NO₂, ecosystem benefits, and visibility improvement that EPA is not currently able to quantify due to data, resource, or methodological limitations. EPA continues to pursue data and methods to further improve our assessment of benefits that are currently unquantified. In particular, we are evaluating the feasibility of assessing impacts on ecosystem services from reductions in nitrogen deposition and terrestrial acidification. Draft RIA Chapter 4

provides a qualitative description of both the health and environmental effects of the criteria pollutants controlled by the proposed program. These additional unquantified health and welfare benefit categories are listed in Table 8-10.

There would also be benefits associated with reductions in air toxic pollutant emissions that result from the proposed program (See draft RIA Chapter 4.1.6 and draft RIA Chapter 5.3.1), but we did not attempt to monetize those impacts. This is because currently available tools and methods to assess air toxics risk from mobile sources at the national scale are not adequate for extrapolation to incidence estimation or benefits assessment. While EPA has worked to improve these tools, there remain critical limitations for estimating incidence and assessing benefits of reducing mobile source air toxics.

The proposed criteria pollutant standards would also reduce methane (CH₄) emissions due to lower total hydrocarbon emission rates from the tailpipe of heavy-duty gasoline vehicles (see draft RIA Chapter 5.2.2 for more detail). There would be climate-related benefits associated with these projected reductions in CH₄, but we did not monetize them.^{EEEEEEE} We request comment on how to address the climate benefits and other categories of non-monetized benefits of the proposed rule.

^{EEEEEEE} The U.S. District Court for the Western District of Louisiana has issued an injunction concerning the monetization of the benefits of greenhouse gas emission reductions by EPA and other defendants. See *Louisiana v. Biden*, No. 21-cv-01074-JDC-KK (W.D. La. Feb. 11, 2022).

Table 8-10: Unquantified Criteria Pollutant Health and Welfare Benefits Categories

Category	Effect	Effect Quantified	Effect Monetized	More Information
Improved Human Health				
Reduced incidence of morbidity from exposure to NO ₂	Asthma hospital admissions	—	—	NO ₂ ISA ^{447,1}
	Chronic lung disease hospital admissions	—	—	NO ₂ ISA ¹
	Respiratory emergency department visits	—	—	NO ₂ ISA ¹
	Asthma exacerbation	—	—	NO ₂ ISA ¹
	Acute respiratory symptoms	—	—	NO ₂ ISA ¹
	Premature mortality	—	—	NO ₂ ISA ^{1,2,3}
	Other respiratory effects (e.g., airway hyperresponsiveness and inflammation, lung function, other ages and populations)	—	—	NO ₂ ISA ^{2,3}
Improved Environment				
Reduced visibility impairment	Visibility in Class 1 areas	—	—	PM ISA ¹
	Visibility in residential areas	—	—	PM ISA ¹
Reduced effects on materials	Household soiling	—	—	PM ISA ^{1,2}
	Materials damage (e.g., corrosion, increased wear)	—	—	PM ISA ²
Reduced effects from PM deposition (metals and organics)	Effects on individual organisms and ecosystems	—	—	PM ISA ²
Reduced vegetation and ecosystem effects from exposure to ozone	Visible foliar injury on vegetation	—	—	Ozone ISA ¹
	Reduced vegetation growth and reproduction	—	—	Ozone ISA ¹
	Yield and quality of commercial forest products and crops	—	—	Ozone ISA ¹
	Damage to urban ornamental plants	—	—	Ozone ISA ²
	Carbon sequestration in terrestrial ecosystems	—	—	Ozone ISA ¹
	Recreational demand associated with forest aesthetics	—	—	Ozone ISA ²
	Other non-use effects	—	—	Ozone ISA ²
	Ecosystem functions (e.g., water cycling, biogeochemical cycles, net primary productivity, leaf-gas exchange, community composition)	—	—	Ozone ISA ²
Reduced effects from acid deposition	Recreational fishing	—	—	NO _x SO _x ISA ^{448,1}
	Tree mortality and decline	—	—	NO _x SO _x ISA ²
	Commercial fishing and forestry effects	—	—	NO _x SO _x ISA ²
	Recreational demand in terrestrial and aquatic ecosystems	—	—	NO _x SO _x ISA ²
	Other non-use effects	—	—	NO _x SO _x ISA ²
	Ecosystem functions (e.g., biogeochemical cycles)	—	—	NO _x SO _x ISA ²
Reduced effects from nutrient enrichment	Species composition and biodiversity in terrestrial and estuarine ecosystems	—	—	NO _x SO _x ISA ²
	Coastal eutrophication	—	—	NO _x SO _x ISA ²
	Recreational demand in terrestrial and estuarine ecosystems	—	—	NO _x SO _x ISA ²
	Other non-use effects	—	—	NO _x SO _x ISA ²
	Ecosystem functions (e.g., biogeochemical cycles, fire regulation)	—	—	NO _x SO _x ISA ²
Reduced vegetation effects from ambient exposure to SO ₂ and NO _x	Injury to vegetation from SO ₂ exposure	—	—	NO _x SO _x ISA ²
	Injury to vegetation from NO _x exposure	—	—	NO _x SO _x ISA ²

¹ We assess these benefits qualitatively due to data and resource limitations for this draft RIA.

² We assess these benefits qualitatively because we do not have sufficient confidence in available data or methods.

³ 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.

Chapter 9 Comparison of Benefits and Costs

This chapter compares the estimated range of total monetized health benefits to total costs associated with the criteria pollutant program proposed Options 1 and 2. This chapter also presents the range of monetized net benefits (benefits minus costs) associated with the same options. Criteria pollutant program costs are detailed and presented in Chapter 7 of this draft RIA. Those costs include costs for both the new technology and the operating costs associated with that new technology, as well as costs associated with the proposed warranty and useful life provisions for Options 1 and 2. Criteria pollutant program benefits are detailed and presented in draft RIA Chapter 8.^{FFFFF} Those benefits are the monetized economic value of the reduction in PM_{2.5}-and ozone-related premature deaths and illnesses that result from reductions in NO_x emissions and directly emitted PM_{2.5} attributable to implementation of the proposed options.

9.1 Methods

EPA presents three different benefit-cost comparisons for the proposed Options 1 and 2.^{GGGGGG}

1. A future-year snapshot comparison of annual benefits and costs in the year 2045, chosen to approximate the annual health benefits that would occur in a year when the program would be fully implemented and when most of the regulated fleet would have turned over. Benefits, costs and net benefits are presented in year 2017 dollars and are not discounted. However, 3 percent and 7 percent discount rates were applied in the valuation of avoided premature deaths from long-term pollution exposure, to account for a twenty-year segmented cessation lag.
2. The present value (PV) of the stream of benefits, costs and net benefits calculated for the years 2027-2045, discounted back to the first year of implementation of the proposed rule (2027) using both a 3 percent and 7 percent discount rate, and presented in year 2017 dollars. Note that year-over-year costs are presented in draft RIA Chapter 7 and year-over-year benefits can be found in draft RIA Chapter 8.
3. The equivalent annualized value (EAV) of benefits, costs and net benefits, representing a flow of constant annual values that, had they occurred in each year from 2027 to 2045, would yield an equivalent present value to those estimated in Method 2 above (using either a 3 percent or 7 percent discount rate). Each EAV represents a typical benefit, cost or net benefit for each year of the analysis and is presented in year 2017 dollars.

^{FFFFF} As noted in draft RIA Chapter 5.4, there are differences between the standards, emission warranty, and useful life provisions of proposed Option 1 presented in Sections III and IV and those included in our control case scenario modeled for the air quality analysis (as noted in Section VII, due to resource constraints we only conducted air quality modeling for the proposed Option 1). As detailed in draft RIA Chapter 8, estimates of health benefits are based on our air quality analysis, and thus differences between proposed Option 1 and modeling are not reflected in the benefits analysis.

^{GGGGG} We are not including an analysis of costs or benefits of the Alternative (described in Preamble Sections III and IV) because we currently do not have sufficient information to conclude that the Alternative standards would be feasible in the MY2027 timeframe. Preamble Section III presents our feasibility analysis for the Alternative.

The two estimates of benefits (and net benefits) in each of these benefit-cost comparisons reflect 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 (see Chapter 8 for more detail).

9.2 Results

Table ES presents the benefits, costs and net benefits of the proposed Options 1 and 2 in annual terms for year 2045, in PV terms, and in EAV terms.

Annual benefits of proposed Option 1 are larger than the annual costs in 2045, with annual net benefits of \$8.1 and \$28 billion using a 7 percent discount rate, and \$9.2 and \$31 billion using a 3 percent discount rate.^{HHHHHHH} Benefits also outweigh the costs when expressed in PV terms (net benefits of \$33 and \$130 billion using a 7 percent discount rate, and \$61 and \$220 billion using a 3 percent discount rate) and EAV terms (net benefits of \$2.9 and \$12 billion using a 7 percent discount rate, and \$4.1 and \$15 billion using a 3 percent discount rate).

The benefits also outweigh the costs in annual 2045 terms when looking at proposed Option 2, with annual net benefits of \$5.3 and \$21 billion using a 7 percent discount rate and \$6.2 billion and \$23 billion using a 3 percent discount rate. Benefits also outweigh the costs in PV and EAV terms for proposed Option 2.

Comparing the proposed Options 1 and 2, our analysis shows that proposed Option 2 has lower net benefits than proposed Option 1 due to both higher costs and lower emission reductions relative to proposed Option 1. As discussed further in Preamble Section I.G, we have considered several other factors, including lead time and technological feasibility, in developing this proposal and considering possible regulatory alternatives.

Given these results, EPA expects that implementation of the proposed rule would provide society with a substantial net gain in welfare, notwithstanding the health and other benefits we were unable to quantify (see draft RIA Chapter 8.8 for more information about unquantified benefits). EPA does not expect the omission of unquantified benefits to impact the Agency's evaluation of regulatory options since unquantified benefits generally scale with the emissions impacts of the proposed Options.

^{HHHHHHH} The range of benefits and net benefits presented in this section reflect a combination of assumed PM_{2.5} and ozone mortality risk estimates and selected discount rate.

Table 9-1: 2045 Annual Value, Present Value and Equivalent Annualized Value of Costs, Benefits and Net Benefits of the Proposed Options 1 and 2 (billions, 2017\$)^{a,b}

		Proposed Option 1		Proposed Option 2	
		3% Discount	7% Discount	3% Discount	7% Discount
2045	Benefits	\$12 - \$33	\$10 - \$30	\$9.1 - \$26	\$8.2 - \$23
	Costs	\$2.3	\$2.3	\$2.9	\$2.9
	Net Benefits	\$9.2 - \$31	\$8.1 - \$28	\$6.2 - \$23	\$5.3 - \$21
Present Value	Benefits	\$88 - \$250	\$52 - \$150	\$71 - \$200	\$41 - \$120
	Costs	\$27	\$19	\$30	\$21
	Net Benefits	\$61 - \$220	\$33 - \$130	\$41 - \$170	\$21 - \$96
Equivalent Annualized Value	Benefits	\$6.0 - \$17	\$4.7 - \$13	\$5.0 - \$14	\$4.0 - \$11
	Costs	\$1.9	\$1.9	\$2.1	\$2.0
	Net Benefits	\$4.1 - \$15	\$2.9 - \$12	\$2.9 - \$12	\$2.0 - \$9.3

^a All benefits estimates are rounded to two significant figures; numbers may not sum due to independent rounding. The range of benefits (and net benefits) in this table are two separate estimates and do not represent lower- and upper-bound estimates, though they do reflect a grouping of estimates that yield more and less conservative benefits totals. The costs and benefits in 2045 are presented in annual terms and are not discounted. However, all benefits in the table reflect a 3 percent and 7 percent discount rate used to account for cessation lag in the valuation of avoided premature deaths associated with long-term exposure.

