# Exhaust Emission Rates for Heavy-Duty Onroad Vehicles in MOVES4

United States
Environmental Protection
Agency

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

*NOTICE*

*This technical report does not necessarily represent final EPA decisions or positions. It is intended to present technical analysis of issues using data that are currently available. The purpose in the release of such reports is to facilitate the exchange of technical information and to inform the public of technical developments.*

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# List of Acronyms

| | |
|---|---|
| ABT | emissions averaging, banking and trading program |
| A/C | Air Conditioning |
| ACES | Advanced Collaborative Emission Study (CRC) |
| APU | auxiliary power units |
| ARCO | Atlantic Richfield Company |
| BC | black carbon |
| bhp | brake horsepower |
| BTU | British Thermal Unit |
| CARB | California Air Resources Board |
| CBD | Central Business District |
| CFR | Code of Federal Regulations |
| $CH_4$ | methane |
| CNG | Compressed Natural Gas |
| CO | carbon monoxide |
| $CO_2$ | carbon dioxide |
| CRC | Coordinating Research Council |
| CTI | Cleaner Trucks Initiative (later known as “Clean Trucks Rule”) |
| DB | database |
| DOC | diesel oxidation catalysts |
| DOE | U.S. Department of Energy |
| DPF | diesel particulate filter/periodic trap oxidizer |
| EC | elemental carbon |
| ECOSTAR | gaseous and exhaust flow measurement system |
| ECU | Engine Control Unit |
| EFEE | Engine, Fuel and Emissions Engineering Inc. |
| EGR | exhaust-gas recirculation |
| EMFAC | CARB emissions factors model |
| EPA | U.S. Environmental Protection Agency |
| ESC | European Stationary Cycle |
| FEL | family emission limit |
| FHWA | Federal Highway Administration |
| FID | Flame Ionization Detection |
| FTP | Federal Test Procedure |
| g | Grams |
| GDI | Gasoline Direct injection engines |
| GHG | Greenhouse Gases |
| g/mi | Grams per mile |
| GPS | Global Positioning System |
| GVWR | Gross Vehicle Weight Rating |
| THC | Hydrocarbons |
| HD | Heavy-Duty |
| HDIU | Heavy-Duty Diesel In-Use |
| HDT | Heavy-Duty Truck |
| HFC | Hydrofluorocarbon |

| | |
|---|---|
| H-GAC | Houston-Galveston Area Council |
| HHD | Heavy-Heavy-Duty Class 8 Trucks (GVWR > 33,000 lbs) |
| HHDD | Heavy Heavy-Duty Diesel |
| $HNO_2$ | nitrous acid (HONO) |
| HP | horsepower |
| hr | hour |
| HV | heating value |
| $H_2O$ | water |
| I/M | Inspection and Maintenance program |
| IUVP | In-Use Verification Program |
| kJ | Kilojoules |
| kW | Kilowatt |
| LHD | Light-Heavy-Duty |
| LHD2b3 | Light-Heavy-Duty Class 2b and 3 Truck (8,500 < GVWR ≤ 14,000 lbs) |
| LHD45 | Light Heavy-Duty Class 4 or 5 Truck (14,000 < GVWR ≤ 19,500 lbs) |
| LHDDT | Light Heavy-Duty Diesel Truck |
| LNT | Lean $NO_x$ Trap aftertreatment |
| MDPV | Medium-Duty Passenger Vehicle |
| MECA | The Manufacturers of Emission Controls Association |
| MEMS | Mobile Emissions Measurement System |
| mg | milligram |
| MHD | Medium-Heavy-Duty Class 6 and 7 Trucks (19,500 < GVWR ≤ 33,000 lbs) |
| MOBILE6 | EPA Highway Vehicle Emission Factor Model, Version 6 |
| MOVES | Motor Vehicle Emission Simulator Model |
| MOVES201X | Motor Vehicle Emission Simulator Model development version |
| MSOD | Mobile Source Observation Database |
| MY | model year |
| MYG | model year group |
| NCHRP | National Cooperative Highway Research Program |
| NCP | nonconformance penalty |
| NDIR | non-dispersive infrared |
| NFRAQS | Northern Front Range Air Quality Study |
| $NH_3$ | ammonia |
| NMHC | Non-Methane Hydrocarbon |
| NMOG | non-methane organic gases |
| NonEC | non-elemental carbon |
| NonECnonSO4PM | non-elemental carbon non-sulfate particulate matter |
| NonECPM | non-elemental particulate matter carbon |
| NO | nitric oxide |
| $NO_x$ | nitrogen oxide |
| $NO_y$ | combined $NO_x$ and NOz compound |
| $NO_z$ | nitrous oxide |
| $NO_2$ | nitrogen dioxide |
| NREL | National Renewal Energy Laboratory |
| NTE | Not-to-Exceed |
| NYSDEC | New York Department of Environmental Conservation |

| | |
|---|---|
| $N_2O$ | nitrous oxide |
| OBD | On-Board Diagnostics |
| OC | oxidation catalyst |
| OEM | Original Equipment Manufacturer |
| OM | operating mode |
| OMNMHCE | organic material non-methane hydrocarbon equivalent |
| PCV | positive crankcase ventilation |
| PEMS | portable emissions measurement system |
| PERE | Physical Emission Rate Estimator |
| PHA | Port of Houston Authority |
| PM | Particulate Matter |
| $PM_{2.5}$ | fine particles of particulate matter with aerodynamic diameters $\leq 2.5$ μm |
| $PM_{10}$ | particles of particulate matter with aerodynamic diameters $\leq 10$ μm |
| ROVER | EPA dataset measurement collection system |
| RPM | revolutions per minute |
| SCAQMD | South Coast Air Quality Management District |
| SCR | selective catalytic reduction |
| $SO_4$ | sulfate |
| STP | scaled tractive power |
| ST01 | 258-second driving cycle |
| T&M | Tampering and Maintenance |
| TC | total carbon |
| TEOM | Tapered Element Oscillating Microbalance |
| THC | Total Hydrocarbon (FID detection) |
| TOG | Total Organic Gases |
| TTI | Texas Transportation Institute |
| TWC | three-way catalysts |
| UDDS | Urban Dynamometer Driving Schedule |
| UL | useful life |
| ULSD | Ultra Low Sulfur Diesel |
| VIN | Vehicle Identification Number |
| VIUS | Vehicle Inventory and Use Survey |
| VMT | Vehicle Miles Traveled |
| VOC | Volatile Organic Compounds |
| VSP | vehicle specific power |
| WMATA | Washington Metropolitan Area Transit Authority |
| WVU | West Virginia University |
| ZML | zero-mile emissions level |

# 1 Introduction

The United States Environmental Protection Agency's Motor Vehicle Emission Simulator (MOVES) is a set of modeling tools for estimating air pollution emissions produced by onroad (highway) and nonroad mobile sources. MOVES estimates the emissions of greenhouse gases (GHGs), criteria pollutants and selected air toxics. The MOVES model is currently the official model for use for state implementation plan (SIP) submissions to EPA and for transportation conformity analyses outside of California. The model is also the primary modeling tool for estimating the impact of mobile source regulations on emission inventories.

This report describes the analyses conducted to generate exhaust emission rates and energy rates representing exhaust emissions and energy consumption for heavy-duty vehicles in MOVES4 as revised to support EPA rulemakings. Heavy-duty vehicles in MOVES are defined as any vehicle with a Gross Vehicle Weight Rating (GVWR) above 8,500 lbs.

Emission rates for THC, CO, $NO_x$, $PM_{2.5}$ and $NH_3$ are stored in the "EmissionRateByAge" table in the MOVES database according to the following:

- Pollutant
- Emission process
- Fuel type
- Regulatory class
- Model year group
- Operating mode
- Vehicle age

Energy emission rates are stored in the "EmissionRate" table, which is similar to the "EmissionRateByAge" table, except emission rates are not differentiated by vehicle age. The MOVES framework and additional details regarding the "EmissionRateByAge" and "EmissionRate" table are discussed in the report documenting the rates for light-duty vehicles.[9]

In Section 1, we provide more background on the factors used to estimate heavy-duty exhaust emissions in the "EmissionRateByAge" and "EmissionRate" tables. We then discuss the major updates made to the heavy-duty emissions in MOVES4 in Section 1.8.

Sections 2 through 4 document the tailpipe exhaust emission rates for heavy-duty diesel, heavy-duty gasoline, and heavy-duty compressed natural gas (CNG) vehicles. Section 5 documents the crankcase emission rates used for each fuel type of heavy-duty vehicles. Section 7 documents the methods used to estimate nitric oxide (NO), nitrogen dioxide ($NO_2$), and nitrous acid ($HNO_2$ or HONO) emissions from $NO_x$ emissions using ratios.

## 1.1 Pollutant

This report discusses the development of tailpipe exhaust emission rates for total hydrocarbons (THC), carbon monoxide (CO), nitrogen oxides ($NO_x$), fine particulate matter, defined as particulate matter with mean aerodynamic diameter less than 2.5 microns ($PM_{2.5}$), ammonia ($NH_3$) and energy consumption (in units of kJ).

Total hydrocarbons (THC) is the measurement of hydrocarbons from a flame ionization detector.[1] From THC emissions, MOVES generates other estimates of hydrocarbon and organic gas missions, including volatile organic compounds (VOCs), methane ($CH_4$) and total organic gases (TOG). MOVES then uses VOC emission rates to estimate individual toxic compounds such as formaldehyde and benzene. The derivation of the factors used to compute aggregate measures of organic gases and individual toxic emissions are available in the Speciation[1] and Toxics[2] MOVES Reports.

MOVES reports $PM_{2.5}$ emissions in terms of elemental carbon (EC) and the remaining non-elemental carbon PM (nonECPM). This heavy-duty report covers the derivation of EC/PM fractions used to estimate elemental carbon (EC), and the remaining non-elemental carbon PM (nonECPM). MOVES also estimates 18 PM subspecies beyond elemental carbon, including organic carbon, sulfate, nitrate, and other trace elements and ions through the use of speciation profiles as documented in the Speciation Report.[1]

In MOVES4, we updated the heavy-duty $NH_3$ emission rates, which are now documented in Section 5. From $NO_x$, MOVES estimates NO, $NO_2$, and HONO emissions as documented in Section 7. Nitrous Oxide ($N_2O$) emissions from heavy-duty vehicles are documented in the MOVES Greenhouse Gas and Energy Report.[3] MOVES estimates $CO_2$ emissions from the energy rates documented in this report, using conversion factors, which are also documented in the Greenhouse Gas and Energy Report.

In order to incorporate HD2027 final standards, we made updates for $NO_x$, PM, HC, and CO emission rates for model year 2027 and later. Refer to Section 1.8.2 for an overview of these changes.

## 1.2 Emission Process

MOVES models vehicle emissions from fourteen different emission processes as listed in Table 1-1. This report covers the emission rates for the exhaust emission processes (running exhaust, start exhaust, extended idle exhaust, auxiliary power exhaust, crankcase running exhaust, crankcase start exhaust, and crankcase extended idle exhaust). We discuss the different processes below:

### 1.2.1 Running Exhaust

The running exhaust process occurs as the vehicle is operating on the road either under load or in idle mode, and also includes “off-network idle. The running process is delineated by 23 operating modes as discussed in Section 1.6.

### 1.2.2 Start Exhaust

The start exhaust process is the incremental emissions that occur when starting a vehicle, including the incremental emissions that occur after the engine start before the aftertreatment system is fully functional. Ideally, start emission rates are calculated as the difference in emissions measured between two otherwise identical drive cycles, where the first cycle includes a start and in the second drive cycle the vehicle is already running and in a warmed-up condition as shown in Equation 1-1.

$$\text{Start emission rate }\left(\frac{\text{g}}{\text{start}}\right)$$
$$= (\text{emissions from drive cycle}_i\text{ with start}$$
$$- \text{emissions from same drive cycle}_i\text{ without start and with vehicle in warm condition})$$

**Equation 1-1**

Starts also have operating modes to characterize different amount of soak time (time since the vehicle has last been running before being started again). Cold starts, (or starts after a long soak period) generally have higher emission rates than warm starts (starts after a short soak period), due to additional fueling needed due to increased condensation of fuel at colder engine temperatures, and because the catalytic aftertreatment needs to reach a warm temperature to be fully operational. MOVES defines eight operating start operating modes based on soak time as discussed in Section 1.6.

Operationally, we typically don't have two identical drive cycles that fit the conditions of Equation 1-1, and cold starts in this report are calculated using Equation 1-2 which is a reasonable approximation since cold start emissions are typically much higher than hot-start emission.

$$\text{Operationally} - \text{defined cold start emission rate }\left(\frac{\text{g}}{\text{start}}\right) =$$
$$= (\text{emissions from drive cycle}_i\text{ with cold start}$$
$$- \text{emissions from drive cycle}_i\text{ with hot start and vehicle in warm condition})$$

**Equation 1-2**

### 1.2.3 Extended Idle and Auxiliary Power Exhaust

The extended idle exhaust process in MOVES occurs during periods of hotelling, when long-haul trucks are used during rest periods, such as when a vehicle is parked for the night and left idling. Extended idle in generally defined to cover idling periods for longer than one hour. Extended idle can result in different emissions than incidental idle that occurs during running operation because the engine may be operated at a higher engine speed and the exhaust aftertreatment system may be too cool to operate at its full efficiency.

Auxiliary power exhaust are emissions that come from diesel-powered generators that power the truck's accessory loads, sometimes are used in place of the main engine during periods of hotelling. In MOVES4, the scope of extended idle and APU emissions was expanded to include CNG and electric (EV) combination long-haul trucks, as opposed to only diesel. MOVES does not allow combination long-haul trucks to use the gasoline fuel type. Documentation of the extended idle and auxiliary power exhaust emissions for heavy-duty diesel trucks are in Sections 2.3 and 2.4 while documentation of CNG rates are in Section 4.3 and EV energy consumption rates are documented in the Greenhouse Gas and Energy Consumption Rates Technical Report.[3]

MOVES4 also includes the capability to model energy consumption for trucks that are plugged into a facility's electricity to run their accessories, known as "shore power." Shore power energy consumption rates are documented in the Greenhouse Gas and Energy Consumption Technical Report.

### *1.2.4 Crankcase Exhaust*

Crankcase exhaust emissions (for running, start, and extended idle) include combustion products and oil that are vented from the engine crankcase to the atmosphere. Crankcase emissions are estimated for THC, CO, $NO_x$, $PM_{2.5}$ emissions and their chained pollutants as discussed in Section 6. We do not estimate energy or $CO_2$ emissions because crankcase emissions are a small contribution to the total $CO_2$ emissions. Crankcase emissions are significant sources of THC and $PM_{2.5}$ emissions from heavy-duty diesel engines. Crankcase emission rates for all four pollutants for all heavy-duty source types and fuels are discussed in Section 6.