^b The benefits associated with the standards presented here do not include the full complement of health, environmental, and climate-related benefits that, if quantified and monetized, would increase the total monetized benefits.

Chapter 10 Economic Impact Analysis

This proposed rulemaking is considered economically significant, because it is expected to have an annual impact on the economy of \$100 million or more, and thus an economic analysis has been completed as part of this draft RIA. This rule is not expected to have measurable inflationary or recessionary effects.

The benefits to human health and the environment are discussed in Chapter 8, and the costs of the proposed standards are discussed in Chapter 7. The benefit-cost analysis for this proposal is presented in Chapter 9. This chapter provides an analysis of the impacts of the proposed standards on vehicle sales and employment.

10.1 Impact on Sales, Fleet Turnover and Mode Shift

As explained in Chapter 7, this proposed rule is expected to increase the cost of heavy-duty (HD) vehicles by requiring emissions control technologies capable of controlling NO_x at lower levels than are currently permitted, as well as longer emissions warranty periods for emissions control technology components. In addition, there is an expected small increase in operating costs mainly due to an increase in the use of diesel exhaust fluid (DEF).

Three sectors expected to be most immediately affected by this action are: 1) HD vehicle and engine manufacturers, 2) HD vehicle and engine buyers, and 3) HD engine equipment suppliers (e.g., suppliers of emissions control components). Effects on industries downstream of these sectors, such as HD vehicle dealerships or delivery industries, would be relatively smaller due to the limited role of the cost of a HD vehicle in pricing in those sectors. The three sectors will also be responding to the 2016 rulemaking, “Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles – Phase 2” (the Phase 2 rule). The proposed standards, if finalized as proposed, would phase in during the same time frame as the final Phase 2 rule standards. Both this proposed rulemaking, if finalized, and the Phase 2 rule would require HD engine manufacturers to develop and implement improvements in engine emissions controls.

As discussed in the Phase 2 rule RIA,⁴⁴⁹ increases in costs of HD vehicles from improved emissions controls would be likely to lead to increases in final prices for HD vehicles; the magnitude of that effect would depend on how much of the cost is passed along to potential buyers. These price increases may affect HD vehicle sales in several ways. First, as basic economic supply and demand theory suggests, higher prices are expected to reduce HD vehicle sales. Second, HD vehicle buyers may strategically seek to avoid increased prices by “pre-buying,” increasing the purchases of new vehicles before the compliance deadline for the new requirements. This might lead to an associated period immediately afterward of “low-buying,” during which purchases decrease, and thereby impact the rate of fleet turnover. A third potential effect is transportation mode shift, changing from on-highway trucking to other modes of transportation (e.g., shipping via barge or rail instead of by truck). The magnitude of each of

these three categories of effects (sales, fleet turnover, mode shift) would depend on the costs. This section discusses these impacts.^{IIIIII}

10.1.1 **Sales**

The effects of the proposed standards on HD vehicle sales depends on the magnitude of the cost increase associated with implementing improved emissions controls to comply with the proposed requirements, and on the degree to which the costs get passed through to vehicle buyers.

As discussed in Chapter 7, an increase in cost of HD vehicles could result from the proposed standards requiring the use of emissions control technologies capable of controlling NO_x at lower levels, as well as imposing longer useful life and emissions warranty periods for emissions control technology components. While the proposed requirement for longer emissions warranty periods would likely increase the purchase price of new HD vehicles, the corresponding lengthened useful life periods are expected to make emissions control technology components more durable. More durable components coupled with manufacturers paying for repairs during a longer warranty period would in turn reduce repair costs, which may increase (or reduce the decrease in) sales of new HD vehicles due to fleets and independent owner-operators being inclined to purchase vehicles with lower repair costs.^{JJJJJJ} Nevertheless, the exact purchase behavior of fleet owners and independent owner-operators is challenging to predict, particularly in the time period immediately after new standards go into effect, when buyers may be waiting to see how the new vehicles perform relative to manufacturer claims.

If cost increases are small, either purchasers or sellers may absorb the cost increase without measurable changes in behavior. Significant cost increases passed through to buyers may lead potential buyers to purchase fewer vehicles than without the higher costs, or to buy vehicles sooner than they would have otherwise, in advance of the requirements. The National Academies of Sciences, Engineering, and Medicine comment that both pre-buy and low-buy are likely to be short-lived phenomena, and potentially unavoidable.⁴⁵⁰ Phasing in the standards would likely reduce pre-buy, by phasing in the additional costs associated with the standards. In addition, allowing early credits for compliance in advance of the standards would be expected to mitigate pre-buy; instead of early compliance imposing only net costs, early compliance now provides a benefit in terms of reduced compliance costs in the future.⁴⁵¹ The timing of the proposed standards, including the possibility of a phase-in, and early compliance credits are discussed in Section IV of the Preamble.

Measuring the existence and magnitude of pre- and low-buy depends on separating those effects from other factors that affect HD vehicle sales. If, for example, the timing of the standards coincides with a decrease in HD vehicle sales due to an economic downturn, as likely happened with standards that went into effect in 2007, the eve of the Great Recession, then the estimated effects of the standard would somehow have to be disentangled from the effects of the economic slowdown. Researchers estimating pre- or low-buy may seek to control for underlying

^{IIIIII} We recognize that additional external factors, including the current global COVID-19 pandemic, might impact the heavy-duty vehicle market, however due to data limitations we are unable to include possible effects of such external factors in our analyses. We request comment on this topic in Section X of this proposal.

^{JJJJJJ} The reduced repair costs may counteract some of the sales effect of increased vehicle purchase cost. As a result, they may reduce incentives for pre- and low-buy and mitigate adverse sales impacts.

sales patterns like this by including other factors, such as diesel price and gross domestic product (GDP), that also influence new HD vehicle sales. They then look for deviations from these trends at the time that the standards go into effect.

Using this approach to control for other influential factors, Lam and Bausell found a pre-buy of around 18,000 to 21,000 HD trucks, about 20 to 25 percent of total production, when looking at sales in the 6-month period before October 2002, a compliance deadline for HD engine manufacturers to reduce NO_x emissions.⁴⁵² Similarly, Rittenhouse and Zaragoza-Watkins (RZW) looked for pre-buy in the seven months preceding EPA's HD criteria pollutant standards' compliance deadlines in 1998, 2002, 2007 and 2010, as well as for low-buy in the seven months after the standards.⁴⁵³ For the 2007 standards, they found a sales increase of about 31,000 vehicles in those preceding months compared to the baseline, matched by an “approximately symmetric” drop in sales in the following months. For 2002, they found a similarly symmetric, though smaller, result of 14,000 - 18,000 Class 8 vehicles. These results suggest that the standards induced earlier purchases of vehicles that would have otherwise been bought after the standards were promulgated. The resulting effect was slower adoption of lower-emissions vehicles, compared to the assumed rate of sales in the absence of new emissions standards, although there was essentially no net change in sales (the sum of pre-buy and low-buy was not statistically different from zero in 2007 or 2002). RZW did not find evidence of pre- or low-buy for standards that went into effect in 1998 and 2010. They speculated that the standards in those years were less costly and involved use of less risky, already available technologies.

A limitation of the method used by the researchers discussed above is that they do not suggest a way to predict how future cost changes may influence sales. This is because they do not include price impacts in the approach to estimate pre- and low-buy impacts, yet vehicle price is expected to change when the standard goes into effect due to an increase in cost to the manufacturers. Both the change in price and the timing of the standard would influence pre- and low-buy because they occur at the same time, and it is statistically difficult to separate the two effects. In addition, manufacturers of HD vehicles may affect either the magnitude or timing of price increases in response to cost increases, confusing the effect of price on sales. Thus, while these studies suggest that the current rule may lead to increases in sales through pre-buying behavior, and decreases in sales through low-buying, the estimation approaches used by the studies do not allow EPA to predict existence or magnitude of potential pre- and low-buy impacts from future standards. In an effort to improve our analyses, EPA has been working on a method to estimate these impacts. The approach and an example are explained in Draft RIA Chapter 10.1.2, below.

An unpublished report attempted to develop a predictive model based on the impact of the 2007 standards. The authors assumed that a change in cost translates directly into a change in price, which was then converted into a change in sales (Harrison and LeBel).⁴⁵⁴ The price change was based on asking manufacturers to estimate the costs of meeting the standards. The study then applied a price elasticity of demand of -1.9 (that is, a 1 percent increase in price will lead to a 1.9 percent decrease in sales) to estimate sales increases of 104,000 trucks during 2005-2006, and sales reductions of 149,000 trucks over 2007-2008. (The study did not provide details on the source of this elasticity estimate.) The study then reported “actual”^{KKKKKKK} results of sales

KKKKKKK Quotation marks around “actual” are included in Harrison and LeBel (2008).

increases of 120,000 vehicles in 2005-6 and decreases of 183,000 vehicles in 2007-8, based on comparing estimated sales to an EPA estimate of baseline sales increased by a constant amount each year. Unlike the published studies reviewed above, Harrison and LeBel did not control for GDP, diesel prices, or other factors that might independently affect vehicle sales.⁴⁵⁴ As a result, the EPA baseline used for the “actual” results is not likely to reflect actual sales in the absence of the standards, and the “actual” pre- and low-buy values likely do not reflect changes due only to the standards. For comparison, RZW’s finding of pre-buy of about 31,000, based on controlling for other factors, is about one-third of Harrison and LeBel’s prediction and one-fourth of their “actual” estimate.⁴⁵³

In sum, existing literature does not provide clear guidance on the relationship between a change in vehicle cost due to a new standard and sales impacts. Neither Lam and Bausell nor RZW links a change in vehicle cost to sales impacts (a major interest of the EPA); instead, both papers focus on the magnitude of sales impacts in the periods surrounding compliance deadlines of HD emission regulations.^{452,453} The method proposed by Harrison and LeBel links costs to sales via a demand elasticity, but omits controls for shifts in baseline conditions as well as omitting details on the source of the demand elasticity they used.⁴⁵⁴

For this NPRM, EPA acknowledges that these standards may lead to some pre-buy before the standards go into effect, and some low-buy after the standards are effective. The estimated increase in operating costs is not expected to have much effect on pre- or low-buy behavior because the increase is small, and may be offset by lower expected repair costs due to longer useful life and warranty periods. Based on the literature previously described, EPA is not able to quantify these effects. In the following subsection we propose an approach to do so.