### *1.2.5 Evaporative and Brake and Tire Wear Emissions*

Estimation of evaporative hydrocarbon emissions from heavy-duty gasoline vehicles is described in the evaporative report.[4] MOVES does not estimate evaporative emissions for diesel-powered vehicles, but does estimate fuel spillage emissions which are part of the refueling emissions documented in the evaporative report.[4] Brake and tire wear emission rates from heavy-duty vehicles are discussed in the Brake and Tire Wear Report.[5]

**Table 1-1 Emission Processes for Onroad Heavy-Duty Vehicles**

| **processID** | **processName** | **Covered in this report?** |
|---|---|---|
| 1 | Running Exhaust | Y |
| 2 | Start Exhaust | Y |
| 9 | Brakewear | N |
| 10 | Tirewear | N |
| 11 | Evap Permeation | N |
| 12 | Evap Fuel Vapor Venting | N |
| 13 | Evap Fuel Leaks | N |
| 15 | Crankcase Running Exhaust | Y |
| 16 | Crankcase Start Exhaust | Y |
| 17 | Crankcase Extended Idle Exhaust | Y |
| 18 | Refueling Displacement Vapor Loss | N |
| 19 | Refueling Spillage Loss | N |
| 90 | Extended Idle Exhaust | Y |
| 91 | Auxiliary Power Exhaust | Y |

## *1.3 Fuel Type*

This report is primarily organized around the exhaust emission rates by fuel type: heavy-duty diesel (Section 2), heavy-duty gasoline (Section 3), and heavy-duty CNG (Section 4). These three fuel types can be modeled in all the heavy-duty sourcetypes, with the exception of long-haul combination trucks which can only model diesel vehicles. Note that the emissions from the heavy-duty sector predominantly come from diesel vehicles and the majority of the data analyzed were from diesel vehicles. MOVES also models E85 for light-duty vehicles, but this fuel type is not available to be modeled for heavy-duty vehicles.[6] And MOVES models energy consumption from battery electric and fuel cell electric vehicles as explained in the MOVES4 GHG and Energy report.[3]

## *1.4 Regulatory Class*

The MOVES regulatory classes group vehicles that have similar emission rates. The MOVES heavy-duty regulatory classes are largely determined based on gross vehicle weight rating (GVWR) classifications, because the heavy-duty emission standards are based on GVWR as shown in Table 1-2.

There are additional criteria that define the heavy-duty regulatory classes in MOVES. Urban Bus vehicles are distinguished from other heavy heavy-duty vehicles (GVWR >33,000 lbs.) because they have tighter PM emission standards for the 1994 through 2006 model years.[7] Urban bus is a regulatory class that is defined by its intended use as well as the GVWR. EPA regulations define urban buses as “heavy heavy-duty diesel-powered passenger-carrying vehicles with a load capacity of fifteen or more passengers and intended primarily for intra-city operation.”[8].

In MOVES, gliders (regClassID 49) are defined as heavy heavy-duty diesel trucks with an old powertrain, combined with a new chassis and cab assembly. Currently in MOVES, gliders are limited to the diesel long-haul and short-haul combination truck source types. As discussed in Section 2.5, the emissions are equivalent to MY 2000 HHD diesel vehicles.

In MOVES4, we classified diesel light-heavy-duty Class 3 engine-certified vehicles in model year 2017 and later years as LHD45 vehicles. The emission rates for LHD2b3 vehicles are based on the assumption that all vehicles are chassis-certified, and subject to the Tier 3 standards (Discussed in Section 2.1.1.5.5), and the Heavy-duty Phase 1 and 2 greenhouse gas emission standards (Discussed in Section 2.1.4.3.2). Because Class 3 engine-certified vehicles are instead subject to the same emission standards as Class 4 and 5 engine-certified vehicles, we reclassified these vehicles as LHD45 vehicles. Model year 2017 is selected because this is the first model year the emission rates are different between LHD2b3 and LHD45. The reclassification of diesel LHD2b3 as diesel LHD45 vehicles is documented in the Population and Activity report.[6]

MOVES classifies vehicles of similar activity, usage patterns, and body type into source use types, often simply referred to as “source types.” The MOVES source types are defined in the Population and Activity Report.[6] As shown in Table 1-2, vehicles of a regulatory class may be mapped to multiple source types. Likewise, each source type used to model heavy-duty vehicles includes population from several different regulatory classes. For example, single unit short-haul trucks (sourceTypeID 52), include vehicles from the following regulatory classes: LHD2b3, LHD45, MHD, and HHD.

**Table 1-2 Regulatory Classes for Heavy-Duty Vehicles**

| Regulatory Class Description | regClassName | regClassID | Gross Vehicle Weight Rating (GVWR) [lb.] | Existing Source Types in default database (sourceTypeID) |
|---|---|---|---|---|
| Light Heavy-Duty Class 2b and 3 trucks | LHD2b3 | 41 | 8,501 – 14,000* | Passenger Trucks (31), and Light-Commercial Trucks (32), School Buses (43), and Single Unit Trucks (51, 52, 53, 54) |
| Light Heavy-Duty Class 4 and 5 Trucks | LHD45 | 42 | 14,001 – 19,500* | Buses (41, 42, 43) and Single Unit Trucks (51, 52, 53, 54) |
| Medium Heavy-Duty (Class 6 and 7 Trucks) | MHD | 46 | 19,501 – 33,000 | Buses (41,42,43), Single Unit Trucks (51, 52, 53, 54), and Combination Trucks (61, 62) |
| Heavy Heavy-Duty (Class 8 Trucks) | HHD | 47 | > 33,000 | Buses (41, 42, 43), Single Unit Trucks (51, 52, 53, 54), and Combination Trucks (61, 62) |
| Urban Bus | Urban Bus[8] | 48 | > 33,000 | Transit Bus (42) |
| Gliders (Class 8 Trucks) | Glider Vehicles | 49 | > 33,000 | Combination Trucks (61, 62) |

*Model year 2017-and-later engine-certified Class 3 (GVWR 10,001-14000 lbs) trucks (only present within source types 52, 53, and 54) are classified as LHD45 (regclassID 42).

## *1.5 Model Year Groups*

MOVES model year groupings are designed to represent major changes in emission rates due to changing vehicle and aftertreatment technologies introduced in response to EPA emission standards. Model year groups in MOVES can represent a single model year (e.g., 2007), or a range of model years (e.g., 2030-2060). The emission rates discussed in the following sections are discussed in terms of model year ranges. The model year groups cover all the model years between 1960 through 2060. When data are limited or unavailable for model year groups, we make assumptions about the impact of emission standards and vehicle aging to estimate those emission rates.

## *1.6 Operating Modes*

Emission rates in MOVES are stored by regulatory class, fuel type, model year, and operating mode. To calculate emissions from each process, MOVES sums the product of the emission rate for each operating mode by the time spent in each operating mode.

For example, the activity basis for running process is source hours operating (SHO). The running process is divided into 23 operating modes (as shown in Table 1-4). Using Equation 1-3, the total running emissions is calculated by summing the product of the emission rates with the fraction of time spent in each operating mode (the operating mode distribution). This is multiplied by the total hours (SHO) spent in this emission process.

$$Running\ Emissions = SHO \times \sum_{i=1}^{23} (Operating\ Mode\ Distribution_i \times Emission\ Rate_i)$$

**Equation 1-3**

MOVES performs the calculations shown in Equation 1-3, at a detailed level that accounts for each factor that impacts the emission rates (e.g., model year, vehicle age, fuel type, regulatory class) and the operating mode distribution (source type, roadtype, average speed (which varies across hour of the day)). Then, the emissions can be aggregated to different levels (e.g., by sourcetype). Similar equations can be constructed for other process, the equation for starts is shown in Equation 1-4, where the starts are classified into eight operating modes (Table 1-5).

$$Start\ Emissions = Starts \times \sum_{i=1}^{8} (Operating\ Mode\ Distribution_i \times Emission\ Rate_i)$$

**Equation 1-4**

The operating modes for running exhaust are defined in terms of power output (with the exception of the idle and braking modes). For light-duty vehicles, the parameter used is known as vehicle-specific power (VSP), which is calculated by normalizing the continuous power output for each vehicle to its own weight as shown in Equation 1-5 (hence the term “vehicle-specific”). As discussed in the light-duty emission rate report,[9] VSP is a robust predictor of vehicle emissions. In the laboratory, light-duty vehicles are tested on full chassis dynamometers, and emission standards are in units of grams per mile. The emission standards are largely independent of the weight (and other physical characteristics) of the vehicle.

In developing emission rates for MOVES, light-duty emissions data from individual vehicles are assigned to VSP operating mode bins using Equation 1-5, using the individual vehicle’s measured weight as the source mass, and ideally using vehicle-specific road load coefficients. In contrast, when MOVES calculates VSP from driving cycles and assigns operating modes for an entire source type, the average source type mass and average road load coefficients are used instead.

$$VSP_t = \frac{Av_t + Bv_t^2 + Cv_t^3 + m \cdot v_t(a_t + g \cdot sin\theta_t)}{m}$$ **Equation 1-5**

Where:

$VSP_t$ = vehicle specific power at time $t$ [kW/ton]
$A$ = the rolling resistance coefficient [kW·sec/m],
$B$ = the rotational resistance coefficient [kW·sec$^2$/m$^2$],
$C$ = the aerodynamic drag coefficient [kW·sec$^3$/m$^3$],
$m$ = mass of individual test vehicle [metric ton],
$v_t$ = instantaneous vehicle velocity at time $t$ [m/s],
$a_t$ = instantaneous vehicle acceleration [m/s$^2$]
$g$ = the acceleration due to gravity [9.8 m/s$^2$]
$\sin\theta_t$ = the (fractional) road grade at time $t$

For heavy-duty vehicles, we classify running exhaust using Scaled Tractive Power (STP) as shown in Equation 1-6 using road-load coefficients. STP is equivalent to VSP, except the power for all vehicles within the same regulatory class and model year are scaled using a fixed mass factor, rather than the individual weight of the vehicle. The $f_{scale}$ is used to bring the numerical range of tractive power from heavy-duty vehicles into the same numerical range as the VSP values when assigning operating modes. When developing emission rates for MOVES, operating modes are assigned to individual vehicles using both the individual truck mass, $m$, and the common $f_{scale}$ value used for all heavy-duty vehicles from the same regulatory class, source type and model year group. Because a common $f_{scale}$value is used, individual vehicles assigned to the same STP-defined operating mode bin are producing the same absolute tractive power, regardless of differences in their individual source masses.

$$STP_t = \frac{Av_t + Bv_t^2 + Cv_t^3 + m \cdot v_t(a_t + g \cdot sin\theta_t)}{f_{scale}}$$ **Equation 1-6**

Where:

$STP_t$ = the scaled tractive power at time $t$ [scaled kW or skW]
$f_{scale}$ = fixed mass factor (see Table 1-3)
Other variables as previously defined in Equation 1-5

When MOVES estimates STP and assigns operating mode distributions for the heavy-duty source types, Equation 1-6 uses the average source type mass ($m$) for each regulatory class, source type, and model year group in the numerator and uses the common $f_{scale}$ value for the regulatory class and model year group which was also used in the emission rate analysis. At County and Default National Scale, MOVES uses the instantaneous speed ($v_t$) from the second-by-second driving cycles associated with average speed, source types, and road types. For Project Scale, MOVES can use user-supplied driving cycles and grade. The default average speed driving cycles and the load road coefficients are discussed in the Population and Activity Report.[6]

The equation for STP is generalized below in Equation 1-7, with units in scaled kW or skW:

$$STP = \frac{P_{axle}}{f_{scale}}$$ **Equation 1-7**

Where: $P_{axle}$ is the power demand at the axle for the heavy-duty truck.

As presented in Equation 1-6, $P_{axle}$ can be estimated using the road-load coefficients from chassis-dynamometer tests (for example, pre-2010 heavy-duty diesel THC, CO, and $PM_{2.5}$ emission rates in Sections 2.1.2 and 2.1.3). Road-load coefficients can also be used to estimate power demand from onroad tests when more accurate power demand measurements are not available (for example, the 2010+ heavy-duty gasoline emission rates in Section 3.1).

The $P_{axle}$ can be estimated from an engine dynamometer or from an engine control unit (ECU) for chassis or onroad testing by measuring the engine power and estimating the accessory loads and powertrain efficiencies for the vehicle.

For onroad tests, measuring power from the ECU is generally more accurate than estimating power from road-load coefficients. Unlike a generic road-load equation where vehicle characteristics, such as aerodynamic drag and rolling resistance are assumed, the ECU measures engine speed and calculates torque directly during the test, avoiding the need to capture the impact of wind speed and wind direction, as well as weight and the road grade throughout the entire test cycle and route. Wind can have a significant impact on power needs, and the payload of heavy-duty vehicles can be greater than the vehicle weights itself, while also varying significantly over the test. Thus, for onroad tests, we generally use power calculated from the ECU measurements, because the vehicle and environmental characteristics determine the axle power (Section 2.1.1.3).

The use of STP instead of VSP is preferable for modeling heavy-duty vehicles emissions because heavy-duty vehicle emissions are strongly correlated with power output. Heavy-duty vehicles are regulated using engine dynamometer tests, and emissions standards are in units of grams per brake-horsepower-hour (g/bhp-hr). Additionally, each heavy-duty regulatory class contains a wide variety of truck sizes, truck weight, power ratings, and in-use payloads. Using STP, we can scale the heavy-duty emission rates to different power outputs that were not measured in our emission rate database. The sample of trucks we used to develop emission rates for each regulatory class has a limited number of trucks and loads compared to the in-use fleet, which may not be representative of the average vehicle weight and power output of the in-use fleet. The use of VSP would require the sample of vehicles to match the average vehicle weights and load to accurately estimate average in-use emission rates. By using STP, MOVES scales the measured emissions to match the estimated weight and power output of the modeled in-use fleet.

The $f_{scale}$ values can be considered as a surrogate for the average mass of heavy-duty vehicles within each regulatory class, as reported in Table 1-3. For the pre-2010 emission rates, we used an $f_{scale}$ equivalent to the average mass of the light-commercial trucks (2.06 metric tons) for the LHD2b3 and LHD45 emission rates. For the other heavy-duty source types, a single $f_{scale}$ (17.1 metric tons) was used, which provided emissions within each operating mode bin for the largest heavy-duty truck vehicles.

However, in our analysis of in-use data from recent trucks, we found that an $f_{scale}$ of 17.1 metric tons limited most of the real-world activity to low and medium power bins within a speed-bin, especially for the light-heavy and medium-heavy-duty regulatory classes. In MOVES3 (and carried over to MOVES4), we revised the $f_{scale}$ values for MY 2010 and later to provide more resolution in the $f_{scale}$ by regulatory class. Derivation of the new $f_{scale}$ values is described in Appendix G.

**Table 1-3 Fixed Mass Factor, $f_{scale}$ (metric tons)**

| Regulatory Class (regClassID) | MY 1960-2009 | MY 2010+ |
|---|---|---|
| LHD2b3 (41) | 2.06 | 5.0 |
| LHD45 (42) | 2.06 | 5.0 |
| MHD (46) | 17.1 | 7.0 |
| HHD (47) | 17.1 | 10.0 |
| Urban Bus (48) | 17.1 | 10.0 |
| Glider (49) | 17.1 | 17.1 |

NOTE: OpMode-based emission rates **CANNOT** be compared directly between regClasses or model years (MYs) with different $f_{scale}$ values. For example, the OpMode 14 emission rates for MY 2012 MHD ($f_{scale}$ = 7) cannot be directly compared to the same OpMode rates from MY 2009 MHD ($f_{scale}$ = 17.1) or MY 2012 HHD ($f_{scale}$ = 10). That is because data assigned to an OpMode based on different $f_{scale}$ values will have different absolute power (numerator of Equation 1-6 and Equation 1-7). When using vehicle mass in the denominator (Equation 1-5), this is not an issue because the unit is kW/ton and the power is normalized to the mass of the vehicle. However, when using $f_{scale}$ in the denominator, as is the case for all heavy-duty vehicles, the unit is scaled kW and there is no normalization to a physical quantity.

The operating modes bins for running exhaust are shown in Table 1-4.