10.1.2 EPA’s Research to Estimate Sales Effects

In 2020 EPA contractors conducted a review of available peer reviewed literature on the effects of EPA’s HD standards on HD sales (see Draft RIA Chapter 10.1.1 for literature review results). The contractors then conducted an original analysis of the effects of previous EPA standards on pre- and low-buy for HD vehicles.⁴⁵⁵

The analysis uses monthly vehicle sales data from the twelve-month period before and after previous EPA standards went into effect (2002,^{LLLLLL} 2007, 2010, and 2014) to estimate pre- and low-buy due to each standard. The analysis examined controls for the effects of month of year, GDP, Brent Oil price, total imports and exports, and consumer sentiment and then used binary indicator variables from 1 through 12 months pre- and post-regulation to identify deviations from trends in sales specifically around those regulations. Unlike in previous studies, all other variables (except for the binary variables of interest and the month of year) were transformed into log-differences in order to address statistical issues associated with time series data. Independent regressions were estimated for vehicle Classes 6 through 8, and for each of the four previous HD regulations. Additional details of this analysis are available in the contractors’ report.

^{LLLLLL} Because court rulings for the 2004 regulation pulled the compliance date for most HD truck manufacturers forward to 2002, we will refer to that regulation as the 2002 standards, instead of the 2004 standards, in order to keep the focus on compliance dates.

Results show no statistically significant sales effects for Class 6 vehicles. There were a few statistically significant results for Class 7, but the majority were of the opposite sign than expected (that is, sales reductions before the standards and sales increases afterwards). For Class 8 vehicles, there were statistically significant results in the expected directions, with evidence of short-lived pre-buy before the 2010 and 2014 standards and low-buy after the 2002, 2007, and 2010 standards. The rest of this section focuses only on Class 8 vehicles. For more discussion on Classes 6 and 7, see Appendix 7.2 and Chapter 4.4.3 of the report.

The results provide estimates of the percent deviation in sales from trend for the combined months leading up to and following the start of new emissions standards. For pre-buy, statistically significant results range from no change persisting for the eleven months before the 2002 standards, to a 13.2 percent increase in the percent change in sales persisting for one month before the 2014 standard. Statistically significant effects persist for up to eleven months before the 2002 standards. For low-buy, statistically significant effects range from no change to a 14.9 percent decrease in the percent change in sales persisting for six months after the 2007 standards. Statistically significant effects persist for up to twelve months following the 2007 standard. Importantly, in addition to capturing the effects due to price changes associated with the regulations, the coefficients also capture unobserved factors, such as concerns over vehicle reliability and control technology uncertainty. Table 10-1 provides the results for the coefficients on the pre- and low-buy indicators, along with their length of persistence and the regulation to which the result is attributed. The significant coefficients are shown in bold face type.

Table 10-1: Pre and Low-Buy Sales Effects Coefficients

		2002	2007	2010	2014
Combined Months Pre-Regulation	12	0.024	0.004	0.009	0.000
	11	-0.0**	-0.006	0.021	0.000
	10	0.0**	-0.005	0.041	0.010
	9	0.032	-0.008	0.032	0.032
	8	0.041	-0.004	0.057**	0.013
	7	0.044	-0.006	0.059**	0.019
	6	0.037	-0.004	0.043	0.021
	5	0.029	0.003	0.054*	0.019
	4	0.004	-0.011	0.079***	0.030
	3	0.047	-0.013	0.071**	0.014
	2	-0.017	-0.012	0.105***	0.003
	1	-0.032	-0.01	0.078***	0.132***
Combined Months Post-Regulation	1	0.065***	-0.07***	-0.144***	-0.009
	2	-0.051	-0.099***	-0.083*	-0.012
	3	-0.115	-0.133***	-0.051	-0.015
	4	-0.065	-0.143***	-0.052	0.003
	5	-0.066	-0.144***	-0.075**	-0.009
	6	-0.076*	-0.149***	-0.052	-0.006
	7	-0.017	-0.121***	-0.022	0.001
	8	-0.018	-0.114***	-0.034	0.000
	9	-0.018	-0.099***	-0.020	0.003
	10	-0.007	-0.073**	-0.030	0.006
	11	-0.027	-0.07**	-0.010	-0.013
	12	-0.014	-0.065**	-0.005	0.000

*** p < 0.01; ** p < 0.05; * p < 0.1

As can be seen in Table 10-1, results vary by regulation. For the purposes of this discussion, we focus on results for the 2007 and 2010 standards.^{MMMMMMM} For the 2007 standards, there is no statistically significant pre-buy. There is statistically significant low-buy for all the periods from the period of one month after the standard through the combined period of 12 months after the standard, with magnitude increasing up to, and falling after, the combined period of 6 months post-standard. For the 2010 standards, there is some evidence of both pre- and low-buy. Statistically significant pre-buy can be seen for the period of 1 month up to the combined period of 5 months, and again at the combined periods of 7 and 8 months pre-standard. There is significant low-buy for the periods of 1, 2 and 5 months post-regulation. Results indicate that the observed effects are short-lived, on the order of months rather than years.

^{MMMMMMM} We do not consider the results of the 2002 compliance date to be generalizable for several reasons. Litigation may have affected purchase plans for many firms resulting from the pulling forward of compliance dates from 2004 to 2002. In addition, there may have been greater concerns over the reliability of new engines compared to other regulatory actions, which may have led to more low-buy. Also, the cost of compliance in 2002 was estimated to be lower than that of other regulations. We do not consider the 2014 standards to be generalizable either. This rule reduced greenhouse gas (GHG) emissions, which had lower technology costs and fuel savings relative to other rules. In addition, numerous pathways for compliance leads to difficulty estimating the price change in HD vehicles due to the regulation. More details and discussion on the 2002 and 2004 standards are available in the contractors' report.

10.1.2.1 Estimating Elasticities

To estimate a change in Class 8 vehicle sales due to future EPA emission standards, we transform the coefficients on the indicator variables, explained above, into demand elasticities. These elasticities measure the percent change in vehicle sales due to a percent change in vehicle prices:

Equation 10-1

$$\varepsilon = \frac{\% \Delta \text{Sales}}{\% \Delta \text{Price}}$$

The percent change in sales for Class 8 vehicles comes from the coefficients on the indicator variables from Table 10-1. In estimating elasticities, we only use the significant coefficients, while noting that no response (an elasticity of 0) is also represented in the results. The percent change in price is estimated by dividing the estimated cost of compliance published in the EPA RIAs associated with the relevant standards (2007 and 2010) by the estimated purchase price of a Class 8 vehicle in that year (adjusted to 2010 dollars).^{NNNNNN} Table 10-2 shows the regulatory cost, the HD vehicle prices and the resulting percent change in price we are using to estimate the elasticities from the 2007 and 2010 standards.

Table 10-2: Regulatory Costs and HD Vehicle Prices Used to Estimate Elasticities

Statutory Deadline	Regulatory Cost (2010\$)	HD Vehicle Price	% Change in Price
2007	\$9,741	\$98,900	9.8%
2010	\$7,662	\$108,250	7.1%

From the statistically significant pre- and low-buy sales effects for Class 8 vehicles, we estimate a set of pre- and low-buy elasticities by dividing the percent change in sales, from Table 10-1, by the percent change in price, from Table 10-2.

Table 10-3 shows the estimated statistically significant coefficients (percent change in sales) from Table 10-1, their period of effect, and the associated estimated elasticity. We expect pre-buy elasticities to be positive (more sales before new emission standards) and low-buy elasticities to be negative (fewer sales after new emission standards). Because the smallest statistically significant sales effect is zero, and a number of other effects are not statistically different from zero, the smallest pre- and low-buy elasticities are zero – no effect due to the standards. Not only the magnitude of the elasticity matters, but also the time period over which the elasticity applies. A large elasticity for a short period may measure less effect than a small elasticity over a longer period.

^{NNNNNN} The estimated cost of compliance was based on EPA's cost of compliance in the RIA for each regulation. The price of a Class 8 HD vehicle for each standard was calculated as an average of a high and low list price from an online source for HD vehicle sales (Commercial Truck Trader, a site that advertises new and used trucks for sale).

Table 10-3: Elasticity Estimates

	Statutory Deadline	Period of Effect (Months)	% Change in Sales (β)	Estimated Elasticity
Pre-Buy	All	Any	0	0
	2010	8	0.057	0.805
		7	0.059	0.834
		5	0.054	0.763
		4	0.079	1.116
		3	0.071	1.003
		2	0.105	1.483
		1	0.078	1.102
Low-Buy	All	Any	0	0
	2007	12	-0.065	-0.660
		11	-0.070	-0.711
		10	-0.073	-0.741
		9	-0.099	-1.005
		8	-0.114	-1.157
		7	-0.121	-1.229
		6	-0.149	-1.513
		5	-0.144	-1.462
		4	-0.143	-1.452
		3	-0.133	-1.350
		2	-0.099	-1.005
		1	-0.070	-0.711
	2010	5	-0.075	-1.060
		2	-0.083	-1.173
		1	-0.144	-2.034

There are several limitations to the results presented in Table 10-3. As noted in Chapter 10.1.2, the sales coefficients used to estimate the elasticities likely capture aspects of the proposed regulation not solely limited to changes in price (e.g., adverse fuel consumption effects, or concerns about the reliability of untested control technology). Similarly, base vehicle prices and estimated regulatory costs are estimates and may not correspond with observed base prices or increased regulatory costs.

These elasticities are based on monthly data, and so it is appropriate to apply the estimated elasticities to monthly series. Analysis of the coefficients over time indicates that the observed effects are short-lived, on the order of months rather than years. As noted above and described below, the time period is a critical factor for estimating the impacts.

10.1.2.2 Illustrative Example

This subsection outlines how we could apply the pre- and low-buy elasticities presented in Table 10-3 to this rulemaking. Though the methodology to develop the elasticities has been peer

reviewed,⁴⁵⁶ the application in this rulemaking would be new. Thus, in this subsection, we are illustrating how we could use this new approach in the FRM, or other future rulemakings.

Expanding Equation 10-1, elasticity measures can be approximated as

Equation 10-2

$$\varepsilon = \frac{\% \Delta Sales}{\% \Delta Price} = \frac{\Delta Sales}{Sales} * \frac{Price}{\Delta Price}$$

In this application, we want to estimate how a change in price leads to a change in sales. Therefore, rearranging Equation 10-2, we get

Equation 10-3

$$\Delta Sales = \varepsilon * \frac{\Delta Price}{Price} * Sales$$

The elasticity measures come from the estimates explained above.

For this example, $\Delta Price$ is the estimated cost of compliance for a Class 8 HD vehicle to meet the proposed Option 1 MY 2031 standards, \$4,203 (see DRIA, Chapter 7, Table 7-21). We assume implementation starts January 1.

$Price$ is set to \$130,000.⁰⁰⁰⁰⁰⁰⁰

$Sales$ are the estimated monthly Class 8 vehicle sales in 2030 and 2031. Monthly sales are derived from Class 8 vehicle population data from AEO 2020 and month-specific effects from the contractors' report.^{PPPPPP} To estimate pre-buy, we use the estimated monthly HD vehicle sales in the months before January 1, 2031. That is, pre-buy for the 2031 compliance date is estimated with the calculated monthly sales in 2030. To estimate low-buy, we use the estimated monthly HD vehicle sales in 2031.

To get the sales effects, the elasticity estimates from Table 10-3 are multiplied by the change in price divided by the base price. This value is then multiplied by the estimated Class 8 HD vehicle sales for each month over the period of effect for that elasticity measure. This results in a change in sales for each month over the period of effect. The monthly results are then summed to get a total affect for each elasticity estimate.

For pre-buy, for example, the elasticity measurement of 1.10 has a period of effect of one month, so we use the Class 8 sales from December, 2030 and make the pertinent multiplication for just December, 2030. For the elasticity measurement of 0.81, the period of effect is 8 months, so we use the Class 8 sales estimates from May, 2030 (8 months before January, 2031) through December, 2031 and the pertinent multiplication estimation is made for each affected month.

⁰⁰⁰⁰⁰⁰⁰ The price of HD vehicles varies greatly, and in part due to the features or options of the vehicle. The price we use here comes from the estimated price of a low-end, new, semi-truck from Truckers Bookkeeping Service from June, 2021; a pdf of the page "How much does a semi truck cost?" can be found in the docket for this rule, Docket ID EPA-HQ-OAR-2019-0055.

^{PPPPPP} Because these populations are annual, and the elasticities are monthly, we have to distribute the annual sales throughout the year. To do so, we estimate the average monthly sales and then use the monthly sales effect (the percent change in sales by month) estimated in the contractors' report to better approximate the sales by month.

Then, the changes in sales for each affected month are added together to get the total effect. The results for pre-buy are in Table 10-4 below. As discussed in Chapter 10.1.2.1, for all rules there are sales effects results that are statistically indistinguishable from zero, and thus note that zero impact on sales is the lower bound on effects. In this example, total sales of Class 8 vehicles under the Proposed Option 1 are estimated to increase by between 0 and 1.6 percent on an annual basis before the 2031 compliance deadline. In addition, the duration of the effects is a critical component in the calculation of sales impacts. For example, the elasticity of 0.83 for a duration of 7 months has a larger aggregate impact than the larger elasticity of 1.12 for a duration of 4 months. The result that produces the largest estimate for an aggregate increase in sales is the elasticity of 0.81 for 8 months.

Table 10-4: Illustrative Pre-Buy Results from the 2031 Implementation Date for Proposed Option 1

Period of Effect (Months)	Elasticity	Aggregate Sales Change	Cumulative % Change in Sales
Any	0	0	0
8	0.81	4,108	1.64%
7	0.83	3,727	1.49%
5	0.76	2,461	0.98%
4	1.12	2,900	1.16%
3	1.00	1,971	0.79%
2	1.48	1,919	0.77%
1	1.10	818	0.33%

Low-buy is estimated the same way, though we use monthly sales estimates for the requisite number of months following the January 1, 2031 compliance date. Low-buy results for the Proposed Option 1 are show in Table 10-5. For an elasticity of -1.51 over the course of 6 months (an estimate from the 2007 standards), we use the monthly sales estimates for January, 2031 through June, 2031, make the pertinent multiplication estimations for each affected month, and add the monthly results to get the aggregate sales change. As discussed in Chapter 10.1.2.1, for all rules there are sales effects results that are statistically indistinguishable from zero, and thus note that zero impact on sales is the lower bound on effects. This example estimates sales of Class 8 vehicles in the months following the 2031 compliance date under the Proposed Option 1 to fall by between 0 and 2.3 percent on an annual basis. As with pre-buy, both the magnitude of the elasticity and the duration of effect are important in estimating the total effect. For example, the elasticity of -1.01 for the duration of 9 months (from the 2007 standards) results in a larger aggregate effect than the larger elasticity of -1.23 for the duration of 7 months. The result that produces the largest estimate for an aggregate decrease in sales is the elasticity of -1.16 for a duration of 8 months.

Table 10-5: Illustrative Low-Buy Results from the 2031 Implementation Date for Proposed Option 1 QQQQQQ

Statutory Deadline	Period of Effect (Months)	Elasticity	Aggregate Sales Change	Cumulative % Change in Sales
All	Any	0	0	0
2007	12	-0.66	(5,072)	-2.00%
	11	-0.71	(4,926)	-1.94%
	10	-0.74	(4,723)	-1.86%
	9	-1.01	(5,720)	-2.25%
	8	-1.16	(5,843)	-2.30%
	7	-1.23	(5,420)	-2.13%
	6	-1.51	(5,773)	-2.27%
	5	-1.46	(4,601)	-1.81%
	4	-1.45	(3,640)	-1.43%
	3	-1.35	(2,513)	-0.99%
	2	-1.01	(1,111)	-0.44%
	1	-0.71	(323)	-0.13%
2010	5	-1.06	(3,335)	-1.31%
	2	-1.17	(1,296)	-0.51%
	1	-2.03	(924)	-0.36%

10.1.3 Fleet Turnover and Emissions Impacts

At the level of an individual HD vehicle, the emissions standards proposed in this rule would result in a new vehicle emitting less than a legacy vehicle; these lower emissions impacts would occur immediately upon the new vehicle entering into service (e.g., 2027). In contrast, the total emissions impact of the proposed standards across the fleet would occur more gradually, because, initially, vehicles meeting the standards will be only a small portion of the total fleet. For instance, in 2017 about 312,000 new medium-/heavy-duty trucks and buses were sold, compared to almost 14 million total medium-/heavy-duty vehicle registrations.⁴⁵⁷ Over time, as more vehicles subject to the standards enter the market and older vehicles leave the market, the emissions reductions due to the standards would increase. This relationship holds true even if new vehicle sales are unaffected by the standards.

If pre-buy and low-buy behaviors occur, they can shift emissions impacts in several ways. First, under low-buy, there is slower adoption of new vehicles, which implies that emissions reductions would be slower than under the assumption of no change in vehicle sales (RZW).⁴⁵³ On the other hand, the pre-bought HD vehicles are likely to displace older, more polluting vehicles, which may provide an earlier reduction in emissions than would occur without the standards. However, although the pre-bought new HD vehicles are likely to have lower emissions than the older, displaced vehicles, the emissions reductions are likely to be much smaller than the reductions that would be realized from the purchase and use of new vehicles

QQQQQQ The 2007 and 2010 Statutory Deadline column indicates the rule the low-buy sales effects estimates come from as seen in Table 10-1.

subject to these proposed standards, so that the net effect of pre-buy is to slow reductions in emissions.⁴⁵³

Another potential effect of the standards is a net reduction in new vehicle sales. This could result from either a smaller pre-buy than the post-standards low-buy,^{RRRRRRR} or some potential buyers deciding not to purchase at all. In this case, the vehicle miles traveled (VMT) of older vehicles may increase to make up for the VMT otherwise expected of the newer ("missing") vehicles. To the extent that the older vehicles emit more than the missing vehicles, emissions may increase.^{SSSSSSS} However, because the VMT is likely to be shifted to the newer HD vehicles among the existing fleet, and most of those vehicles are expected to be in compliance with the existing HD vehicle standards, this effect is expected to be small.

Quantifying these effects would require a robust method to estimate the effects of the standards on pre-buy and low-buy, as well as a method to estimate shifts in VMT among vehicle vintages in the case of an expected change in the net sales of newer vehicles. In the absence of robust methods to estimate these effects, EPA is not quantifying the fleet turnover or emissions impacts in this proposed rule, though, as with pre-buy and low-buy, we acknowledge these potential impacts.

The estimated increase in operating costs due to an increase in the use of DEF may lead to a slower fleet turnover if VMT does not shift from older (lower DEF requirements) vehicles to the newer (higher DEF requirements) vehicles. This would lead to slower emission reductions than if those newer vehicles were used. However, as this increase in operating costs is small, and may be offset in part by reduced repair costs, we expect minimal effects on fleet turnover due to the change in operating costs.

10.1.4 **Potential for Mode Shift**

Another possible response to the new emissions standards is shifting freight shipments to other transportation modes, such as rail or barge. This may happen, for example, if the new standards were to raise operating costs such that truck transportation becomes more expensive than rail or marine alternatives.

EPA does not expect that this proposed rule is likely to result in a transportation mode shift. Generally, shipping cargo via truck is more expensive per ton-mile than barge or rail, and less expensive than air.^{458,459} This is due to many factors, not the least of which is labor costs (each truck has at least one driver). Even though trucking is more expensive than rail or marine on a ton-mile basis, it is a very attractive transportation alternative for several reasons: shipping via truck is generally faster and more convenient than rail or marine, trucks can reach more places, and trucks may be less constrained by available infrastructure than barge or rail. In addition, shipping via truck does not require trans-shipments (transferring from one mode to another, for example to deliver cargo to or from the port or rail yard), and it allows partial deliveries at many locations. This speed, infrastructure availability, and delivery flexibility make trucking the

^{RRRRRRR} Though this is a possibility, it should be noted that the RZW (2018) study found that the pre-buy approximately equaled the low-buy. Harrison and LeBel (2008) found that low-buy exceeded pre-buy.

^{SSSSSSS} This effect is sometimes called the "Gruenspecht effect," based on the theory presented in Gruenspecht, Howard (1982), "Differentiated Regulation: The Case of Auto Emissions Standards," *American Economic Review* 72: 328-331.

transportation solution of choice for many kinds of cargo across most distances. As a result, smaller shipments of higher-valued goods (e.g., consumer goods) tend to be transported by air or truck, while larger shipments of lower-valued goods (e.g., raw materials) tend to go via rail or barge.^{458,460}

Studies of intermodal freight shifts, such as Comer et al. or Bushnell and Hughes, focus on changes in cost per ton-mile as a potential source of transportation mode shift.^{458,460} Comer et al. note, for instance, that fuel consumption “depend[s] on the type of freight being moved, route characteristics, transport speed, and locomotive/truck characteristics.”⁴⁵⁸ Bushnell and Hughes estimate that increased fuel prices for truck transportation lead to small substitutions between truck and rail for small for large shipments, and higher shifts for intermediate-sized shipments.⁴⁶⁰ The findings from this study suggest that the variation in the kinds and values of goods shipped by different means likely result in only a small amount of mode shift in response to a change in operating cost (e.g., fuel prices). However, due to data availability, this study approximates freight rates with fuel costs, assumes shipping distances using different modes are the same, and mostly does not consider transportation availability constraints affecting some modes in some regions. These limitations may distort the effects they estimate.

A mode shift study EPA carried out in 2012 in the context of new sulfur limits for fuel used in large ships operating on the Great Lakes may help address some of these limitations.⁴⁵⁹ The methodology used a combination of geospatial modeling and freight rate analysis to examine the impact of an increase in ship operating costs. While the focus of the study was transportation mode shift away from marine and toward land, it noted that truck transportation is far more expensive than both rail and marine on a ton-mile basis.^{TTTTTTT} It also shows that even a large percentage increase in marine operating costs did not raise freight rates by a similar percentage, because fuel costs are only part of total operating costs. In the case of truck transportation, operating costs are a much smaller portion of total costs. The results of this study combined with the others cited in this section indicate that changing the cost of truck transportation is unlikely to create mode shift.