**Table 1-4 Operating Mode Definition for Running Exhaust for Heavy-Duty Vehicles**

| **OpModeID** | **Operating Mode Description** | **Scaled Tractive Power (STP$_t$, skW)** | **Vehicle Speed ($v_t$, mph)** | **Vehicle Acceleration including grade (mph/sec)[1]** |
|---|---|---|---|---|
| 0 | Deceleration/Braking[2] | | | $a_t + g \cdot sin(\theta_t) \le -2.0$ OR<br>[$a_t + g \cdot sin(\theta_t) < -1.0$<br>AND<br>$a_{t-1} + g \cdot sin(\theta_{t-1}) < -1.0$<br>AND<br>$a_{t-2} + g \cdot sin(\theta_{t-2}) < -1.0$) |
| 1 | Idle | | $v_t < 1.0$ | |
| 11 | Coast | $STP_t < 0$ | $1 \le v_t < 25$ | |
| 12 | Cruise/Acceleration | $0 \le STP_t < 3$ | $1 \le v_t < 25$ | |
| 13 | Cruise/Acceleration | $3 \le STP_t < 6$ | $1 \le v_t < 25$ | |
| 14 | Cruise/Acceleration | $6 \le STP_t < 9$ | $1 \le v_t < 25$ | |
| 15 | Cruise/Acceleration | $9 \le STP_t < 12$ | $1 \le v_t < 25$ | |
| 16 | Cruise/Acceleration | $12 \le STP_t$ | $1 \le v_t < 25$ | |
| 21 | Coast | $STP_t < 0$ | $25 \le v_t < 50$ | |
| 22 | Cruise/Acceleration | $0 \le STP_t < 3$ | $25 \le v_t < 50$ | |
| 23 | Cruise/Acceleration | $3 \le STP_t < 6$ | $25 \le v_t < 50$ | |
| 24 | Cruise/Acceleration | $6 \le STP_t < 9$ | $25 \le v_t < 50$ | |
| 25 | Cruise/Acceleration | $9 \le STP_t < 12$ | $25 \le v_t < 50$ | |
| 27 | Cruise/Acceleration | $12 \le STP_t < 18$ | $25 \le v_t < 50$ | |
| 28 | Cruise/Acceleration | $18 \le STP_t < 24$ | $25 \le v_t < 50$ | |
| 29 | Cruise/Acceleration | $24 \le STP_t < 30$ | $25 \le v_t < 50$ | |
| 30 | Cruise/Acceleration | $30 \le STP_t$ | $25 \le v_t < 50$ | |
| 33 | Cruise/Acceleration | $STP_t < 6$ | $50 \le v_t$ | |
| 35 | Cruise/Acceleration | $6 \le STP_t < 12$ | $50 \le v_t$ | |
| 37 | Cruise/Acceleration | $12 \le STP_t < 18$ | $50 \le v_t$ | |
| 38 | Cruise/Acceleration | $18 \le STP_t < 24$ | $50 \le v_t$ | |
| 39 | Cruise/Acceleration | $24 \le STP_t < 30$ | $50 \le v_t$ | |
| 40 | Cruise/Acceleration | $30 \le STP_t$ | $50 \le v_t$ | |

Notes:

[1] The units of vehicle acceleration for determining the braking mode are in units of mph/sec. MOVES converts the acceleration in meters/sec$^2$ to mph/sec using 0.4470 meter*hours = 1 mile*second.

[2] The deceleration/braking definition will overlap with some of the other operating modes. In these cases, the deceleration/braking categorization takes precedence over other definitions.

Start emission rates are also distinguished according to operating modes in MOVES, as shown in Table 1-5. MOVES uses eight operating modes to classify starts according to the amount of time a vehicle was parked prior to vehicle start (soak time). These range from a hot start (opMode 101) where the vehicle has been soaking for less than 6 minutes, to a cold start (opMode 108) where the vehicle has been soaking for more than 12 hours.

**Table 1-5 Operating Modes for Start Emissions (as a function of soak time)**

| Operating Mode | Description |
|---|---|
| 101 | Soak Time < 6 minutes |
| 102 | 6 minutes ≤ Soak Time < 30 minutes |
| 103 | 30 minutes ≤ Soak Time < 60 minutes |
| 104 | 60 minutes ≤ Soak Time < 90 minutes |
| 105 | 90 minutes ≤ Soak Time < 120 minutes |
| 106 | 120 minutes ≤ Soak Time < 360 minutes |
| 107 | 360 minutes ≤ Soak Time < 720 minutes |
| 108 | 720 minutes ≤ Soak Time |

Extended idle exhaust and diesel auxiliary power unit (APU) exhaust are each modeled in MOVES with a single operating mode (opModeIDs 200 and 201, respectively).

## *1.7 Vehicle Age*

In MOVES, the start and running emission rates for THC, CO, $NO_x$, and $PM_{2.5}$ are stored in the “emissionRateByAge” table by age group, meaning that different emission rates can be assigned to different aged vehicles of the same model year, regulatory class, fuel type and operating mode. MOVES uses six different age classes to model the age effects, as shown in Table 1-6. The effects of age on the emission rates were developed separately for gasoline and diesel vehicles.

**Table 1-6 MOVES Age Group Definitions**

| 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 | None |

For diesel running exhaust, we estimated the effects of tampering and mal-maintenance (T&M) on emission rates as a function of age. Tampering refers to intentional disabling or modifying the vehicle engine, control systems, and/or exhaust aftertreatment systems that results in increased emissions. Mal-maintenance refers to lack or improper maintenance of the engine and aftertreatment, including neglecting to repair broken or mal-functioning engine and aftertreatment parts, which increase emissions. Based on surveys and studies, we developed estimates of frequencies and emission impacts of specific emission control component malfunctions, and then aggregated them to estimate the overall emissions effects for each pollutant (see Appendix B). We adopted this approach due to the lack of adequate data to directly estimate the deterioration for heavy-duty vehicles, and because the effects of T&M are believed to be the dominant source of emission deterioration on fleet-wide heavy-duty diesel emissions. MOVES currently does not allow explicit modeling of tampered vehicles – we hope to address this in future versions of MOVES as more data on tampering become available.

Start emissions are generally a small contributor to total exhaust emissions from heavy-duty diesel vehicles. No T&M effects are currently applied to the diesel start emissions.

For gasoline heavy-duty vehicles, the age effects are estimated directly from the a sample of emissions data, or are adopted from light-duty deterioration as discussed in Section 3.1.1.1. These effects are applied to both running and start exhaust emissions.

Not all emission rates are distinguished by vehicle age. Rates with no age dependence in MOVES are stored in the "EmissionRate" table. This table includes energy consumption rates for all processes as well as THC, CO, $NO_x$, $PM_{2.5}$, and ammonia ($NH_3$) emission rates for extended idle and auxiliary power units (APU), nitrous oxide ($N_2O$) rates for start and running emissions, and tire and brake wear emission rates. We calculate T&M effects for the diesel extended idle emission rates without regard to vehicle age as discussed in Section 2.3.2.3. This report documents the THC, CO, $NO_x$, and $PM_{2.5}$ emissions from extended idle and APU usage, and heavy-duty ammonia emissions for all emission processes. However, heavy-duty nitrous oxide[3] and tire and brake wear[5] emission rates are documented in separate MOVES reports.

## *1.8 MOVES4 Updates*

This section provides an overview of the updates to heavy-duty emission rates in MOVES4.

### *1.8.1 General Updates*

MOVES4 updates include:

- Application of Tier 3 for LHD2b3 diesel vehicles
- Heavy-duty ammonia ($NH_3$) emission rates
- Crankcase emissions
- $NO_x$ composition for heavy-duty diesel vehicles
- Tampering and mal-maintenance effects for LHD vehicles due to a minor correction in warranty and useful life assumptions.
- Due to a 2021 appeals court ruling vacating the portions of the HDGHG2 rule that apply to trailers,[10] for combination trucks of model year 2018 and later, we revised MOVES inputs that describe weight, aerodynamics, and rolling resistance as explained in the vehicle population and activity report[6] and "other efficiency" improvements as described in Section 2.1.4.3 below. This slightly increases the modeled emissions of $CO_2$ and other pollutants from these trucks.
- We now expect the Phase 2 requirements for LHD2b3 to be met via electrification starting in MY2025. Therefore, in MOVES4, we only model reductions in diesel energy rates through MY2024. See Section 2.1.4.3.2.

While most of these updates were routine, we conducted a peer-review of the updated ammonia emission rates. Materials from peer review, including peer-review comments and EPA responses are located on the EPA's science inventory webpage. [11,12]

### 1.8.2 Updates to incorporate HD2027 Standards

We made additional updates in MOVES4 to incorporate "Control of Air Pollution from New Motor Vehicles: Heavy-Duty Engine and Vehicle Standards" (also known as the "HD2027 standards") finalized on December 20, 2022.[13] This rule sets more stringent $NO_x$, PM, HC, and CO emissions standards for heavy-duty vehicles and engines starting in model year 2027.

To account for the impact of the HD2027 standards, we updated the MY2027+ heavy-duty vehicle exhaust emission rates in MOVES4 for the LHD45, MHD, HHD and Urban Bus regulatory classes, with focus on:

- Heavy-duty diesel vehicles:
    - Updated $NO_x$ emission rates for running, start, and extended idle processes in response to the HD2027 duty-cycle and off-cycle standards (as described in Sections 2.1.1.6, 2.2.1.3, and 2.3.3)
    - Revised running emission rates for $NO_x$, $PM_{2.5}$, THC, and CO due to the changes to the regulatory useful life and warranty, by modifying MOVES tampering and mal-maintenance (T&M) calculations (as described in Sections 2.1.1.7, 2.1.2.3.3, 2.1.3.3, and Appendix B)
    - Revised crankcase emission rates to consider the impacts of the closed crankcase design option available in the rule (as described in Sections 6.2.2.4)
- Heavy-duty gasoline vehicles:
    - Revised $NO_x$, THC, CO and $PM_{2.5}$ emission rates for running processes only (as described in Sections 3.1.1.3.2 and 3.1.2.3)
- Heavy-duty natural gas vehicles:
    - No updates were made since the average $NO_x$ FTP emission level for MY 2010-2017 CNG engine families is already close to the 0.1 g/hp-hr standard and any further reductions due to the rule are expected to be small.

There were no additional updates affecting heavy-duty gasoline and natural-gas vehicles.

# 2 Heavy-Duty Diesel Exhaust Emissions

This section details our analysis to develop emission rates for heavy-duty diesel vehicles. Four emission processes (running, extended idling, starts, and auxiliary power unit exhaust) are discussed.

## 2.1 Running Exhaust Emissions

The analysis for running exhaust emissions requires accurate second-by-second measurements of emission rates and parameters that can be used to estimate the tractive power exerted by a vehicle. This section describes how we analyzed continuous second-by-second heavy-duty diesel emissions data to develop emission rates applied within the predefined set of operating modes (Table 1-4).

Stratification of the data sample and generation of the final MOVES emission factors was done according to the combination of regulatory class (shown in Table 1-2) and model year group. As mentioned in Section 1.6, the emission rates were developed using scaled-tractive power (STP), using the power scaling factors shown in Table 1-3.

### *2.1.1 Nitrogen Oxides ($NO_x$)*

For $NO_x$ rates, we stratified heavy-duty vehicles into the model year groups listed in Table 2-1. These groups were defined based on changes in $NO_x$ emissions standards and the outcome of the Heavy-Duty Diesel Consent Decree[14], which required additional control of $NO_x$ emissions during highway driving for model years 1999-and-later. This measure is referred to as the "Not-to-Exceed" (NTE) limit.

**Table 2-1 Model Year Groups for $NO_x$ Analysis Based on Emissions Standards**

| Model year group | Standard (g/bhp-hr) | NTE limit (g/bhp-hr) |
|---|---|---|
| Pre-1988 | None | None |
| 1988-1989 | 10.7 | None |
| 1990 | 6.0 | None |
| 1991-1997 | 5.0 | None |
| 1998 | 4.0 | None |
| 1999-2002 | 4.0 | 7.0 HHD; 5.0 other reg. classes |
| 2003-2006 | $2.4^1$ | 1.5 times the standard or family emission limit (FEL)<br>(or 1.25 standard or FEL, when FEL > 1.50 g/bhp-hr) |
| 2007-2009 | $1.2^{1,2}$ | |
| 2010-2026 | 0.2 | |
| 2027+ | 0.035 for LHD, 0.05 for MHD/HHD | The off-cycle NTE standards was replaced by a moving average window (MAW) approach in the HD2027 rule. |

Notes:
$^1$ NMHC+$NO_x$ Standard
$^2$ Assumes Phase-in of $NO_x$ standard

#### *2.1.1.1 Data Sources*

In modeling $NO_x$ emissions from HHD, MHD, LHD, and urban buses, we relied on the following data sources:

**ROVER.** This dataset includes measurements collected during onroad operation using the ROVER system, a portable emissions measurement system (PEMS) developed by the EPA. The measurements were conducted by the U.S. Army Aberdeen Test Center on behalf of U.S. EPA.[15] This program started in October 2000. Due to time constraints and data quality issues, we used only data collected from October 2003 through September 2007. The data was compiled and reformatted for MOVES analysis by Sierra Research.[16] EPA analyzed the data and developed the emission rates. The data we used represents approximately 1,400 hours of operation by 124 trucks and buses of model years 1999 through 2007. The vehicles were driven mainly over two routes:

- "Marathon" from Aberdeen, Maryland, to Colorado and back along Interstate 70
- Loop around Aberdeen Proving Grounds in Maryland

**Consent Decree Testing.** These data were conducted by West Virginia University using the Mobile Emissions Measurement System (MEMS).[17,18,19] This program was initiated as a result of the consent decree between the several heavy-duty engine manufacturers and the US government, requiring the manufacturers to test in-use trucks over the road. Data was collected from 2001 through 2006. The data we used represented approximately 1,100 hours of operation by 188 trucks of model years 1994 through 2003. Trucks were heavily loaded and tested over numerous routes involving urban, suburban, and rural driving. Several trucks were re-acquired and tested a second time after 2-3 years. Data were collected at 5-Hz frequency, which we averaged around each second to convert the data to a 1.0-Hz basis.

**Heavy-Duty Diesel In-Use Testing (HDIUT).** The manufacturer-run in-use testing program for heavy-duty diesel vehicles was promulgated in June 2005 to monitor the emissions performance of heavy-duty engines operated under a wide range of real world driving conditions within the engine's useful life.[20] It requires each manufacturer of heavy-duty highway diesel engines to assess the in-use exhaust emissions from their engines using onboard, portable emissions measurement systems (PEMS) during typical operation while on the road. The PEMS unit must meet the requirements of 40 CFR 1065 subpart J. The in-use testing program began with a mandatory two-year pilot program for gaseous emissions in calendar years 2005 and 2006. The fully enforceable program began in calendar year 2007 and is ongoing. The vehicles selected for participation in the program are within the engine's useful life, and generally, five unique vehicles are selected for a given engine family. This dataset includes results for HHD, MHD, and LHD vehicles. The HDIUT data are publicly available on EPA's website.[21]

The data available for use in MOVES2014 were collected during calendar years 2005 through 2010 and represent engines manufactured in model years 2003 to 2009. For MOVES3 and later versions, we evaluated data from engines selected for testing in calendar years 2010 through 2018. These engines cover model years 2010 to 2016. The MY 2010+ data set included 40 unique engine families and 372 vehicles. There are about 10 million seconds of quality-assured second-by-second data covering about 85,000 miles of instrumented travel. 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 $NO_x$.[22] For the HHD class, out of a total 159 vehicles selected for testing during 2010-2016, 109 were line-haul, 46 were delivery, and the remaining were marked as "Other" in the metadata. Since the HDIUT data is measured and submitted by the manufacturer and the test vehicles are required to be free of any tampering or mal-maintenance, we can safely assume that they represent zero-mile vehicles for the purpose of assigning base rates and applying the tampering and mal-maintenance effects. We have expanded the characterization of the MY 2010+ HDIUT data set by separating the 0.2 $NO_x$ FEL group for heavy-duty diesel vehicles into two model year groups (2010-2013 and 2014 and later) as described in 2.1.1.5.

**Houston Drayage Data**. In coordination with the Texas Commission on Environmental Quality, the Houston-Galveston Area Council, and the Port of Houston Authority, EPA conducted a study collecting emissions data from trucks in drayage service using portable emission measurement systems (PEMS) from December 2009 to March 2010.[23] The trucks studied were diesel-fueled, heavy heavy-duty trucks used to transport containers, bulk and break-bulk goods to and from ports and intermodal rail yards to other locations. These trucks conducted the majority of their travel on short-haul runs, repeatedly moving containers across fixed urban routes. Note that only small fractions of trucks involved in drayage service are dedicated solely to this function, with most trucks spending large fractions of their time performing other types of short-haul service. No specific drive cycles were used and all PEMS testing was based on actual in-use loads and speeds.

A summary of vehicles by model years for the above-mentioned datasets is provided in Table 2-2.

**Table 2-2 Numbers of Diesel Vehicles from the ROVER, WVU MEMS, HDIUT, and Houston Drayage Programs by Model Year Group**

| | | **Regulatory Class** | | | |
|---|---|---|---|---|---|
| **Data Source** | **MYG** | **HHD** | **MHD** | **LHD[1]** | **BUS** |
| ROVER and Consent Decree Testing | 1991-1997 | 19 | - | - | 2 |
| | 1998 | 12 | - | - | - |
| | 1999-2002 | 78 | 30 | - | 25 |
| | 2003-2006 | 91 | 32 | - | 19 |
| HDIUT | 2003-2006 | 40 | 25 | 15 | - |
| | 2007-2009 | 68 | 71 | 24 | - |
| | 2010-2016 | 194 | 74 | 94 | 10 |
| Houston Drayage | 1991-1997 | 8 | - | - | - |
| | 1998 | 1 | - | - | - |
| | 1999-2002 | 10 | - | - | - |
| | 2003-2006 | 8 | - | - | - |

Note:

[1] LHD45 and LHD2b3 vehicles were grouped together and classified as LHD vehicles for analysis of rates. The only difference in the LHD45 and LHD2b3 emission rates is the application of production volume weighting and T&M effects summarized in Table 2-16.

For the pre-2010 emission rates, we used a combination of the ROVER, Consent Decree Testing and the HDIUT testing to estimate the emission rates. The Houston Drayage Study was used as comparison study only. Additional details are provided in Section 2.1.1.4. The HDIUT data are used exclusively for the 2010-2026 model year emission rates as discussed in Section 2.1.1.5. These 2010-2026 rates were also used as the “base rates” to develop the MY2027+ emission rates based on the duty-cycle standard as explained in Section 2.1.1.6.1.

#### *2.1.1.2 Measurement Accuracy and Quality Assurance*

PEMS devices continue to make improvements that affect measurement accuracy, such as sensor response, sample conditioning, and noise reduction. The data sets represent the accuracy of the instruments at the time of measurement. In compliance determinations, when determining whether the tested vehicle meets the in-use emissions standard or not, an “accuracy margin for portable in-use equipment” (commonly referred to as measurement allowance) is added onto the standard; increasing the vehicle compliance margin. The accuracy margins vary by model year and type of measurement method and are described in 40 CFR 86.1912. This is done to prevent measurements that are biased-high from affecting the compliance decision. However, since the true value for each second of data is unknown and errors could be biased either high or low, the in-use emission rates used in MOVES from each of these data sets are not adjusted to reflect the measurement allowance.

From each data set, we used only tests we determined to be valid. For the ROVER dataset, we eliminated all tests with any reported problems, including GPS malfunctions, PEMS malfunctions, etc., whether or not they affected the actual emissions results. For HDIUT data for MY2009 and earlier and Houston Drayage, the time-alignment was visually confirmed by comparing relevant time-series plots, such as exhaust mass-flow rate vs. $CO_2$ concentration, and exhaust-mass flow rate vs. engine speed, as recorded by the engine control unit (ECU). Data was generally aligned within one second. When an issue with the time-alignment was found, efforts were made to realign the data as much as possible. As our own high-level check on the quality of PEMS and ECU output, we then eliminated any trip from ROVER, HDIUT (MY 2009 and earlier), and Houston Drayage where the Pearson correlation coefficient between $CO_2$ (from PEMS) and engine power (from ECU) was less than 0.6. The correlation check removed approximately 7 percent of the ROVER and HDIUT (MY 2009 and earlier) data. All the data from Houston Drayage met the criteria for correlation between $CO_2$ and engine power. In addition, data were excluded from the analysis when the vehicle speed was not available due to GPS and/or ECU malfunctions, when no exhaust flow was reported, and when a periodic zero correction was being performed on gas analyzers. For the WVU (West Virginia University) MEMS data, WVU itself reported on test validity under the consent decree procedure and no additional detailed quality checks were performed by EPA. Table 2-2 shows the total distribution of vehicles by model year group from the emissions test programs above following evaluation of the validity of the data.

In analyzing the HDIUT data for MY 2010+, we checked the time-alignment and deleted any second of data that met any of the following conditions: (1) instrument was undergoing zeroing, as marked by the zero flag field; (2) engine RPM was below 500; (3) vehicle speed was missing or below zero; (4) acceleration was missing; (5) engine torque was missing; (6) measured exhaust flow rate was missing, or less than or equal to zero; and (7) as catch-all, if the calculated STP and OpMode were invalid numbers. We did not verify the accuracy of exhaust flow rate measurement and $CO_2$ measurement using techniques such as carbon-balance versus ECU reported fuel rate data. Such verifications are assumed to have been done (by the manufacturer) before data is submitted to EPA since they are required by 40 CFR 1065 subpart J.

#### *2.1.1.3 Calculation of Operating Modes*

As discussed in Section 1.6, we prefer to estimate tractive power from engine data collected during real-world operation rather than using the road-load equation. To do so, we first identified the seconds in the data that the truck was either idling or braking based on acceleration and speed criteria shown in Table 1-4. For all other operation, engine speed $\omega_{eng}$ and torque $\tau_{eng}$ from the ECU were used to determine engine power $P_{eng}$, as shown in Equation 2-1.

$$P_{eng} = \omega_{eng}\tau_{eng} \qquad \textbf{Equation 2-1}$$

We then determined the relationship between the power required at the wheels of the vehicle and the power required by the engine. We first had to account for the losses due to accessory loads during operation. Some accessories are engine-based and are required for operation. These include the engine coolant pump, alternator, fuel pump, engine oil pump, and power steering. Other accessories are required for vehicle operation, such as cooling fans to keep the powertrain cool and air compressors to improve braking. The third type of accessories is discretionary, such as air conditioning, lights, and other electrical items used in the cab. None of these power loads are subtracted in the engine torque values that are output from the engine control unit.

We calculated accessory load requirements and mapped them to STP bins in a number of steps. First, we grouped the accessories into five categories: cooling fan, air conditioning, engine accessories, alternator (to run electrical accessories), and air compressor. We identified where the accessories were predominately used on a vehicle speed versus vehicle load map to properly allocate the loads. For example, the cooling fan will be on at low vehicle speed where the forced vehicle cooling is low and at high vehicle loads where the engine requires additional cooling. The air compressor is used mostly during braking operations; therefore, it will have minimal load requirements at high vehicle speeds. Table 2-3 identifies the predominant accessory use within each of the vehicle speed and engine load map areas.

At this point, we translated the vehicle speed and engine load map into engine power levels. The engine power levels were aggregated into low (green), medium (yellow) and high (red) as identified in Table 2-3. Low power means the lowest third, medium is the middle third, and high is the highest third, of the engine’s rated power. For example, for an engine rated at 450 hp, the low power category would include operation between 0 and 150 hp, medium between 150 and 300 hp, and high between 300 and 450 hp. So, for example, when vehicle operation is in middle of the engine load map and vehicle speed is low or mid speed, the engine power level is in medium (yellow) band and the active accessory loads are as listed in the respective cells. However, for the same engine load map operation (mid) with vehicle speed at high, the engine power level is high (red) and active accessory loads are as listed in the cell. Some accessory loads, such as cooling fan, are absent from cells with the same engine power level (identified by color) based on the reasons given in the previous paragraph.

**Table 2-3 Accessory Use as a Function of Speed and Load Ranges, Coded by Power Level**

| | | Vehicle Speed (mph) | | |
|---|---|---|---|---|
| | | Low (0-25) | Mid (25-50) | High (50+) |
| Engine Load Map | Low | 🟩 Cooling Fan<br>Air Cond.<br>Engine Access.<br>Alternator<br>Air Compress | 🟩 Air Cond.<br>Engine Access.<br>Alternator<br>Air Compress | 🟨 Air Cond.<br>Engine Access.<br>Alternator |
| | Mid | 🟨 Cooling Fan<br>Air Cond.<br>Engine Access.<br>Alternator<br>Air Compress | 🟨 Cooling Fan<br>Air Cond.<br>Engine Access.<br>Alternator<br>Air Compress | 🟥 Air Cond.<br>Engine Access.<br>Alternator |
| | High | 🟥 Cooling Fan<br>Air Cond.<br>Engine Access.<br>Alternator<br>Air Compress | 🟥 Cooling Fan<br>Air Cond.<br>Engine Access.<br>Alternator<br>Air Compress | 🟥 Cooling Fan<br>Air Cond.<br>Engine Access.<br>Alternator |

Next, we estimated the power required when the accessory was “on” and percentage of time this occurred. The majority of the load information and usage rates are based on information from "*The Technology Roadmap for the 21st Century Truck*."[24]

The total accessory load is equal to the power required to operate the accessory multiplied by the percent of time the accessory is in operation. The total accessory load for each cell in Table 2-3 is equal to the sum of each accessory load. The calculations are included in Appendix A. The total accessory loads $P_{loss,acc}$ listed below in Table 2-4 are subtracted from the engine power determined from Equation 2-1 to get net engine power available at the engine flywheel.

For pre-2010 model years, LHD losses were set to zero. The losses for MY 2010+ LHD vehicles were estimated by adjusting the MHD vehicle losses as such: (1) removed the loss for air compressor; (2) no change to air condition loss; (3) scaled the losses for cooling fan, alternator, and engine accessories by 5/7 (where 5 and 7 are rough estimates of the average engine displacement in liters for LHD and MHD engines, respectively). Based on these adjustments, the LHD losses are estimated to be approximately 60 percent of MHD losses for the low power band and 70 percent for the mid and high power bands. We acknowledge this calculation relies on a number of assumptions, but we believe it is a step forward from having LHD losses equal to zero for all model years (as was the case in MOVES2014).

**Table 2-4 Estimates of Accessory Load in kW by Engine Power Level**

| Engine Power Level (of rated power) | HHD | MHD | LHD[1] (pre-2010) | LHD[1] (2010+) | Urban Bus |
|---|---|---|---|---|---|
| Low (0 – 1/3rd) | 8.1 | 6.6 | 0.0 | 4.1 | 21.9 |
| Medium (1/3rd to 2/3rd) | 8.8 | 7.0 | 0.0 | 4.8 | 22.4 |
| High (2/3rd to 1) | 10.5 | 7.8 | 0.0 | 5.5 | 24.0 |

Note:
[1] In MOVES2014, the accessory load losses for LHD were assumed to be zero for all model years. In MOVES3 and later models, MY 2010+ LHD data (Table 2-2) is analyzed with non-zero accessory load losses. However, for pre-2010 MY LHD, we continue to assume zero accessory load loss.

We then adjusted for the driveline efficiency, accounting for efficiency losses in the wheel bearings, differential, driveshaft, and transmission. The efficiency values were determined through literature searches. Driveline efficiency $\eta_{driveline}$ varies with engine speed, vehicle speed, and vehicle power requirements. Using sources available in the literature, [25,26,27,28,29,30,31,32,33] we estimated an average value for driveline efficiency. Table 2-5 summarizes our findings.

**Table 2-5 Driveline Efficiencies Found in the Literature**

| Vehicle Type | Data Source | Driveline Efficiency |
|---|---|---|
| General Truck | Barth (2005) | 80-85% |
| General Truck | Ludic (2001) | 75-95% |
| HDT | Rakha | 75-95% |
| | NREL (1998) | 91% |
| | Goodyear Tire Company | 86% |
| | Ramsay (2003) | 91% |
| | 21st Century Truck (2000) | 94% |
| HDT Single Drive/direct | SAE J2188 Revised Oct. 2003 | 94% |
| HDT Single Drive/indirect | | 92% |
| HDT Single Drive/double indirect | | 91% |
| HDT Tandem Drive/direct | | 93% |
| HDT Tandem Drive/indirect | | 91% |
| HDT Tandem Drive/double indirect | | 89% |
| Bus | Prtichard (2004): Transmission Eff. | 96% |
| | Hedrick (2004) | 96% |
| | MIRA | 80% |

Based on this research, we used a driveline efficiency of 90 percent for all HD regulatory classes. Equation 2-2 shows the translation from engine power $P_{eng}$ to axle power $P_{axle}$. MOVES uses the $P_{loss,acc}$ from Table 2-4 for each regulatory class and engine power-level (high, medium, or low).

$$P_{axle} = \eta_{driveline}(P_{eng} - P_{loss,acc}) \qquad \textbf{Equation 2-2}$$

Finally, we scaled the axle power using Equation 2-3, and the STP-scaling factors $f_{scale}$ presented in Table 1-3 for every second of data.

$$STP = \frac{P_{axle}}{f_{scale}} \qquad \textbf{Equation 2-3}$$

We then constructed operating mode bins defined by STP and vehicle speed according to the methodology outlined earlier in Section 1.5. It is possible that future test programs might acquire accessory load information from the ECU and axle efficiency data available through certification information during the HD GHG Phase 2 compliance program.

#### ***2.1.1.4*** *1960-2009 Model Years*

The 1960-2009 model year emission rates were originally developed for MOVES2010 using the ROVER and Consent Decree Testing data and then evaluated using MY 2003-2009 HDIUT testing data and the Houstan Drayage Program data.[34,35] In MOVES2014, the emission rates were considered for an update using the HDIUT or Houston Drayage Program data if:

1. MOVES2010 rates were not based on actual data, and
2. The comparison to the new independent data shows that more than a half of MOVES2010 emission rates are outside the boundary of the 95 percent confidence intervals of the independent data.

Using this methodology, the emission rates for HHD MY 2003-2006 vehicles and LHD2b3 and LHD45 MY 2003-2006 vehicles were updated using the MY 2003-2006 HDIUT data.[a] The Houston Drayage Program was not used to estimate any of the emission rates in MOVES.

Table 2-16 outlines the data sets used to estimate emission rates for each model year group and regulatory class. ROVER and Consent Decree testing data was used to estimate the following regulatory class and model year groups combinations: HHD 1991-1997, 1998, 1999-2002, 2003-2006, MHD 1999-2002, 2003-2006[b], and Urban Bus 1991-1997, 1999-2002, 2003-2006. The HDIUT was used to estimate emissions for HHD 2007-2009 and LHD 2003-2006.

Emissions in each data set were reported in grams per second. To calculate MOVES heavy-duty exhust emission rates, we first averaged all the 1-Hz $NO_x$ emissions by vehicle and operating mode because we did not believe the amount of driving done by each truck was necessarily representative. Then, the emission rates were again averaged by regulatory class and model year group. For trucks MY 2009 and older, these data sets were assumed to be representative and each vehicle received the same weighting. Equation 2-4 summarizes how we calculated the mean emission rate for each stratification group (i.e., model year group, regulatory class, and operating mode bin).

$$\bar{r}_p = \frac{\sum_{j=1}^{n_{veh}} \left( \frac{\sum_{i=1}^{n_j} r_{p,\, j,\, i}}{n_j} \right)}{n_{\text{veh}}} \qquad \textbf{Equation 2-4}$$

Where:

$n_j$ = the number of 1-Hz data points *(for a given operating mode bin)* for each vehicle $j$,
$n_{\text{veh}}$ = the total number of vehicles,
$r_{p,j,i}$ = the emission rate of pollutant $p$ for vehicle $j$ at second $i$,
$\bar{r}_p$ = the mean emission rate (meanBaseRate) for pollutant $p$ *(for a given model year group, regulatory class and operating mode bin).*

We calculated a mean emission rate, denoted as the “meanBaseRate” in the MOVES emissionRateByAge table, for each combination of regulatory class, model year group, and

---

[a] This analysis is described in more detail in the MOVES2014 heavy-duty exhaust report  However, since we have updated the $f_{scale}$ values used to assign STP bins, the MOVES3 rates are no longer directly comparable (see Presentation by Choi et al. (2012[34]).