The primary effect of the standards on operating costs is an increase in the use of DEF, which is expected to have a small effect on operating costs, less than 1 cent per vehicle mile traveled (see Chapter 7.2.1). Because the cost effect is expected to be small, and substitution between trucks and other modes is limited by the nature of the goods and their routes, we do not expect significant effects on mode shift. Finally, given the higher costs of truck transportation, a relatively small increase in truck freight rates due to the small increase in operating costs are unlikely to affect the competitive dynamics of the transportation sector.

10.1.5 Effects on Domestic and International Shares of Production

The proposed standards are not expected to provide incentives for manufacturers to shift between domestic and foreign production. This is because the standards would apply to any vehicles sold in the U.S. regardless of where they are produced. If foreign manufacturers already have increased expertise in satisfying the requirements of the standards, there may be some initial incentive for foreign production, but the opportunity for domestic manufacturers to sell in

^{TTTTTTT} Figure 1-5 in U.S. EPA Office of Transportation and Air Quality. "Economic Impacts of the Category 3 Marine Rule on Great Lakes Shipping." EPA-420-R-12-005. 2012.

other markets might increase. To the extent that the requirements of these final rules might lead to application and use of technologies that other countries may seek now or in the future, developing this capacity for domestic producers now may provide some additional ability to serve those markets.

10.1.6 Summary of Sales, Turnover, and Mode Shift Impacts

As discussed in Chapter 7, EPA expects the cost of new HD vehicles to increase (see Chapter 7 for details). This increase may have some impact on new vehicle sales; in particular, it is possible that truck buyers would increase purchases before the standards become effective (pre-buy), and reduce purchases afterwards (low-buy). Studies of pre-buy and low-buy suggest that these phenomena have occurred in the past, but those studies do not provide methodologies for estimating the impact of new rules on future vehicle sales. For that reason, EPA conducted an analysis to develop a relationship between estimated changes in vehicle price due to a new regulation and corresponding changes in vehicle sales (i.e., pre- and low-buy elasticities). We present the details of this new analysis and provide an illustrative example of applying pre- and low-buy elasticities to estimate potential sales impacts on Class 8 vehicles. For both pre-buy and low-buy, the illustrative example shows that sales impacts on Class 8 vehicles are of limited duration and range from zero impact to about two percent.

Whether shippers might choose a different mode for freight depends not only on the cost per ton-mile of the shipment, but also the value of the shipment, the time needed for shipment, and the availability of infrastructure. This proposed rule is expected to affect the cost per ton-mile by only a small amount. For that reason, EPA expects little transportation mode shift to occur due to the proposed standards. EPA also does not expect changes in where production happens in response to the proposed standards.

10.2 Employment Impacts

This section explains the methods and estimates of employment impacts due to this proposed regulation. Though the rule primarily affects HD vehicles, the employment effects may be felt more broadly 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 sectors likely to be most affected by the proposed standards. Chapter 10.2.1 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 10.2.2 discusses EPA's qualitative and quantitative estimates of the partial employment impacts of this proposed rule on regulated industries. Chapter 10.2.3 examines employment impacts in some closely related sectors, and Chapter 10.2.4 summarizes expected employment impacts.

10.2.1 Economic Framework for Employment Impact Assessment

Economic theory of labor demand indicates that employers affected by environmental regulation may increase their demand for some types of labor, decrease demand for other types of labor, or for still other types, not change it at all. A variety of conditions can affect employment impacts of environmental regulation, including baseline labor market conditions and employer and worker characteristics such as industry, and region.

A growing literature has investigated employment effects of environmental regulation. Morgenstern et al. decompose the labor consequences in a regulated industry facing increased abatement costs. They identify three separate components.⁴⁶¹ First, there is a demand effect caused by higher production costs raising market prices. Higher prices reduce consumption (and production) reducing demand for labor within the regulated industry. Second, there is a cost effect where, as production costs increase, plants use more of all inputs including labor to produce the same level of output. Third, there is a factor-shift effect where post-regulation production technologies may have different labor intensities. These three effects outlined by Morgenstern et al. provide the foundation for EPA's analysis of the impacts of the current regulation on labor.⁴⁶¹

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.^{462, UUUUUUU} If regulation causes marginal cost to increase, it will place upward pressure on output prices, leading to a decrease in the quantity demanded, and resulting in a decrease in production. This is called the output effect. The substitution effect describes how, holding output constant, regulation affects labor intensity of production. Deschênes describes environmental regulations as requiring additional capital equipment for pollution abatement that does not increase labor productivity.⁴⁶³ These higher production costs induce regulated firms to reduce output and decrease labor demand (an output effect) while simultaneously shifting away from the use of more expensive capital towards increased labor demand (a substitution effect).^{VVVVVVV} 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.⁴⁶⁴ Labor demand might also respond to regulation if compliance activities change labor intensity in production.

To study labor demand impacts empirically, researchers have compared employment levels at facilities subject to an environmental regulation to employment levels at similar facilities not subject to that environmental regulation; some studies find no employment effects, and others find statistically significant, usually small differences. For example, see Berman and Bui, Greenstone, Ferris et al., Walker, and Curtis.^{465, 466, 467, 468}

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. Localized reductions in employment may adversely impact individuals and communities just as localized increases may have positive impacts. 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 and Hafstead and Williams).^{468, 469}

UUUUUUU Berman and Bui 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. Morgenstern, Pizer and Shih (2002) use a very similar model, but they break the employment effect into three parts: 1) a demand effect; 2) a cost effect; and 3) a factor-shift effect.

VVVVVVV For an overview of the neoclassical theory of production and factor demand, see Chapter 9 of Layard and Walters (1978).

10.2.2 Employment Impacts in the Motor Vehicle and Parts Manufacturing Sectors

The overall effect of the proposed rule on motor vehicle sector employment depends on the relative magnitude of demand, cost, and factor-shift effects, as described below. As described in Chapter 10.1.2.2, we provide an example of how pre- and low-buy elasticities could be applied in the FRM or other future rulemakings, but do not estimate pre- or low-buy for this NPRM; further, we do not account for the factor-shift effect. Thus, we cannot estimate an overall employment effect of this proposed rule in these sectors, nor can we infer whether the total effect would be positive or negative.

Also, due to a lack of firm- and plant-specific data for HD engines and vehicles, EPA is not quantifying the cost effect impacts of the proposed regulation on employment at the firm level, although we acknowledge these potential impacts.

In this section, EPA presents partial estimates of industry-level employment effects of the proposed rule. We do not identify impacts separately for motor vehicle manufacturing and motor vehicle parts manufacturing, because we do not have information on the division of costs between these two sectors. Instead, we use the labor intensity of production for these sectors to provide a range of potential employment impacts.

Our analysis follows the structure of Morgenstern et al., as described above, to estimate the impacts of this proposed rule on the regulated sector.⁴⁶¹ In their theoretical model, a change in labor demand arising from a change in regulations is decomposed into three main components: demand, cost, and factor-shift effects. In what follows, we qualitatively describe the employment impacts due to the demand and factor-shift effects, and quantitatively estimate the employment impacts due to the cost effect. Because our quantitative estimates of the demand effect are illustrative, and we do not estimate factor-shift effects, we cannot estimate the total effects on employment in the regulated industries.

10.2.2.1 The Demand Effect

The demand effect reflects employment changes due to changes in new vehicle sales. Because we are in the process of refining and finalizing how we might quantify sales impacts, we do not estimate the demand-effect impact on employment due to the proposed standards. If HD vehicle sales decrease, fewer people would be needed to assemble trucks and the components used to manufacture them. On the other hand, if pre-buy occurs, HD vehicle sales may increase temporarily, leading to temporary increases in employment. Draft RIA Chapter 10.1.1 and Chapter 10.1.2 discuss the factors influencing the effect of proposed requirements on demand for new HD vehicles, explain why that effect is difficult to quantify, proposes a new method to quantify the impacts and explains how we might use it to estimate pre- and low-buy sales effects in the FRM.

10.2.2.2 The Factor-Shift Effect

The factor-shift effect reflects employment changes due to changes in labor intensity of production resulting from compliance activities. The labor intensity of manufacturing HD vehicle engines or HD vehicles might increase or decrease because of the proposed rule. Due to a lack of information on expected changes in labor intensity, the estimated employment impacts in this chapter do not include the factor-shift effect on employment impact estimates.

10.2.2.3 The Cost Effect

The cost effect reflects the impact on employment due to increased costs from adopting technologies needed for vehicles to meet the standards. The analysis holds output constant, meaning that it does not include sales impacts. We estimate 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 proposed regulation. Specifically, we multiply the share of labor in production costs by the production cost increase estimated as an impact of this rule. This provides a sense of the order of magnitude of expected impacts on employment.

The use of the ratio of the share of labor in production costs to estimate "cost effect" employment has both advantages and limitations. It is often possible to estimate these ratios for specific sectors, for example, the average number of workers in the HD 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 means that it is not necessary to extrapolate employment ratios from possibly unrelated 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 vehicles manufacturing sector represents this ratio for all vehicle manufacturing, not just for the HD sector, and not just for production processes related to emission reductions compliance activities. In addition, these estimates do not include changes in sectors that supply these sectors, such as steel or electronics producers. The effects estimated here can be viewed as effects on employment in the HD motor vehicle sector due to the changes in expenditure in that sector, rather than as an assessment of all employment changes due to the proposed standards. In addition, labor intensity is held constant in the face of increased expenditures; this approach does not take in account changes in labor intensity due to changes in the nature of production (the factor-shift effect), which could either increase or decrease the employment impacts estimated here.

Some vehicle parts are made in-house by HD vehicle manufacturers. Other parts are made by independent suppliers who are not directly regulated but would be affected by the proposed rulemaking as well. Because EPA does not know whether abatement equipment to comply with the proposed standards would be produced by the original equipment manufacturers (OEMs) or by suppliers, we use labor ratios for both sectors (and their subsectors) to provide a range of estimates for the cost effect impacts.

We include estimates from two sectors that are broadly defined and two that are more narrowly defined. Specifically, we estimate labor impacts for the aggregated sectors 'motor vehicle manufacturing' and 'motor vehicle parts manufacturing', and for the more specific sectors 'light truck and utility vehicle manufacturing' and 'heavy-duty truck manufacturing.'^{www}

We rely on three different public sources to get a range of estimates of employment per \$1 million expenditures: the Annual Survey of Manufactures (ASM) and the Economic Census

^{www} The 'light truck and utility vehicle manufacturing' sector is included because these estimates include results for trucks from class 2b/3 through 6. See Preamble Section I of this proposal for more discussion on the HD engine classes included in this rulemaking.

(EC), 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. 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 2016. 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 in this employment analysis.^{xxxxxxx} 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 provides data through 2018. Table 10-6 below shows the sector definition, the NAICS code, and the ERM sector number where appropriate that EPA uses to estimate employment effects in this analysis.