[b] For 2003-2006 MHD, the emission rates are different than the 2003-2006 HHD emissions for operating modes 0, 1, 11, 21, and 33. For the other operating modes, the emission rates are equivalent to the HHD emission rates.

operating mode bin combination. 95% confidence intervals of the mean emission rate were calculated by accounting for the variability of the averages across different trucks in a regulatory class and model year group. Examples of mean emission rates are displayed in Figure 2-1. As expected, the emissions increase with power, with the lowest emissions occurring in the idling/coasting/braking bins.

The data included in the emissions analysis does not cover all operating modes or regulatory classes and model year combinations needed for MOVES. In the following sections, we discuss the methods used to fill missing operating mode bins, and missing regulatory class and model year combinations. In addition, we also estimate the impact of low- $NO_x$ rebuilds which were not included in the sampled vehicles. To do so, we rely on the heavy-duty diesel emission standards, as well as engineering knowledge and test data of emission control technologies that were implemented or forecasted to be implemented to meet the standards.

##### *2.1.1.4.1 Light Heavy-Duty Class 2b3 and Classs 4&5 Trucks*

As described in Section 1.5, the LHD regulatory classes were redefined for MOVES3, and the $f_{scale}$ value for 2009-and-earlier LHD2b3 and LHD45 regulatory classes is now 2.06 metric tons.[c] This differs from MOVES2014 where the value for these vehicles was 17.1 metric tons. Thus, it was not possible to carry over the emission rates from MOVES2014. Instead, in MOVES3 and later versions, the 2009-and-earlier LHD2b3 and LHD45 regulatory classes were assigned the same emission rates as the LHD≤10K in MOVES2014.

##### ***2.1.1.4.2*** *High-Power Operating Modes*

As described in Section 1.5, $f_{scale}$ values for MHD and HHD trucks were not changed for model years 2009-and-earlier. Thus, for MHD and HHD trucks, the maximum operating mode (opModeID = 40) represents a tractive power greater than 513 kW (STP= 30 skW × 17.1). This value exceeds the capacity of most HHD vehicles; MHD vehicles and buses exert even less power. Nearly all of the HHD activity occurs in modes 0, 1, 11-16, 21-28, and 33-38, with activity for buses and MHD vehicles usually occurring over an even smaller range.

To estimate emission rates in the modes beyond the ranges of available data, for each model year group we linearly extrapolated the rates from the highest operating mode in each speed range where significant data were collected. In most cases, this mode was mode 16 for the lowest speed range, mode 27 or 28 for the middle speed range, and mode 37 or 38 for the highest speed range. For each of these operating modes, work-specific emissions factors (g/kW-hr) were calculated using the midpoint STP (Table 1-4). Then, these emissions factors were multiplied by the midpoint STP of the higher operating modes (e.g., modes 39 and 40 for speed>50 mph) to input emission rates for the modes lacking data. For the highest bins in each speed range, a “midpoint” STP of 33 skW (564.3 kW) was used. Equation 2-5 displays an example calculation of the emission rate for opModeID 40, using a mean emission rate from opModeID 37, for a given regulatory class and model year group.

---

[c] This is consistent with the 2.06 $f_{scale}$ used to develop LHD2b3 and LHD45 emission rates in MOVES2010.

$$Emission\ Rate_{opModeID\ 40} = Emission\ Rate_{opModeID\ 37} \times \left(\frac{STP_{opModeID\ 40}}{STP_{opModeID\ 37}}\right)$$ **Equation 2-5**

Figure 2-1 shows $NO_x$ emission rates by operating mode for HHD trucks in MY 2002. The mean emission rates for the highest STP operating mode bins (30 and 40) are extrapolated using the method explained above. In addition, the confidence intervals for the extraplolated bins are copied from the closest bin with collected data. However, because the data are extrapolated, the uncertainty of these rates is larger than what is shown by the copied confidence intervals.

Figure 2-2 displays the MY 2002 MHD and Urban Bus regulatory classes emission rates, with the error bars removed for clarity. For these vehicle, less data was captured at the highest operating mode bins, and more of the high speed, high power emission rates were extrapolated, which explains the strictly linear trend in the emission rates between operating mode 27 -30 and 37-40.

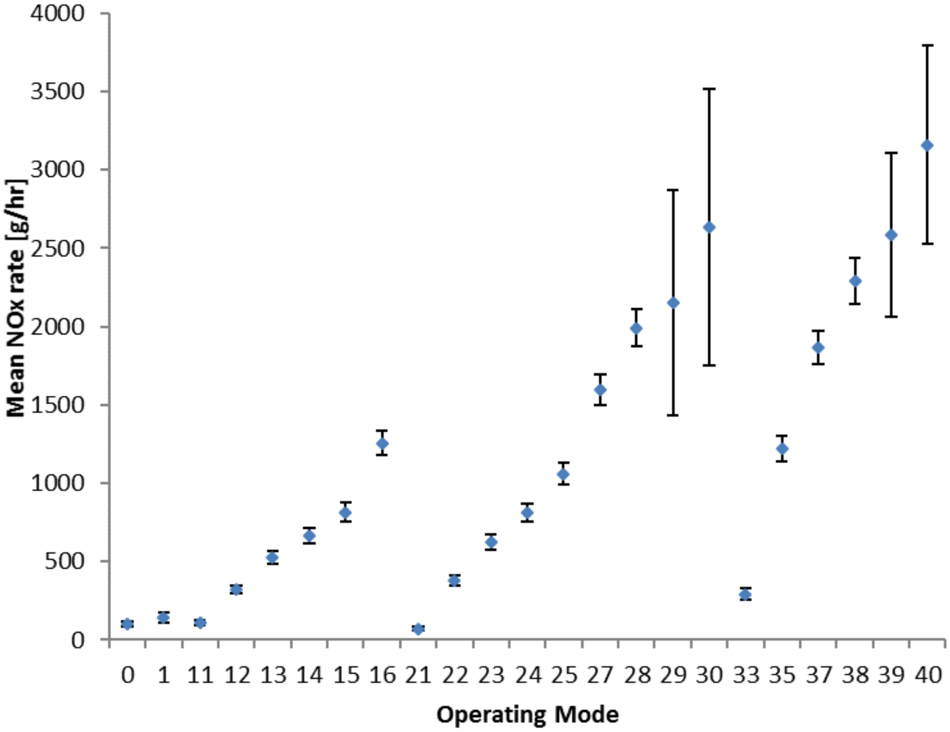

**Figure 2-1 $NO_x$ Emissions by Operating Mode from HHD Trucks for Model Year 2002. Error Bars represent the 95 percent confidence interval of the Mean**

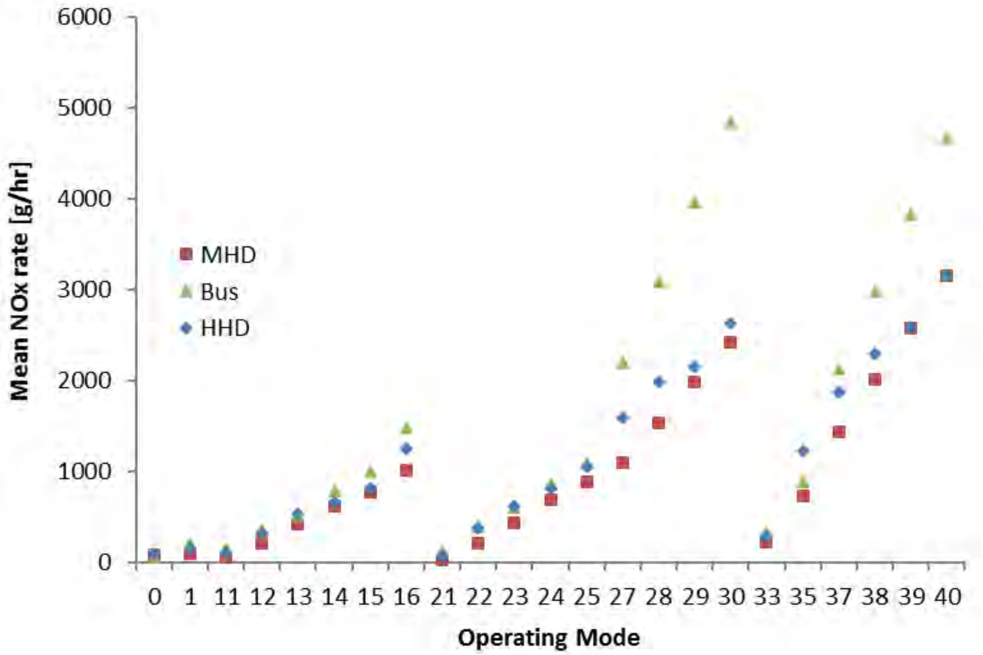

**Figure 2-2 NO$_x$ Emissions by Operating Mode from MHD, HHD, and Urban Bus Regulatory Classes for Model Year 2002.**

#### *2.1.1.4.3 Missing Regulatory Class and Model Year Combinations*

For regulatory class and model year combinations with missing data, we set the emissions equal to regulatory class/model year combinations which had equivalent emission standards or proportionally adjusted the existing emissions data using ratios of certification data or vehicle emission standards as specified in Table 2-1. For HHD model year groups 1988-1989 and 1990, we increased the 1991-1997 model year group emission rates by a factor proportional to the increase of the certification levels as analyzed for MOBILE6.[36] On average, the MY 1990 and MY 1988-1989 rates are 1.055 times and 1.367 times the baseline rates of MY 1991-1997, respectively. We applied the 1988-1989 emission rates to model years 1987 and earlier. For MHD vehicles from MY 1960-1997, we used the HHD emission rates.

For model year 1998, data existed for HHD trucks but not for buses. In these cases, we calculated the rates for Urban Buses by multiplying the Urban Bus emission rates for 1999-2002 by the ratio of HHD emission rates between the 1998 and the 1999-2002 model year groups, as shown in Equation 2-6.

$$Urban\ Bus\ rates_{1998} = \frac{HHD\ rates_{1998}}{HHD\ rates_{1999-2002}} \times Urban\ Bus\ rates_{1999-2002} \qquad \textbf{Equation 2-6}$$

For LHD2b3 and LHD45 vehicles, no data were available for the pre-2003 model year vehicles. For MY 1999-2002, we analyzed MHD engine data using an $f_{scale}$ of 2.06 as appropriate for LHD vehicles (See Table 1-3). For MY 1998, we copied the LHD emission rates from MY group 1999-2002. We also used thse rates as base rates to back-cast emission rates for the 1991-1997 model years, using the ratio of emission standards between these two model-year groups (5.0 g/bhp-hr over 4.0 g/bhp-hr) such that the 1991-1997 rates are 1.25 times the rates for MY 1998.

Table 2-16 provides a summary of the assumptions used to estimate emission rates for regulatory class-model year groups with missing data.

#### *2.1.1.4.4 Defeat Device and Low-NO$_x$ Rebuilds for 1991-1998 Model Year HHD and MHD*

The default emission rates for HHD and MHD diesel vehicles in MOVES for model years 1991 through 1998 are intended to include the effects of defeat devices as well as the benefits of heavy-duty low-NO$_x$ rebuilds (commonly called reflash) that occurred as the result of the heavy-duty diesel consent decree.[14] Reflashes reduce NO$_x$ emissions from these engines by reconfiguring certain engine calibrations, such as fuel injection timing.

Since defeat devices were in effect mostly during highway or steady cruising operation, we assumed that NO$_x$ emissions were elevated for only the top two speed ranges in the running exhaust operating modes (>25mph). To modify the relevant emission rates to represent reflash programs, we first used emission rates from model year 1999 (the first model year with not-to-exceed emission limits, see Table 1-2) to calculate baseline ratios of the emission rates for operating modes 27 and 37 to the rate for opMode 16 (as discussed in the beginning of Section 2.1.1.4). We then multiplied the MY 1999 ratios by the emission rates in operating mode 16 for model years 1991 through 1998, to get estimated “reflashed” emission rates for operating modes 27 and 37. This step is described in Equation 2-7 and Equation 2-8. To estimate “reflashed” rates in the remaining operating modes, we multiplied the reflashed rates by ratios of the remaining operating modes to mode 27 for MY 1991-1998, as shown in Equation 2-9 and Equation 2-10. The second step preserves the relationship among operating mode 21 and operating modes 21-30, and among operating mode 37 and operating modes 31-40, that existed in the original 1991-1998 data.

.

Where: operating modes (OM) 21-30

$$\bar{r}_{reflash,91-98,27} = \bar{r}_{91-98,16}\left(\frac{\bar{r}_{1999,27}}{\bar{r}_{1999,16}}\right)$$

**Equation 2-7**

$$\bar{r}_{reflash,91-98,\mathrm{OM}x} = \bar{r}_{reflash,91-98,27}\left(\frac{\bar{r}_{91-98,\mathrm{OM}x}}{\bar{r}_{91-98,27}}\right)$$

**Equation 2-8**

Where: operating modes (OM) 31-40

$$\bar{r}_{reflash,91-98,37} = \bar{r}_{91-98,16}\left(\frac{\bar{r}_{1999,37}}{\bar{r}_{1999,16}}\right)$$

**Equation 2-9**

$$\bar{r}_{reflash,MY1991-1998,OMx} = \bar{r}_{reflash,91-98,37}\left(\frac{\bar{r}_{91-98,\mathrm{OM}x}}{\bar{r}_{91-98,37}}\right)$$

**Equation 2-10**

Because the reflash occurred over time after the engines were sold, we phase-in the reflash rates with age. An EPA assessment shows that about 20 percent of all vehicles eligible for reflash had been reflashed by the end of 2008.[37] We assumed that vehicles were reflashed at a steady rate from the time of the consent decree (1999/2000 calendar year), such that in 2008, about 20 percent had been reflashed. Figure 2-3 displays the results of the reflash calculations on the HHD fleet-average emission rate for operating mode 37. For model years 1994-1997 and 1998, we approximated a linear increase in reflash rate from age zero to the age 20+ age group. For model years 1991-1993, the adjustments do not start until calendar year 2001, when the 1991 model years exist in the age 10-15 group. When all of the 1991-1998 vehicles have reached the age 20+ group (CY 2018), MOVES assumes that close to 30% of all the 1991-1998 engines have been reflashed. The reflashed HHD 1991-1998 MY emission rates were also applied to the 1991-1998 MHD diesel emission rates. Note that there are no tampering and mal-maintenance aging effects in MOVES for pre-2010 $NO_x$ emission rates. Thus, the only change in the $NO_x$ emission rates by vehicle age for these model years is due to reflashing.

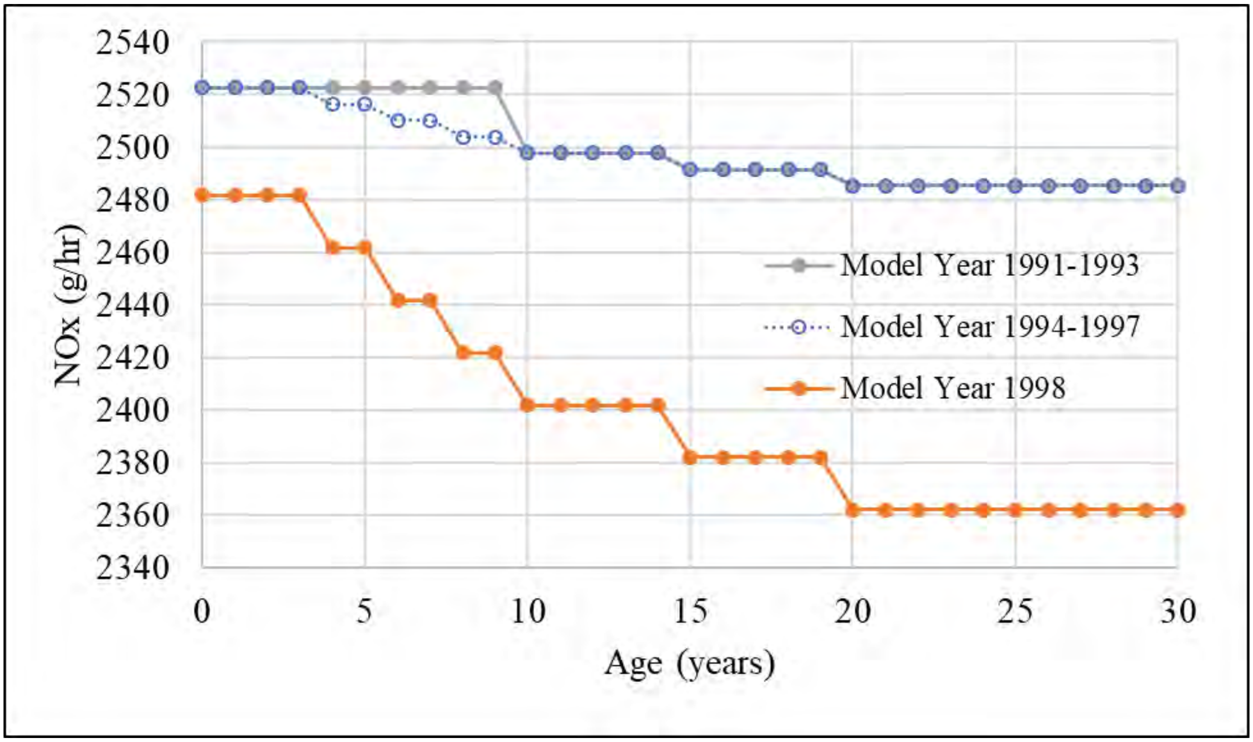

**Figure 2-3. HHD $NO_x$ emission rates for OpModeID 37 for Model Years 1991-1998 Adjusted for Low-$NO_x$ Rebuilds by Vehicle Age**

#### ***2.1.1.4.5 2007-2009 Model Year HHD, MHD, and Urban Bus***

The 2007 Heavy-Duty Rule[108] required the use of ultra-low sulfur diesel fuel; this fuel enabled diesel engines with diesel particulate filters to reach the 0.01 g/bhp-hr PM standard beginning in 2007. In addition, the 2007 Heavy-Duty Rule[108] established much tighter $NO_x$ emission standards (0.2 g/bhp-hr). While the $NO_x$ standard went into effect for MY 2007 at 0.2 g/bhp-hr, it was phased in over a three-year period ending in MY 2010. Rather than phasing in the aftertreatment technology needed to meet the new standard, most manufacturers chose to meet a 1.2 g/bhp-hr standard for MY 2007-2009 (down from 2.4 g/bhp-hr in 2006), which did not require $NO_x$ aftertreatment. For the 2007-2009 HHD, we used the data from the HDIUT program. For the $NO_x$ emission rates within the 2007-2009 model year group for MHD and Urban Bus, we assumed that the $NO_x$ emission rates were 50 percent lower than the corresponding Rover and Consent Decree derived 2003-2006 emissions (proportional to the reduction in the $NO_x$ emission standards mentioned above). The MHD MY 2007-2009 rates are consistent with $NO_x$ emission rates measured from 2007-2009 MHD trucks measured in HDIUT.[35]

##### ***2.1.1.4.6*** *2007-2009 Model Year LHD45 and LHD2b3*

For LHD2b3 trucks in 2007-2009, we accounted for the penetration of Lean $NO_x$ Trap technology. Cummins began using Lean $NO_x$ Trap (LNT) aftertreatment starting in 2007 in engines designed to meet the 2010 standard in vehicles such as the Dodge Ram. This technology allows for the storage of $NO_x$ during fuel-lean operation and conversion of stored $NO_x$ into $N_2$ and $H_2O$ during brief periods of fuel-rich operation. In addition, to meet particulate standards in MY 2007 and later, heavy-duty vehicles are equipped with diesel particulate filters (DPF). The DPF must be regenerated at regular intervals to remove and combust accumulated PM to relieve backpressure and ensure proper engine operation. This step requires high exhaust temperatures. However, these conditions adversely affect the LNT's $NO_x$ storage ability, resulting in elevated $NO_x$ emissions.

In order to determine the fraction of time that DPFs spend in PM regeneration mode, in 2007, EPA acquired a truck equipped with a LNT and a DPF and performed local onroad measurements using portable instrumentation and chassis dynamometer tests. We distinguished regimes of PM regeneration from normal operation based on operating characteristics, such as exhaust temperature, air-fuel ratio, and ECU signals. During the testing conducted onroad with onboard emission measurement and on the chassis dynamometer, we observed a PM regeneration frequency of approximately 10 percent of the operating time.

Emissions from this vehicle were not directly used to calculate MOVES emission rates, because only one vehicle was tested. Rather, to estimate average emissions of LHD2b3 vehicles with LNT, we calculated a ratio to the MOVES2010[d] MY 2003-2006 $NO_x$ emission rates. During DPF regeneration, we assumed that the LNT did not reduce emissions from 2003-2006 levels. During all other times, we assumed that emissions were reduced by the percent reduction in the certification standards from 2003-2006 levels (i.e., 90 percent). These assumptions result in an estimated $NO_x$ reduction of 81 percent for LNT equipped trucks from 2003-2006 to 2007-2009, as shown in Equation 2-11.

---

[d] In MOVES2014, we updated the diesel $NO_x$ emission rates for 2003-2006 based on the HDIUT program.

$$
\begin{aligned}
&\frac{LNT\ LHD2b3\ NOx\ emissions}{Baseline\ Emissions} \\
&\qquad = (normal\ op.frequency) \times \left(\frac{LNT\ normal\ emissions}{Baseline\ Emissions}\right) \\
&\qquad + (DPF\ reg.frequency) \times \left(\frac{Baseline\ Emissions}{Baseline\ Emissions}\right) \\
&\qquad = (0.90) \times (0.10)\ + (0.10) \times (1) = 0.19
\end{aligned}
\tag{Equation 2-11}
$$

*Where Baseline Emissions = MOVES2010 MY 2003-2006 NO*$_x$ *emission rates for LHD2b3*

We weighted the average rates for the LHD2b3 regulatory class (regClassID 41) for model years 2007-2009 assuming that LNT-equipped trucks account for 25 percent of the LHD2b3 diesel vehicles. We assume that the remaining 75 percent of MY 2007-2009 LHD2b3 diesel trucks will not have LNT aftertreatment and will exhibit a 50% NO$_x$ reduction from the 2003-2006 model year emission rates as was assumed for the HHD and MHD described in the previous section. Overall, these assumptions result in a 58 percent reduction in NO$_x$ emission rates in the model year 2007-2009 emission rates from the MOVES2010 MY 2003-2006 NO$_x$ emission rates as shown in Equation 2-12.

$$
\begin{aligned}
&\frac{2007 - 2009\ LHD2b3\ NOx\ emissions}{Baseline\ emissions} \\
&\qquad = (LNT\ market\ share) \left(\frac{LNT\ NOx\ emissions}{Baseline\ Emissions}\right) \\
&\qquad + (non \\
&\qquad - LNT\ market\ share) \left(\frac{2007 - 2009\ emission\ standards}{Baseline\ Emissions}\right) \\
&\qquad = (0.25) \times (0.19)\ + (0.75) \times (0.5) = 0.4225
\end{aligned}
\tag{Equation 2-12}
$$

*Where Baseline Emissions = MOVES2010 MY 2003-2006 NO*$_x$ *emission rates for LHD2b3*

In the absence of other data, we applied the LHD2b3 emission rates to LHD45 vehicles. Newer data shows that LNT is not being used in LHD45 vehicles, however, we have not updated this assumption because the LHD results compare well to the HDIUT data.[34]

#### ***2.1.1.5*** *2010-2026 Model Years*

In MOVES3 and later versions, the MY 2010-2026 emission rates for HHD, MHD, Urban Bus, and LHD45, and LHD2b3 are based on analysis of the HDIUT data and model-year specific production volume weighting for each model year from 2010 through 2018. The rates for HHD, MHD, and the two LHD classes use data from vehicles with HHD, MHD, and LHD engines, respectively. The NO$_x$ emission rates are projected to remain constant for MY 2018 and later vehicles for regulatory classes HHD, MHD, Urban Buses, and LHD45. The LHD2b3 trucks are projected to have a further decrease in NO$_x$ emissions through the implementation of the Tier 3 program as discussed in Section 2.1.1.5.5.

In calculating the mean emission rates for MY 2010+ vehicles, we made several additions to the method presented for the pre-2010 model years described in Section 2.1.1.4:

1. For a given regulatory class (HHD, MHD, LHD), we grouped the vehicles in the HDIUT data set into three $NO_x$ family emission limit (FEL)[e] groups as detailed in Section 2.1.1.5.1 below.
2. Within the $NO_x$ FEL group and regulatory classes, we grouped vehicles into model year groups as detailed in Section 2.1.1.5.2.
3. We calculated the operating mode-based average emission rate for each vehicle by regulatory class, $NO_x$ FEL group, and model year group (Equation 2-13). Then, we calculated the operating mode-based average emission rate for all vehicles in the $NO_x$ FEL group and model year group (Equation 2-14).
4. We weighted the operating mode-based average emission rates for each of the $NO_x$ FEL groups, and model year group within each regulatory class by the model year specific production volumes of the engines in the $NO_x$ FEL group to the total production volume of the regulatory class (Equation 2-15). Thus, we created operating mode-based average emission rates for each model year and regulatory class.

$$ER_{pol,OM,C,FEL,MYG,veh} = \frac{\sum_{sec} ER_{pol,OM,C,FEL,MYG,veh,sec}}{sec_{count}}$$ **Equation 2-13**

$$ER_{pol,OM,C,FEL,MYG} = \frac{\sum_{veh} ER_{pol,OM,C,FEL,MYG,veh}}{veh_{count}}$$ **Equation 2-14**

$$ER_{pol,OM,C,MYG,MY} = \sum_{FEL}\left(ER_{pol,OM,C,FEL,MYG} * \frac{PV_{C,MY,FEL}}{\sum_{FEL} PV_{C,MY,FEL}}\right)$$ **Equation 2-15**

Where:

| | |
|---|---|
| C | = Regulatory class (LHD, MHD, HHD, and Urban Bus) |
| ERx,y,z | = Emission rate in mass/time. The subscripts show the categorization. |
| FEL | = $NO_x$ FEL group of engine (0.20 g/bhp-hr, 0.35 g/bhp-hr, and 0.50 g/bhp-hr) |
| MYG | = Model year group (2010-2013, 2014-2016) |
| MY | = Model year |
| OM | = Running exhaust emissions operating mode |
| pol | = Pollutant ($NO_x$, THC, CO) |
| $PV_{C,MY,FEL}$ | = Production volume by class, model year, and FEL group |
| sec; $sec_{count}$ | = a second of data (for a given *veh* and *OM*); number of seconds in that category |
| veh; $veh_{count}$ | = a vehicle (in the class and FEL grouping); number of vehicles in that category |

Figure 2-4 displays the average $NO_x$ emission rates using the described method for HHD model year 2013 vehicles. To calculate the 95% confidence intervals for the model years, the confidence intervals were first calculated for each FEL group, treating the mean emission rate by operating

---

[e] A Family Emission Limit is the maximum emission level established by a manufacturer for the certification of an engine family.

mode from each individual truck as an independent random variable. Then, the confidence interals from the different FEL groups were weighted together using the production volumes, similar to how the means were calculated.

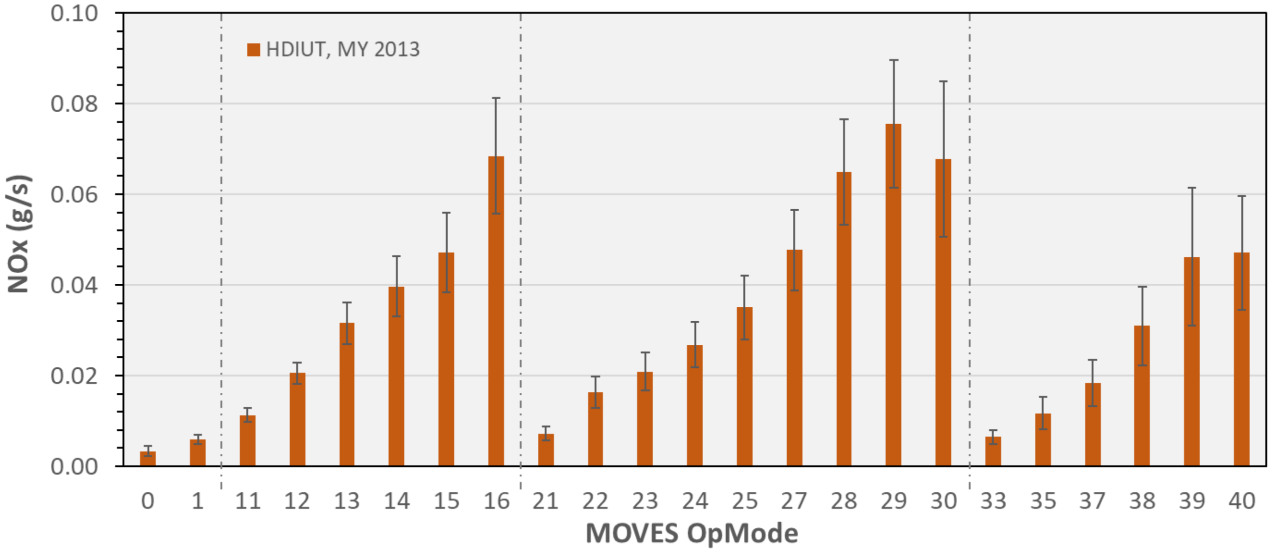

**Figure 2-4 $NO_x$ Emissions by Operating Mode from HHD Trucks for Model Year 2013. Error Bars represent the 95 percent confidence interval of the Mean**

More details about the selection of the $NO_x$ FEL groupings, updated $f_{scale}$ values, and the methods for the production volume weighting are provided in Section 2.1.1.5.1 through 2.1.1.5.4 below.

#### *2.1.1.5.1 $NO_x$ Family Emission Level Groups*

We grouped engines, within a regulatory class, by their $NO_x$ FEL. These groups are shown in Table 2-6.

**Table 2-6 $NO_x$ Family Emission Limit (FEL) based Groups for LHD, MHD, HHD, and Urban Bus Classes in the HDIUT Data**

| Group Name | Range of $NO_x$ FEL (g/bhp-hr) | |
|---|---|---|
| | Lower Limit (Excluded) | Upper Limit (Included) |
| 0.20 | 0.00 | 0.20 |
| 0.35 | 0.20 | 0.35 |
| 0.50 | 0.35 | 0.50 |

Each test vehicle, within a regulatory class, was assigned to one of these three groups. These groupings were applied not only to $NO_x$, but to all pollutants for emission rate calculations. We chose to use $NO_x$ as the basis for creation of these groups because data for $NO_x$ FEL is most abundant in the heavy-duty engine certification database and, for MY 2010-2015 engines, the biggest technology changes and tailpipe exhaust emissions impacts are due to emissions control measures for $NO_x$. We arrived at the specific group bins based on the spread of $NO_x$ FELs for MY 2010-2015 engine families reported in the certification database available at the time of the analysis (not just the engine families tested under the HDIUT program). The $NO_x$ FELs for MY 2010-2015 HD diesel engine families in the certification database are shown in Figure 2-5. As highlighted by the shaded rectangles, most of the engine families are concentrated in the 0.05–0.20, 0.30–0.35, and 0.45–0.50 bands and this trend guided our bin choices, represented by the curly braces, for the three $NO_x$ FEL groups.