Table 10-6: Sectors Used in this Analysis

Sector Definition	NAICS	ERM Sector Number
Motor vehicle manufacturing	3361	80
Light truck and utility vehicle manufacturing	336112	
Heavy-duty truck manufacturing	33612	
Motor vehicle parts manufacturing	3363	82

Table 10-7 provides the estimates of employment per \$1 million of expenditure for each sector for each data source, adjusted to 2017 dollars using the U.S. Bureau of Economic Analysis Gross Domestic Product Implicit Price Deflator retrieved from the Federal Reserve Bank of St. Louis. The values are adjusted to remove effects of imports through the use of a ratio of domestic production to domestic sales of 0.85.^{yyyyyyy} Although the estimated labor ratios are not the same across data sources, they each exhibit a similar pattern across sectors. Within the 4-digit NAICS code level, motor vehicle parts manufacturing seems to be the most labor-intensive sector, followed by the motor vehicle manufacturing sector. Within motor vehicle manufacturing, heavy-duty truck manufacturing appears to be more labor-intensive than light truck and utility vehicle manufacturing.

^{xxxxxxx} The total employment across the four sectors used in this analysis (see Table 10-6) as reported in the ASM and the EC ranges from 213,212 to 226,259 depending on which data source is used; as noted above the most recent ASM and EC were conducted in 2016 and 2017, respectively.

^{yyyyyyy} 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 2009-2018, the proportion averages 85 percent. From 2015-2018, the proportion average is slightly lower, at 84.3 percent.

Table 10-7: Employment per \$1 Million Expenditures (2017\$) in the Motor Vehicle Manufacturing Sector^a

Source	Sector (NAICS)	Ratio of Workers per \$1 Million Expenditures	Ratio of Workers per \$1 Million Expenditures, Adjusted for Domestic vs. Foreign Production
BLS ERM 2017	Motor vehicle manufacturing (3361)	0.584	0.497
ASM 2016	Motor vehicle manufacturing (3361)	0.563	0.479
EC 2017	Motor vehicle manufacturing (3361)	0.615	0.523
BLS ERM 2017	Motor vehicle parts manufacturing (3363)	1.999	1.700
ASM 2016	Motor vehicle parts manufacturing (3363)	2.032	1.728
EC 2017	Motor vehicle parts manufacturing (3363)	2.231	1.897
ASM 2016	Heavy-duty truck manufacturing (33612)	1.048	0.891
EC 2017	Heavy-duty truck manufacturing (33612)	0.988	0.840
ASM 2016	Light truck and utility vehicle manufacturing (336112)	0.454	0.386
EC 2017	Light truck and utility vehicle manufacturing (336112)	0.478	0.407

a BLS ERM refers to the U.S. Bureau of Labor Statistics' Employment Requirement Matrix, 2018 values. ASM refers to the U.S. Census Bureau's Annual Survey of Manufactures, 2016 values. EC refers to the U.S. Census Bureau's Economic Census, 2017 values. These are the most recent data available.

Over time, the amount of labor needed in the motor vehicle industry has changed: automation and improved methods have led to significant productivity increases. The BLS ERM, for instance, provides estimates that, in 1997, about 1.4 workers in the Motor Vehicle Manufacturing sector were needed per \$1 million, but only 0.6 workers by 2018 (in 2017\$).^{ZZZZZZ} Because the ERM is available annually for 1997-2018, we use these data to estimate productivity improvements over time. We regress logged ERM values on a year trend for the Motor Vehicle Manufacturing and Motor Vehicle Parts Manufacturing sectors. 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 of the regressions suggest a 4.3 percent per year productivity improvement in the Motor Vehicle Manufacturing Sector and a 4.0 percent per year improvement in the Motor Vehicle Parts Manufacturing Sector.

We then use those estimated percent improvements in productivity to project the number of workers per \$1 million of production expenditures through 2032. Although the costs and benefits analyses in the preceding chapters go out to 2045, we chose to model the employment effect due to cost increases only through 2032. This is because our method is an approximate, partial employment analysis, as well as being dependent on future, uncertain, macro-economic conditions. The choice of 2032 was also affected by the phase-in of more stringent requirements starting in 2031 in the proposal. The results provided below represent an order of magnitude effect, rather than definitive impacts. We calculate separate sets of projections (adjusted to

^{ZZZZZZ} <https://www.bls.gov/emp/data/emp-requirements.htm>; this analysis used data for sectors 80 (Motor Vehicle Manufacturing) and 82 (Motor Vehicle Parts Manufacturing) from "Chain-weighted (2009 dollars) real domestic employment requirements tables;" see "Cost Effect Employment Impacts calculation" in the docket.

2017\$) for each set of data, ERM, EC, and ASM, for all four 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, we use the ERM's ratio of the projected productivity growth value in each future year to the projected production expenditure value in 2016 for the ASM and 2017 for the EC (the base years in our data) to determine how many workers would be needed per \$1 million of expenditures, in 2017\$. 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 the ten data sources from the ERM, EC, and ASM, and report only the maximum and minimum effects in each year across all sectors.^{AAAAA} 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 labor effect. In Table 10-7, the Motor Vehicle Parts Manufacturing Sector value from the EC provides the maximum employment estimates per \$1 million; the Light Truck and Utility Vehicle Manufacturing Sector value from the ASM provides the minimum estimates.

Cost estimates developed for this proposed rule are provided in Chapter 7. We use the technology cost estimates from that chapter to estimate the employment impacts of a change in cost of manufacturing HD vehicles due to this rule. The technology cost estimates (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 10-8, below. The effects are shown in job-years, where a job-year 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 would, by itself and holding labor intensity and output constant, be expected to increase employment by between 300 and 2,200 per year between 2027 and 2032 under both Proposed Option 1 and Proposed Option 2. 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.

^{AAAAA} To see details, as well as results for all sources, see "Cost Effect Employment Impacts calculation" in the docket.

Table 10-8: Estimated Employment Effects Due to Increased Costs of Vehicles and Parts (Cost Effect), in Job-Years

Year	Proposed Option 1		Proposed Option 2	
	Minimum Employment due to Cost Effect ^a	Maximum Employment due to Cost Effect ^b	Minimum Employment due to Cost Effect ^a	Maximum Employment due to Cost Effect ^b
2027	400	2,200	400	2,200
2028	400	2,100	400	2,000
2029	400	2,000	400	1,900
2030	300	1,800	300	1,700
2031	400	1,900	300	1,600
2032	300	1,800	300	1,500
Note: Though costs differ between Proposed Option 1 and Proposed Option 2, results in this table may be the same due to rounding.				

10.2.2.4 Summary of Employment Effects in the Motor Vehicle Sector

As explained above, the overall effect of the proposed standards on motor vehicle sector employment depends on the relative magnitude of the demand, cost, and factor-shift effects, as described by Morgenstern, et al.⁴⁶¹ EPA proposed a method in draft Chapter 10.1.2.2 to quantify the demand effect, however we are not estimating pre- or low-buy effects in this NPRM, and therefore are not using demand effects to estimate employment impacts. Also, due to a lack of data, we do not estimate factor-shift effects. However, we estimate employment impacts of the proposed standards due to the cost effect.

For the regulated sector, the partial employment impact due to the effect of increased manufacturing costs due to compliance activities is expected to range between 400 to 2,200 job years and 300 to 1,800 job years in 2027 and 2032 respectively under the Proposed Option 1. The partial employment impact under the Proposed Option 2 is expected to range between 400 to 2,200 job years and 300 to 1,500 job years in 2027 and 2032 respectively. We would expect the demand effect to reduce these employment increases, although we are unable to predict the magnitude of that reduction. Finally, we are unable to predict the direction of the factor-shift effect.

10.2.3 Employment Impacts on Related Sectors

10.2.3.1 Effects on Purchasers of Heavy-Duty Vehicles

Because of the diversity of HD vehicles, entities from a very wide range of transportation sectors would be purchasing vehicles subject to these proposed standards. As discussed in Chapter 10.1, vehicles subject to these proposed standards would be likely to be more expensive to purchase compared to vehicles not subject to the proposed standards. HD vehicles are typically commercial, and typically provide an "intermediate good:" that is, they are used to provide a commercial service, rather than being a final consumer good. As a result, the higher costs of the vehicles may result in higher prices for the services provided by these vehicles, and potentially reduced demand for those services. In turn, there might be less employment in the sectors providing those services.

The American Trucking Association, in comments on the ANPR, provided data indicating that, between 2010 and 2018, the up-front costs of HD vehicles were approximately 10 to 16 percent of per-mile costs.⁴⁷⁰ Given that we expect the potential impacts of the proposed standards on up-front costs of vehicles to be only a few percent of total vehicle cost, the likely increase in per-mile costs would likely be less than 1 percent (even a 5 percent increase in vehicle costs would result in only a 0.8 percent increase in per-mile costs, at the high end of the range). Therefore, we do not expect large impacts on transportation services demand, and related employment in transportation services sectors. Per-mile cost increases for some sectors would be higher than this average, while they would be lower in other sectors. The actual effects on demand for the services and related employment would depend on cost pass-through, and responsiveness of demand to transportation cost increases.

Lengthening the warranty period may provide some positive impacts on employment for vehicle purchasers. Both the National Association of Small Trucking Companies (NASTC) and the Owner-Operator Independent Drivers Association (OOIDA), in comments on the ANPRM, expressed concerns over the effects on productivity of downtime due to problems with emission control systems.⁴⁷¹ They requested that EPA pursue ways to reduce those losses, with a NASTC member specifically requesting warranty extensions. As discussed in Chapter 7.2.3, the extended warranty provisions proposed here would not only be expected to reduce repair costs for vehicle purchasers, but may also provide incentives to manufacturers to improve quality and thus reduce the need for repairs. These effects would be expected to reduce costs, and thus mitigate adverse impacts on employment for vehicle purchasers.

10.2.3.2 Effects on Heavy-Duty Vehicle Dealers and Service Providers

If sales of HD vehicles decrease, then HD vehicle dealers would have fewer sales, and may employ fewer people as a result. At the same time, dealers, and other independent service repair shops, often provide repair and maintenance services. The extended warranty provisions would be expected to facilitate repair and maintenance of emission control system components, which could result in increased demand for workers servicing vehicles. On the other hand, as discussed in Chapter 7.2.3, the extended useful life provisions would also be expected to provide incentives to OEMs to improve quality and may reduce the need for warranty claims. Thus, effects on employment for service providers, including dealers, may be positive or negative.

Similarly, as discussed in Preamble Section IV.B.3, this proposal aims to ease the ability of independent service repair shops and independent owner-operators to service vehicles (i.e., serviceability). Comments from OOIDA on the ANPR note that it is currently difficult for anyone other than dealers to service vehicles. It is possible that improving serviceability will improve maintenance due to lower costs of conducting it.⁴⁷² It is also possible that improved serviceability may shift some of the work, and thus employment, from dealers to independent service repair shops or to the owners themselves, with an unclear impact on the overall level of employment.