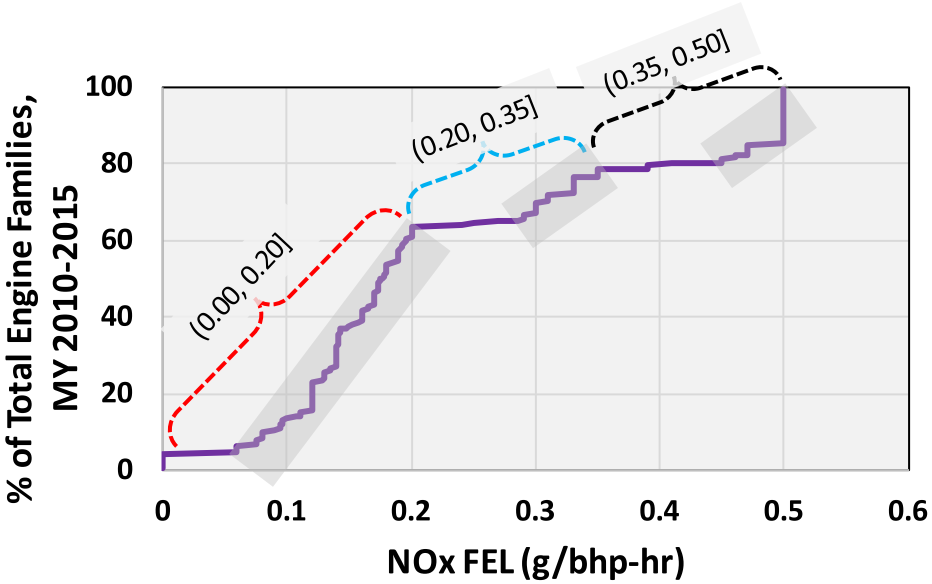

**Figure 2-5 Distribution of $NO_x$ Family Emission Limit (FEL) for Model Year 2010 -2015 Heavy-Duty Diesel Engine Families, as Reported in the Certification Database**

Table 2-7 shows the number of vehicles by regulatory class and $NO_x$ FEL group for MY2010+ engines in the HDIUT program. The number of vehicles by regulatory class in this table match the number of vehicles in Table 2-2. The 10 Urban Bus vehicles in the HDIUT data set were not used in MOVES because they only represented one engine family. The Urban Bus emission rates are set equal to the HHD emission rates because: Urban Buses are in the same GVWR class as HHD; some engines certified as HHD are used in the Urban Bus application; and there is no separate $NO_x$ standard (for MY 2010+) for the Urban Bus regulatory class.

**Table 2-7 Number of 2010 and Later Model Year HDIUT Vehicles by $NO_x$ FEL Group and Model Year Groups[1] Used for Emission Rate Analysis**

| | $NO_x$ FEL Group | | | | |
|---|---|---|---|---|---|
| | 0.2 | | 0.35 | 0.5 | |
| | MY 2010-2013 | MY 2014-2016 | MY 2010-2016 | MY 2010-2016 | Total |
| LHD[2] | 52 | 27 | 0 | 15 | 94 |
| MHD | 19 | 23 | 23 | 9 | 74 |
| HHD[3] | 78 | 50 | 31 | 35 | 194 |
| Total | 149 | 100 | 54 | 59 | 362 |

NOTE:

[1] THC, CO, and $CO_2$ emission rates were analyzed using the same model year groups. Sample size is generally the same, with a few exceptions for vehicles with invalid pollutant measurements for one or more pollutant. For example, one of the MHD 0.35 $NO_x$ FEL vehicles did not have $NO_x$ measurements.

[2] LHD data for the 0.2 FEL group includes MY up to MY 2016. MHD and HHD data for the 0.2 FEL group only include up to MY 2015

[3] The HHD 0.35 group contains five MY 2009 vehicles, which have similar $NO_x$ emission rates as the other vehicles in this group.

The average $NO_x$ emission rates for the 0.2 $NO_x$ FEL Group for model year 2010-2013, compared to the 0.35 and 0.5 $NO_x$ FEL Groups are shown below for LHD (Figure 2-6), MHD (Figure 2-7) and HHD (Figure 2-8). Because the 0.35 and 0.5 $NO_x$ FEL groups do not have a model year distinction like the 0.2 $NO_x$ FEL group, the figures display all the available MY 2010 and later vehicles for the 0.35 and 0.5 $NO_x$ FEL groups.

As shown, the $NO_x$ emission rates in the 0.2 $NO_x$ FEL Group and model year 2010-2013 are consistently lower than those in the 0.35 and 0.50 $NO_x$ FEL groups, with a few minor exceptions. In addition, for many operating mode and regulatory class combinations, the $NO_x$ emission rates in the 0.2 $NO_x$ FEL Group are statistically significantly lower than the $NO_x$ emission rates in the 0.35 and 0.5 $NO_x$ FEL Groups. However, no such trend exists in the $NO_x$ emission rates for the 0.35 and the 0.5 $NO_x$ FEL groups. In general, the $NO_x$ emission rates in the 0.35 and the 0.5 $NO_x$ FEL groups are not statistically different than one another by operating mode for the MHD and HHD regulatory classes.

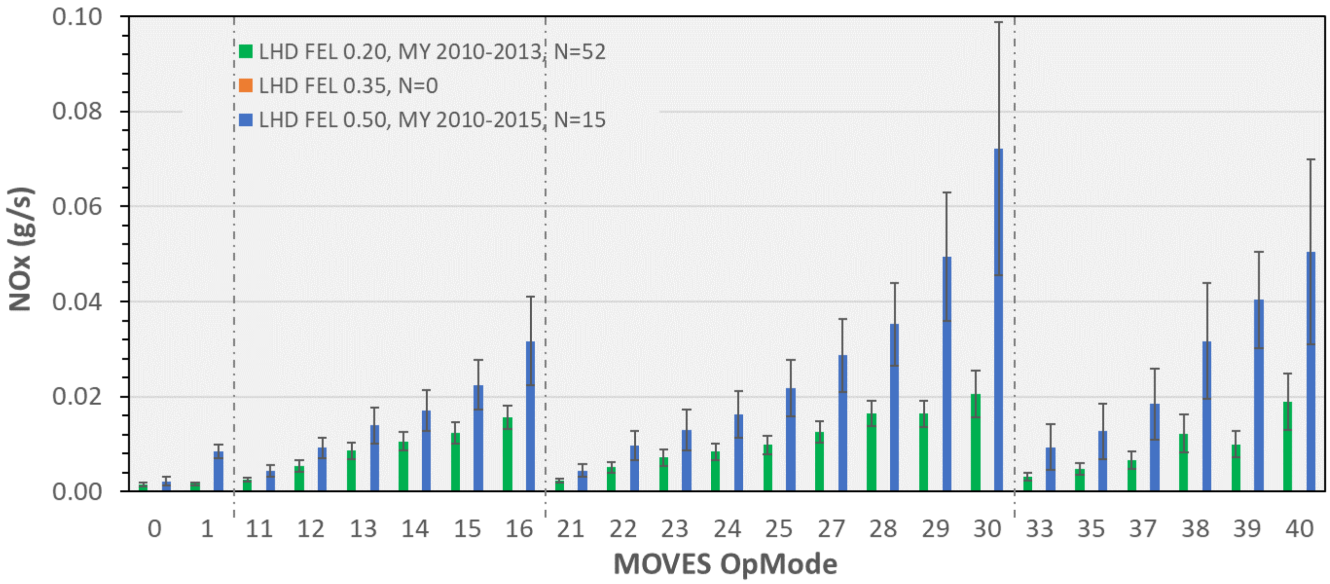

**Figure 2-6 Average LHD NO$_x$ Emission Rates by Operating Mode for the 0.2 NO$_x$ FEL for MY 2010-2013 and the 0.5 NO$_x$ FEL for MY 2010-2015. Error Bars are 95% Confidence Intervals of the Mean**

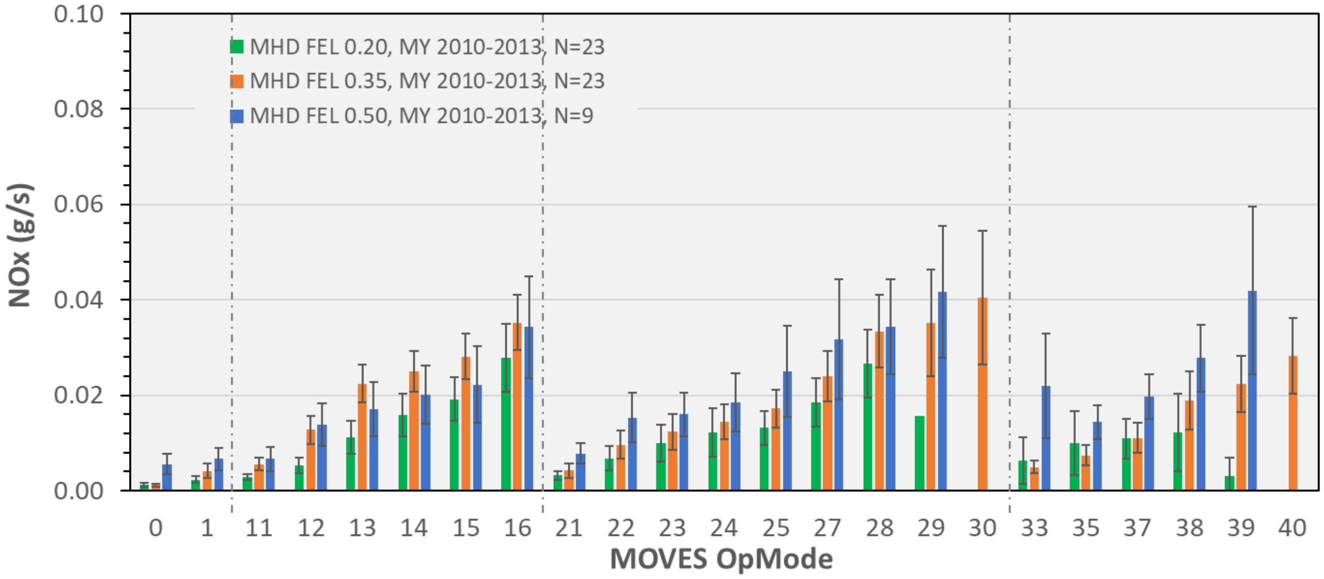

**Figure 2-7 Average MHD NO$_x$ Emission Rates by Operating Mode for the 0.2, 0.35 and 0.50 NO$_x$ FEL Groups for MY 2010-2013 Vehicles. Error Bars are 95% Confidence Intervals of the Mean**

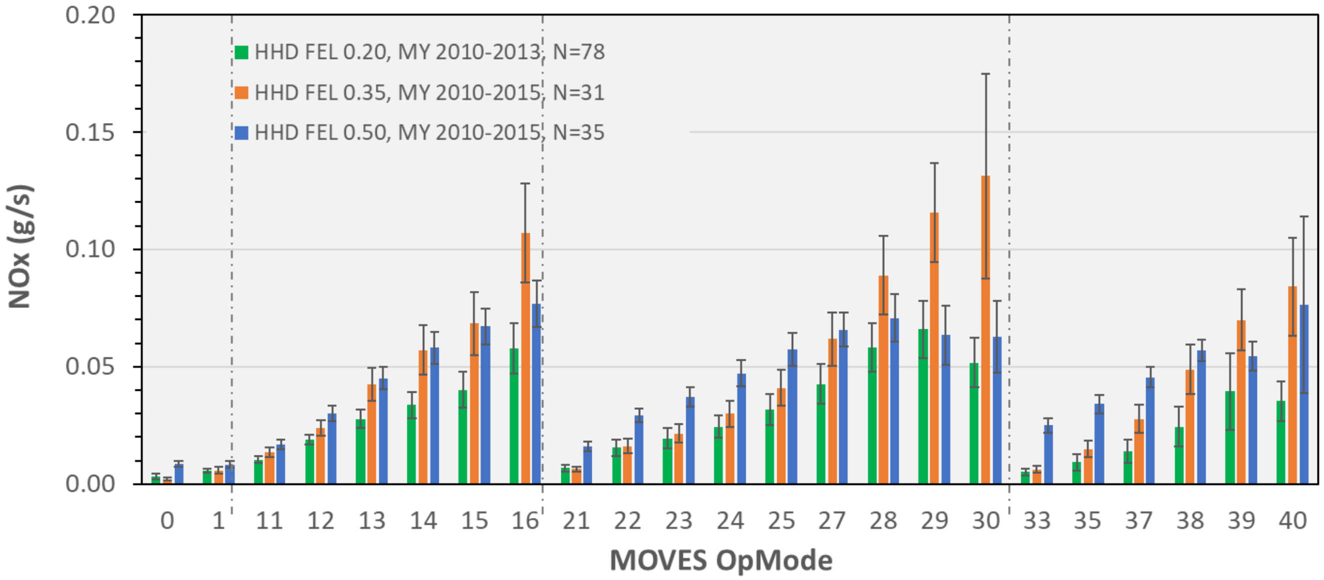

**Figure 2-8 Average HHD $NO_x$ Emission Rates by Operating Mode for the 0.2 $NO_x$ FEL for MY 2010-2013 and the 0.35 and 0.5 $NO_x$ FEL for MY 2010-2015. Error Bars are 95% Confidence Intervals of the Mean**

###### 2.1.1.5.2 *Model Year Groups within the 0.2 $NO_x$ FEL Group*

We grouped the vehicles within the 0.2 $NO_x$ FEL Group further into 2010-2013 and 2014 and later model year groups to account for differences in emissions performance of more recent engines and aftertreatment systems. In a subsequent update for MOVES3 based on studies[49,50,51] that suggested SCR control had improved, we were able to incorporate data from MY 2014-2016 engines to evaluate this recommendation.

Table 2-7 displays the model year groupings used in developing MOVES emission rates by $NO_x$ FEL groups and pollutant. For $NO_x$, THC, CO, and $CO_2$, we grouped 0.2 $NO_x$ FEL group into two model year groups given the sufficient sample size. Within the 0.35 and 0.5 $NO_x$ FEL groups, we only have a single model year group (2010 and later) due to the smaller sample size of HDIUT test vehicles in these groups. For example, for the MHD regulatory class, the HDIUT data set only includes MY 2010-2013 vehicles in the 0.35 and 0.5 $NO_x$ FEL Group (see Table 2-29). Aside from the small sample size, we believe it is defensible to have single model year groups for the 0.35 and 0.5 $NO_x$ FEL groups for two additional reasons. First, with the exception of the 0.35 $NO_x$ FEL Group for MHD, heavy-duty vehicle manufacturers are no longer producing engines certified in the 0.35 or 0.5 $NO_x$ FEL groups beyond MY 2017. Second, we anticipate the MY 2014-2017 MHD engines certified to the 0.35 $NO_x$ FEL group would have similar emission control technology as earlier MY 2010-2013 vehicles certified to the same emission levels. For these reasons, we believe it is reasonable to use only one model year group for the 0.35 and 0.5 $NO_x$ FEL groups, within each regulatory class.