10.2.4 Summary of Employment Impacts

Employment in the HD manufacturing sector depends on three effects: how the effects of the standards on vehicle prices affect demand for new vehicles (demand effect); the labor demand needed to meet the standards (cost effect); and any change in labor intensity of production due to complying with the standards (factor-shift effect). As discussed in Chapter 10.2.2, EPA is

proposing a method to quantify sales effects, which may allow us to quantify demand effects, but we are not using it to quantify effects in this NPRM. In addition, we are unable to quantify the factor-shift effect, and therefore we are unable to estimate their impact on net employment in the HD manufacturing sector. Cost-effect-related employment changes due to the proposed regulation are estimated to be between a few hundred and a few thousand employees. For comparison, in May 2019, the Bureau of Labor Statistics reports about 234,000 employees in Motor Vehicle Manufacturing.⁴⁷³

Other sectors that sell, purchase, or service HD vehicles might also experience employment impacts due to the standards. The effects on these sectors would depend on the degree of cost pass-through to prices for HD vehicles and the effects of useful life and warranty requirements on demand for vehicle repair and maintenance.

Chapter 11 Small Business Analysis

This chapter presents our analysis of the potential impacts of the proposal on small entities that would be subject to the highway heavy-duty engine and vehicle provisions of this proposed rule. These are: heavy-duty vehicle manufacturers, heavy-duty secondary vehicle manufacturers, and heavy-duty alternative fuel engine converters. Other entities that would be subject to the rule are either not small (e.g., engine and incomplete vehicle manufacturers) or are not expected to incur any burden from the proposed rule (e.g., in sectors other than highway heavy-duty engines and vehicles).

11.1 Definition and Description of Small Businesses

Under the Regulatory Flexibility Act (5 USC 601 et seq.), a small entity is defined as: (1) a business that meets the definition for small business based on the Small Business Administration's (SBA) size standards;⁴⁷⁴ (2) a small governmental jurisdiction that is a government of a city, county, town, school district or special district with a population of less than 50,000; or (3) a small organization that is any not-for-profit enterprise which is independently owned and operated and is not dominant in its field.

This analysis considers only small business entities. Small governmental jurisdictions and small not-for-profit organizations are not subject to the proposed rule as they have no certification or compliance requirements.

11.2 Overview of the Heavy-Duty Program and Type of Entities Covered

As described in the proposal and elsewhere in this draft RIA, this rulemaking sets out a comprehensive approach to reduce air pollution from highway heavy-duty engines. The key provisions can be grouped into three broad categories: 1) reducing emissions under a wider range of engine operating conditions than those covered in existing requirements, including refueling events (e.g., revised exhaust and refueling emission standards and updated test procedures); 2) maintaining emission control over a greater portion of an engine's operational life (e.g., lengthened useful life and regulatory emission warranty periods), and 3) providing manufacturers with flexibilities to meet the proposed standards while clarifying our regulations. We are also proposing revisions to a subset of the MY 2027 GHG standards for heavy-duty vehicles.

While the proposed rule also includes regulatory amendments for sectors other than highway heavy-duty engines and vehicles, these amendments for other sectors correct, clarify, and streamline the regulatory provisions, and there is no burden from the proposed rule on small entities in these other sectors.

There are four categories of highway heavy-duty engine and vehicle entities that are subject to the proposed rule:

- Heavy-duty engine manufacturers
- Heavy-duty conventional vehicle manufacturers, including incomplete and secondary vehicle manufacturers
- Heavy-duty electric vehicle manufacturers
- Alternative fuel engine converters

Heavy-duty engine manufacturers have been developing, testing, and certifying engines for many years in compliance with EPA rulemakings adopted under the CAA. Under this proposal, these companies will be required to produce engines that meet new emission standards and certify them using revised test procedures. The heavy-duty engine manufacturers that certify engines to EPA's program include no small entities.

Heavy-duty vehicle manufacturers are one of two types. The first type of company manufactures both the engine and the associated vehicle and these companies are not small entities. The second type of vehicle manufacturer, some of which are small, produces a vehicle of its own design using a certified engine produced by a different company. In a variation on the second type, the heavy-duty vehicle manufacturer finishes an incomplete vehicle produced and certified by a different company; these so-called "secondary manufacturers" complete the vehicle by adding the truck body and other equipment. While these secondary manufacturers are not required to certify with EPA, they may incur costs to accommodate changes made to the certified incomplete vehicles to meet certain proposed requirements. Several secondary manufacturers are small entities under the SBA definition, and the economic impacts of the proposed rule on these companies are described in Section 11.3. The economic impacts of the proposed rule on other heavy-duty vehicle manufacturers, including electric heavy-duty vehicle manufacturers, are described in Section 11.4.

Alternative fuel engine converters are also subject to the proposed rule. Several of these companies are small entities under the SBA definitions, and the impacts on them are described in Section 11.5. Finally, Section 11.6 contains a summary table of the estimated economic impacts on small entities subject to the rule.

11.3 Impacts on Small Entities: Heavy-Duty Secondary Vehicle Manufacturers

A secondary vehicle manufacturer is defined as anyone that produces a vehicle by modifying a complete vehicle or completing the assembly of a partially complete vehicle, although a manufacturer controlled by the manufacturer of the base vehicle (or by an entity that also controls the manufacturer of the base vehicle) is not a secondary vehicle manufacturer; instead both entities are considered to be one manufacturer (40 CFR 1037.801 definition of secondary vehicle manufacturer). EPA's heavy-duty vehicle program allows an engine manufacturer to introduce partially complete vehicles into U.S. commerce to be completed by a secondary vehicle manufacturer (see 40 CFR 1037.622). These incomplete vehicles will typically be certified by the engine manufacturer. The program also allows a manufacturer to introduce complete vehicles into U.S. commerce for modification by a small manufacturer (e.g., a recreational vehicle manufacturer); these also will typically be certified by the engine manufacturer. The provisions specify that a secondary vehicle manufacturer may finish assembly of partially complete vehicles if it obtains a vehicle that is not fully assembled with the intent to manufacture a complete vehicle in a certified configuration.

Secondary vehicle manufacturers that produce a heavy-duty vehicle using a compression-ignition incomplete vehicle are not expected to need to modify their manufacturing or other processes to comply with the proposed rule. As discussed in Chapter 3 of this draft RIA, compression-ignition engine manufacturers are expected to achieve the proposed criteria pollutant engine emission standards by modifying the engine and aftertreatment system technologies already applied to these engines to meet the existing standards (e.g., selective catalytic reduction). As a result, the engine and aftertreatment systems to meet the proposed

criteria pollutant emission standards are expected to be similar to the systems vehicle manufacturers install today and secondary vehicle manufacturers are not expected to need to redesign or modify their production processes to accommodate compression-ignition engine-based certified systems. As a result, we do not expect secondary vehicle manufacturers would experience any adverse impacts by using incomplete vehicles that comply with the compression-ignition exhaust criteria pollutant emission standards in this proposal.

Secondary vehicle manufacturers that finish an incomplete vehicle certified to the proposed spark-ignition engine emission standards would be subject to the provisions of the proposed rule. Similar to manufacturers of compression-ignition engines, Chapter 3 indicates that spark-ignition engine manufacturers are expected to achieve the proposed criteria pollutant engine emission standards by modifying the engine and aftertreatment system technologies already applied to these engines to meet the existing standards (e.g., three-way catalysts). As a result, the engine and aftertreatment systems are expected to be similar to the systems vehicle manufacturers install today and secondary vehicle manufacturers are not expected to need to redesign or modify their production processes to accommodate spark-ignition engine-based certified systems. As a result, we do not expect secondary vehicle manufacturers would experience any adverse impacts by using incomplete vehicles that comply with the spark-ignition exhaust criteria pollutant emission standards in this proposal.

We are also proposing refueling emission standards for incomplete heavy-duty vehicles fueled by volatile fuels (e.g., gasoline and ethanol). Compliance with these standards may require some secondary vehicle manufacturers to change their manufacturing or other processes to accommodate compliant refueling emission control systems. Historically, an incomplete vehicle that is sold to a secondary vehicle manufacturer includes the fuel system and its evaporative emission controls as part of the incomplete vehicle's certified configuration. When manufacturers of chassis-certified complete heavy-duty vehicles (i.e., Classes 2b and 3) adopted ORVR technology to meet refueling emission standards (59 FR 16262, April 6, 1994), the design changes were contained in the fuel system and did not require changes to the vehicle body to accommodate the new technology (i.e., filler door location and designs remained the same). In the case of the proposed provisions, manufacturers of incomplete heavy-duty vehicles fueled by volatile fuels are expected to achieve compliance with the proposed refueling standards by adding to or replacing existing components of the evaporative emission control systems currently being installed on incomplete vehicles. We expect incomplete vehicle manufacturers will design compliant ORVR systems that maintain continuity from previous fuel system designs, minimizing the need for vehicle body redesign to accommodate any changes to emission control systems. Our expectation is reinforced by the comments we received on the ANPR to this rule, in which ORVR suppliers expressed confidence in the relationship between engine OEMs and delegated assemblers (i.e., secondary vehicle manufacturers) to effectively implement refueling requirements for incomplete heavy-duty vehicles.^{BBBBBBBB} Secondary manufacturers that finish the vehicle bodies have many years of experience installing evaporative emission control systems as delegated assemblers, and the ORVR instructions are expected to add very few, if any, steps to the evaporative system instructions currently provided by the chassis manufacturers.

^{BBBBBBBB} See comments from the Manufacturers of Emission Controls Association (EPA-HQ-OAR-2019-0055-0365) and Ingevity Corporation (EPA-HQ-OAR-2019-0055-0271).

Secondary vehicle manufacturers are not required to certify with EPA, and so we do not have a list of secondary manufacturers that will be subject to the rule. Instead, we used the Hoovers D&B database to identify small companies engaged in the Motor Vehicle Body Manufacturing (NAICS Code 336211 with 1,000 employees or fewer) or Motor Home Manufacturing (336213 with 1,250 employees or fewer) sectors.⁴⁷⁵ We limited our search to companies located in the United States. This approach is reasonable because it is unlikely that a foreign entity would purchase a certified incomplete vehicle from a manufacturer located in the United States, transport that vehicle to a location outside the United States, complete the vehicle, and then export that completed vehicle back into the United States with the associated transportation costs. If there were such a company, the cost of the additional transportation to and from the assembling country would likely exceed the expected costs of compliance with the proposed rule (\$2,528 per company per year; see below). Also, the additional transportation costs would likely make the completed vehicle uncompetitive in the U.S. market (with the exception of luxury trucks or recreational vehicles, in which case the company would likely have revenue that can accommodate the costs of the proposed program).

We adjusted the initial list of 1,190 companies to remove those that are subsidiaries of another company (they have a parent or ultimate parent company). For the Motor Vehicle Body Manufacturing sector, we further adjusted the list to reflect only companies engaged in truck and bus body manufacturing (as identified by their Standard Industrial Classification (SIC) code) and removed companies that do not make truck bodies or that make light-duty trucks (these companies would not be subject to the rule).^{CCCCCCCC} For the Motor Home Manufacturing sector, we selected only companies engaged in motor home manufacturing (using their SIC code) and removed van conversions (those are light-duty vehicles not subject to the rule). Finally, we removed companies with four or fewer employees because it is not likely that a company with fewer than five total employees manufactures completed trucks. It should be noted that we also removed one company from the list that does not appear to have become operational (the \$100 annual revenue reported in Hoovers for this company was likely a placeholder). This procedure yielded a list of 249 small entities engaged in the manufacture of secondary vehicles and thereby potentially subject to the proposed refueling standards. It should be noted that the final list of companies does not distinguish between those that produce spark-ignition and compression-ignition vehicles.

We estimated the impacts of the proposed rule on these small entities using the following information. We assume each company would have one-time costs associated with reviewing new instructions for ORVR (10 hours/family), possible vehicle design R&D if the change to the evaporative control cannister requires different mounting assemblies or the area where it is mounted must be adjusted (8 hours/family), and training associated with installing the new ORVR system (1 hour/family). We also assume a recurring production cost for installing the new ORVR system (1 hour/unit). Assuming 2 families with 20 unit per family for each company (40 vehicles produced per year) and \$43.58/hour, the total cost of the program in the first year is

^{CCCCCCCC} Removed: cranes, overhead traveling; dump truck lifting mechanism; fifth wheel, motor vehicle; truck beds; truck bodies (motor vehicles); truck bodies and parts; truck cabs, for motor vehicles; truck tops; van bodies.

expected to be \$2,528 per company. We then compared this to the annual revenue reported in Hoovers for each of the small entities.^{DDDDDDDD}

For these secondary vehicle manufacturers, the expected costs of \$2,528 is less than 1 percent of revenue for 201 of the companies and between 1 and 3 percent of revenue for 48 companies. Figure 11-1 contains a graphical representation of the revenue distribution of these companies. The impacts are summarized in Table 11-1 presented in Section 11.6.

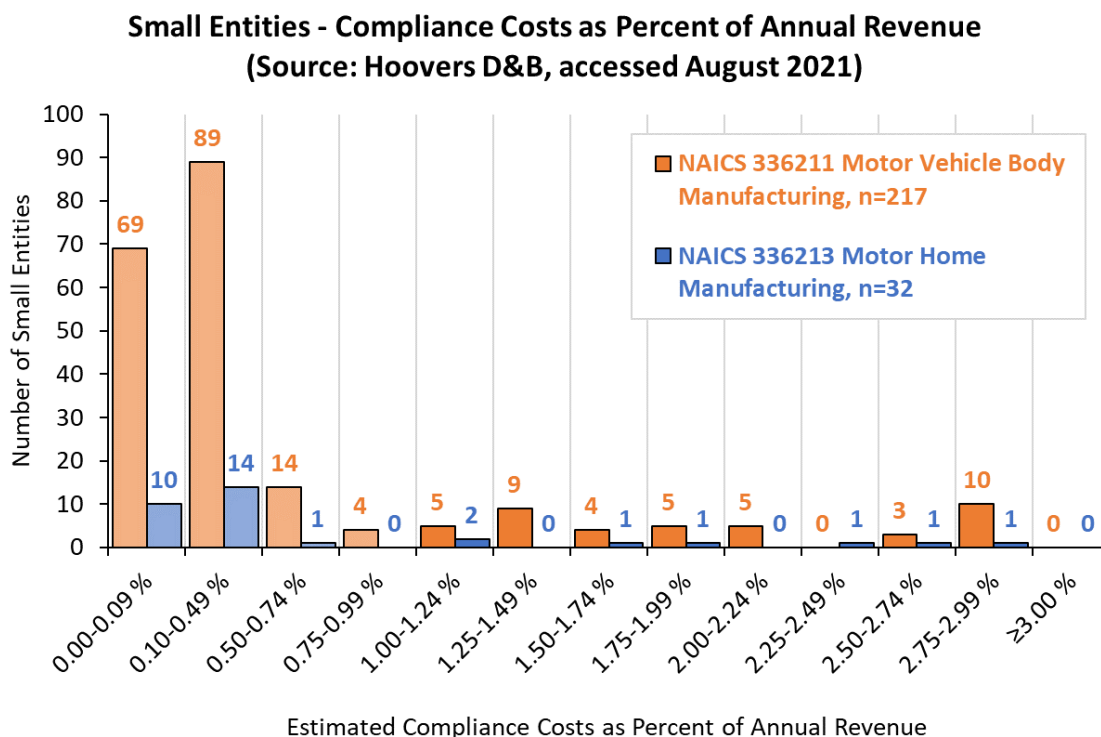


Figure 11-1: Secondary Vehicle Manufacturers, Estimated Impacts as a Percent of Annual Revenues

11.4 Impacts on Small Entities: Heavy-Duty Vehicle Manufacturers

Companies that manufacture heavy-duty vehicles would be subject to the proposed rule, including electric vehicle manufacturers. These companies currently certify their vehicles to EPA’s greenhouse gas emission standards. We discuss the impacts on heavy-duty electric vehicle manufacturers and conventional vehicle manufacturers in the subsections below.

^{DDDDDDDD} While EPA’s guidance for Regulatory Flexibility Act analysis specifies that annual sales should be used in the analysis for small companies, it also indicates that “revenue or receipts (though technically different than sales) can usually serve as a reasonable proxy for sales.” Footnote 19, page 21. EPA’s Action Development Process, Final Guidance for EPA Rulewriters: Regulatory Flexibility Act as amended by the Small Business Regulatory Enforcement Fairness Act. November 2006.

11.4.1 Heavy-Duty Electric Vehicle Manufacturers

Under the proposed revisions to the MY 2027 GHG vehicle standards, the electric vehicle manufacturers would not incur any additional cost. Manufacturers of HD electric vehicles are currently subject to the Heavy-Duty Phase 2 GHG standards. However, electric vehicles are deemed to have zero CO₂/ton-mile emissions and would meet the proposed revised standards without any additional GHG-reducing technologies.

Under the criteria pollutant portion of the proposed rule, electric vehicle manufacturers would attest to meeting the proposed criteria pollutant standards using the same process as they currently use for greenhouse gas standards. For this analysis, we calculated an impact of time to compile materials to certify and to update the labels on their vehicles that we believe conservatively overestimates the burden of our proposal for these manufacturers.

EPA identified 25 companies that make electric heavy-duty vehicles. These are companies that certified with EPA as of 2021. We obtained their employment and annual revenue numbers from Hoovers. Of these, 13 are small entities under the SBA definitions.

We estimated the impacts of the rule on these small entities using the following information. We assume each company would have one-time costs associated with compiling the materials to certify to criteria pollutants (1 hour/family) and with updating their vehicle label (1 hour/family). There are no recurring costs per vehicle expected. Assuming 1 family and \$43.58/hour, the total cost of the program in the first year is expected to be \$88 per company.

Our examination of the annual revenues for the 13 small electric heavy-duty vehicle manufacturers that would be subject to the rule reveals that these costs, \$88 per company per year, would not impose a significant impact on any of them. Even a low significant impact threshold of 1 percent of revenue would correlate to an annual revenue of less than \$8,800. The 13 small electric heavy-duty vehicle manufacturers have annual revenues of \$78,000 or more and would not have a significant impact from the proposed rule. These results are summarized in Table 11-1 presented in Section 11.6.

11.4.2 Heavy-Duty Conventional Vehicle Manufacturers

Heavy-duty vehicle manufacturers are currently subject to the greenhouse gas emission standards in 40 CFR part 1037. As part of the HD GHG Phase 2 rulemaking, consistent with the recommendations of the Small Business Advocacy Review Panel, we adopted a custom chassis program as part of the vocational vehicle program that includes less stringent standards and a simplified GEM process (81 FR at 73526). In addition, we provided a one-year delay in the Phase 2 vehicle GHG emission standards for small vehicle manufacturers (see 40 CFR 1037.150(c)(2)).

In our review of information provided by vehicle manufacturers during the MY 2021 greenhouse gas emissions certification process, we found one conventional vehicle manufacturer that is a small business. For this manufacturer, we reviewed the types of vehicles they manufacture, their most recent production volumes, and their annual revenue per Hoover's.

The small manufacturer produces vehicles that would be considered under the custom chassis program or "urban" vehicles under the vocational vehicle standards in 40 CFR 1037.105. In Phase 2, we projected the technology costs to meet the MY 2027 CO₂ emission standards at

\$2,727 for medium heavy-duty urban vehicles and \$4,121 for heavy heavy-duty urban vehicles (81 FR at 73718, Table V-30). As discussed in Section XI.C of the preamble, the proposed revisions to the MY 2027 emission standards would require manufacturers to apply Phase 2 technologies at the costs presented here to approximately five percent of conventional vehicles that may not otherwise have applied those technologies absent this proposal. Applying these technology costs to five percent of the company's MY 2019 production volumes (the most recent data available) for the two vehicle subcategories, we estimate that the impact of proposed standards would be less than one percent of the company's revenues. Therefore, we determined that there would not be a significant impact on this manufacturer due to the proposed revisions to the MY 2027 CO₂ emission standards. These results are summarized in Table 11-1 presented in Section 11.6.

11.5 Impacts on Small Entities: Heavy-Duty Alternative Fuel Engine Converters

Companies that convert compression-ignition or spark-ignition heavy-duty engines to use alternative fuels would be subject to the proposed rule. Alternative fuel converters do not always need to certify the conversions to the proposed emission standards. However, they may need to perform testing to show that modified engines continue to meet the applicable new standards as part of the process for meeting 40 CFR part 85, subpart F to be exempt from the tampering prohibition. For this analysis, we conservatively assumed the process for these fuel converters would include emission testing using a new test procedure (SET if converting an SI engine or LLC if converting a CI engine), and preparing the data for submission to EPA to obtain an EPA Certificate of Compliance.

EPA identified 5 companies who convert heavy-duty engines to run on alternative fuel. These are companies that certified engines with EPA as of 2020. We obtained their employment and annual revenue numbers from Hoovers. Two of these companies are small entities under the SBA definitions based on annual receipts.

To estimate the impacts of the proposed rule on these small entities we assume that each company will have one-time costs associated with developing and performing the emission test of 20 hours/family. There are no recurring costs per vehicle expected. Assuming 4 families and \$43.58/hour, the total cost of the program in the first year is expected to be \$3,486 per company.

Our examination of the annual revenues for the two small alternative fuel engine converters reveals that these costs, \$3,486 per company per year, would not impose a significant impact on either of them. Even a low significant impact threshold of 1 percent of revenue would correlate to an annual revenue of \$348,640 or less. Each of the two small alternative fuel engine converters has annual revenues in excess of that amount and would not have a significant impact from the proposed rule. These results are summarized in Table 11-1 presented in Section 11.6.

11.6 Summary Table of Impacts on Small Businesses Subject to the Rule

Table 11-1: Summary of Impacts on Small Businesses Subject to the Rule

NAICS Category	Sector description	SBA Threshold	Number of small companies subject to the proposed rule	Impact as percent of annual revenue, number of small companies		
				≥3%	1-3%	<1%
336211	Secondary manufacturer: Motor vehicle body manufacturing	1,250 employees	217	0	41	176
336213	Secondary manufacturer: Motor home manufacturing	1,250 employees	32	0	7	25
<i>Total secondary manufacturer</i>			249	0	48	201
336120	Heavy-duty vehicle manufacturers (including electric and conventional)	1,500 employees	14	0	0	14
811198	Alternative fuel engine converters	\$8.0 million annual receipts	2	0	0	2
<i>TOTAL</i>			265	0	48	217

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