A comparison of the emission rates for the 0.2 $NO_x$ FEL Group by model year group and regulatory class are shown in Figure 2-9 through Figure 2-11. For the LHD vehicles, the $NO_x$ emission rates for MY 2014 and later are lower than the MY 2010-2013 vehicles, with some of the differences being statistically significant. For the MHD and HHD regulatory classes, no significant differences in the NO$_x$ emission rates between the two model year groups are observed across operating modes. In contrast, significant differences are observed for THC and CO emissions for the MHD and HHD regulatory classes between the MY 2010-2013 and MY 2014-2015 model year groups as discussed in Section 2.1.3.2. Even though the differences in NO$_x$ emission rates across regulatory classes and the model year groups were not statistically significant, we separated the 0.2 NO$_x$ FEL group for all three regulatory classes into two model year groups (2010-2013 and 2014 and later) to be consistent in our analysis for all pollutants, and to account for the potential differences in real-world NO$_x$ emissions performance due to the updated engine and aftertreatment systems

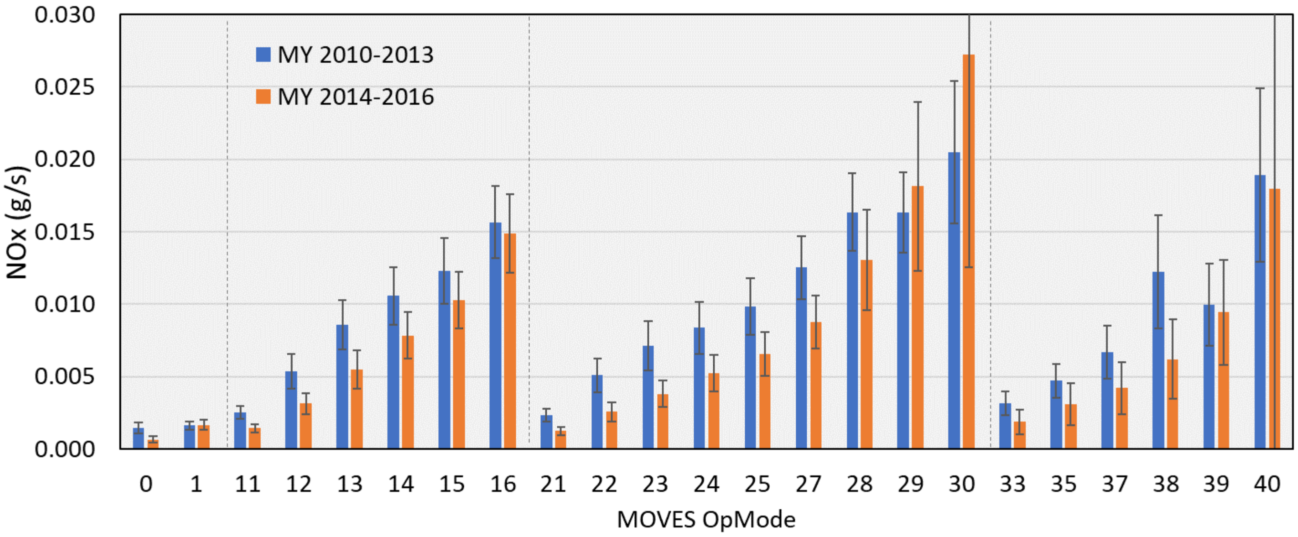

**Figure 2-9 NO$_x$ emission rates for the MY 2010-2013 and MY 2014-2016 vehicles in the LHD 0.20 NO$_x$ FEL Group**

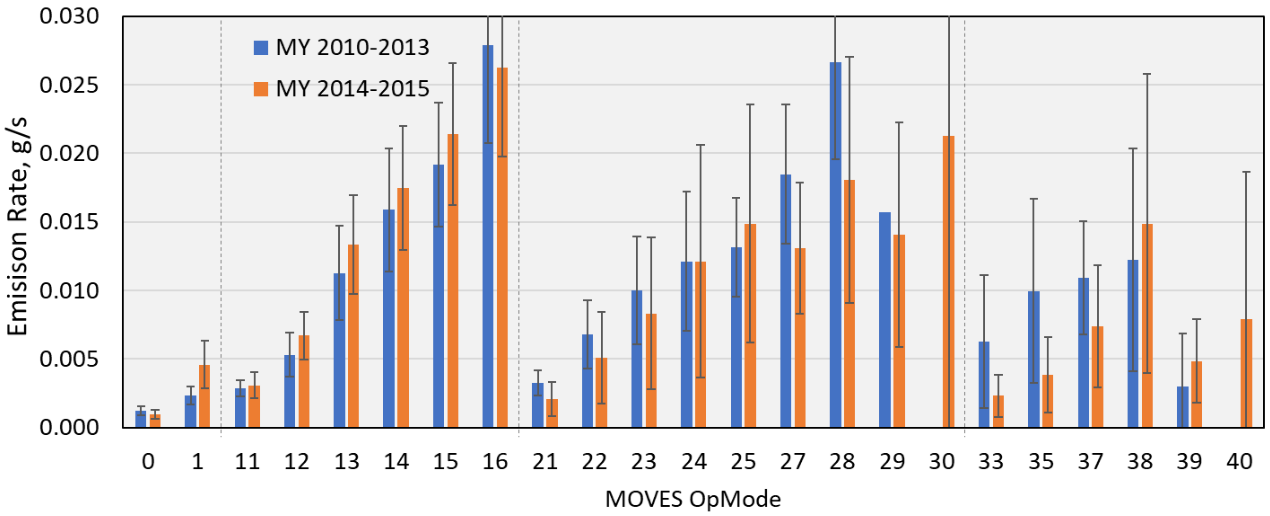

**Figure 2-10 NO$_x$ emission rates for the MY 2010-2013 and MY 2014-2015 vehicles in the MHD 0.20 NO$_x$ FEL Group**

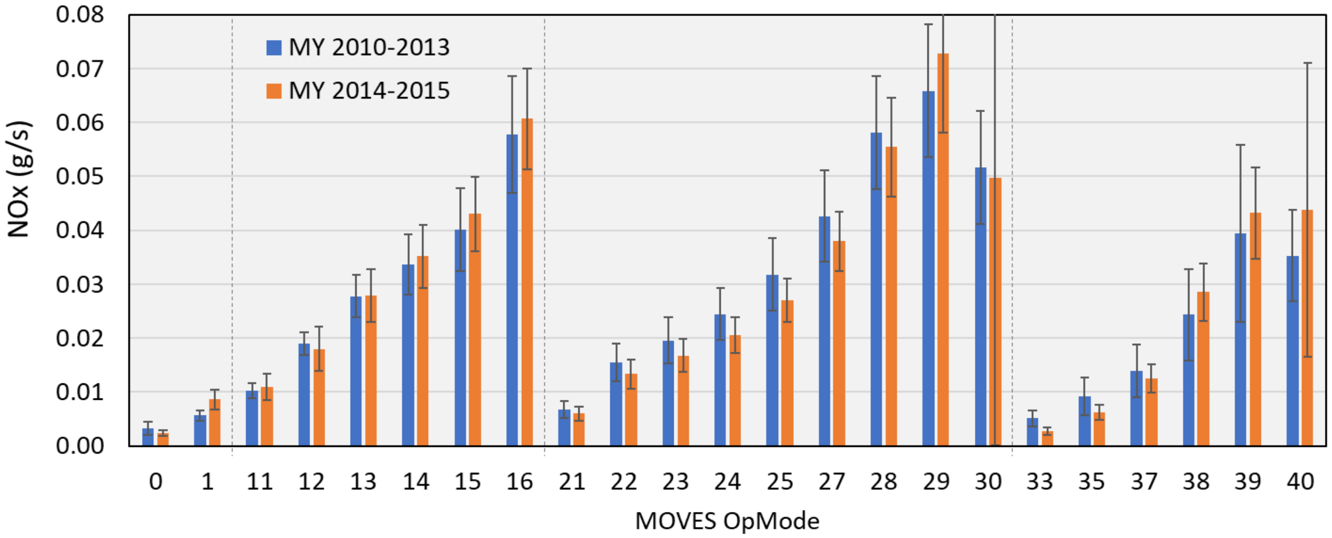

**Figure 2-11 NO NO$_x$ emission rates for the MY 2010-2013 and MY 2014-2015 vehicles in the HHD 0.20 NO$_x$ FEL Group**

#### *2.1.1.5.3 Weighting by Production Volume*

We collected production volume data by the same regulatory classes (LHD, MHD, HHD, Urban Bus) and NO$_x$ FEL groups (0.20, 0.35, 0.50) that we used for the emission rate analysis. We then combined the NO$_x$ FEL group-based rates (averaged within the model year groups described above) with the production volume data (distinct for each model year) to create emission rates unique to each model year. We did this for each model year from 2010 through 2018 (the last model year for which we have production volume data). For MY 2019 and later, we used the same production volume weighting as MY 2018. The per-model-year production volume weighting, by regulatory class and NO$_x$ FEL groups, is shown in Figure 2-12. This method allows us to better represent the technology adoption landscape in the heavy-duty domain. For example, for HHD, model years 2010 through 2013 had engines with NO$_x$ FEL in the 0.50 group (0.35 g/bhp-hr < NO$_x$ FEL ≤ 0.50 g/bhp-hr), but starting with model year 2014, there are no engines in the 0.50 group. Compared to engines in the 0.20 group and 0.35 group, engines in the 0.50 group predominantly use a different emissions control strategy to reduce tailpipe NO$_x$ emissions. Thus, our approach using the NO$_x$ FEL groups and per-model-year production volume correctly captures the prevalence and influence (on emissions) of different technologies in the fleet. Production volume percent contributions of the three NO$_x$ FEL groups sum to 100 percent of the production volume for each regulatory class and model year.

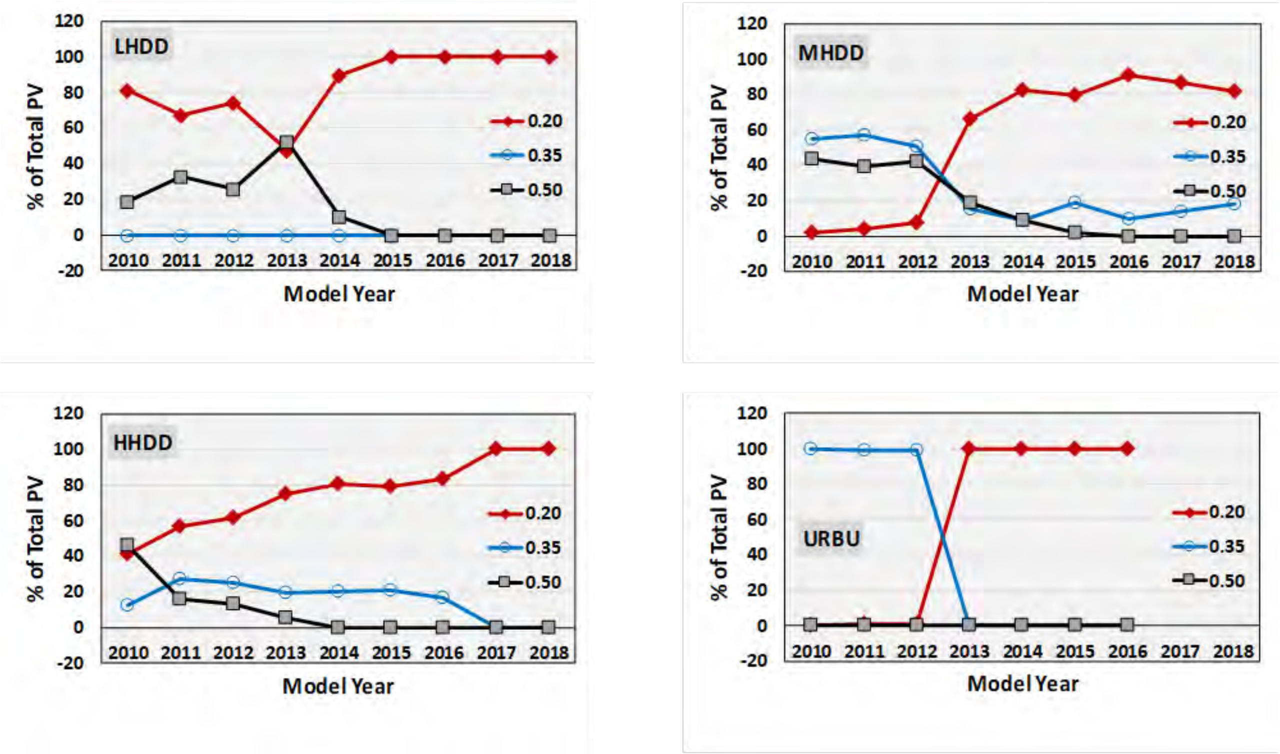

**Figure 2-12 Production Volume Contribution of Heavy-Duty Diesel Engine Families by $NO_x$ Family Emission Limit Group for Each Regulatory Class**

### *2.1.1.5.4 Operating Modes and $f_{scale}$ Values*

For the updates to THC, CO, $NO_x$, $PM_{2.5}$, and energy rates for MY 2010-2026 HD vehicles, we used new $f_{scale}$ values (see Table 1-3 and Appendix G) that allowed all OpModes to be populated with rates based on real-world data. Thus, there was no need to perform the hole-filling approach used to populate the high-power operating modes for the pre-2010 MY vehicles (see 2.1.1.4.2).

Figure 2-13 to Figure 2-15 show the effect of the new $f_{scale}$ values on OpMode coverage using the example of $NO_x$ emission rates for the vehicles in the $NO_x$ FEL=0.20 group for LHD, MHD, and HHD regulatory classes, respectively.[f] Note that the absolute mass/time OpMode-based emissions rates between the two series based on different $f_{scale}$ cannot be compared. The main benefit of the new $f_{scale}$ values is that all the operating modes are populated even if the trends may not be perfectly monotonically increasing for each pollutant in a regulatory class. The comparison is similar for the 0.35 and 0.50 $NO_x$ FEL groups. Note the final rates input into MOVES are estimated as production volume weighted rates from each of the $NO_x$ FEL groups.

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[f] These plots were generated using model year 2010-2015 HDIUT data that was available at the time of the analysis. The final emission rates were developed using the complete HDIUT data that includes both MY 2010-2015 and MY 2016-2018.

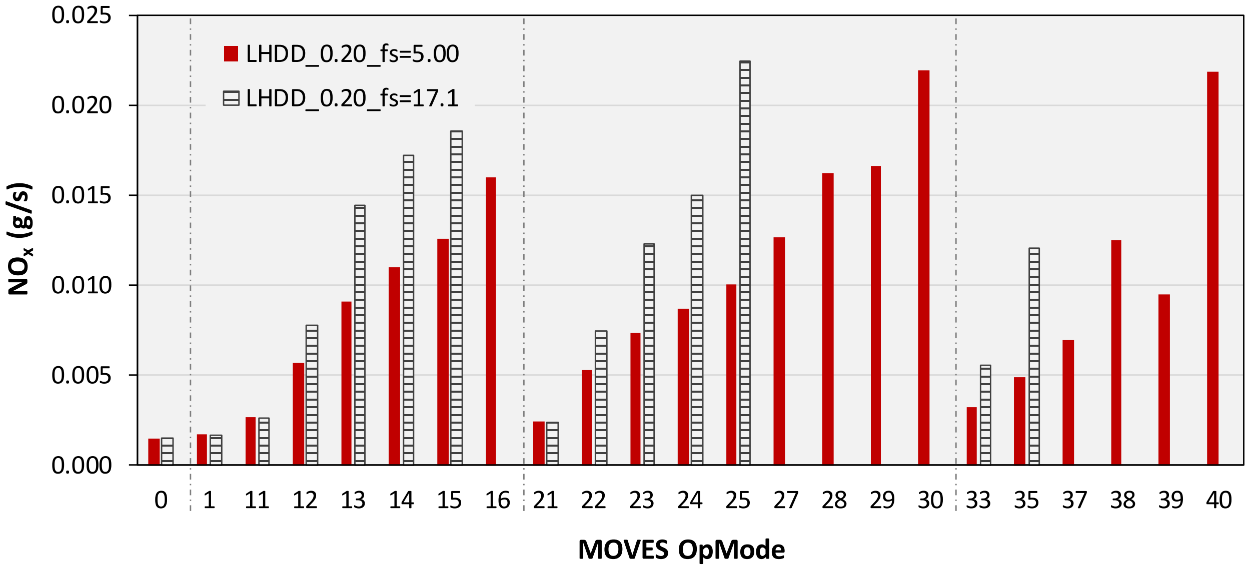

**Figure 2-13 Effect of MOVES2014 (17.1) and MOVES3 (5.00) $f_{scale}$ Values on OpMode Coverage for $NO_x$ Emission Rates for Light Heavy-Duty Vehicles in the $NO_x$ FEL = 0.20 Group**

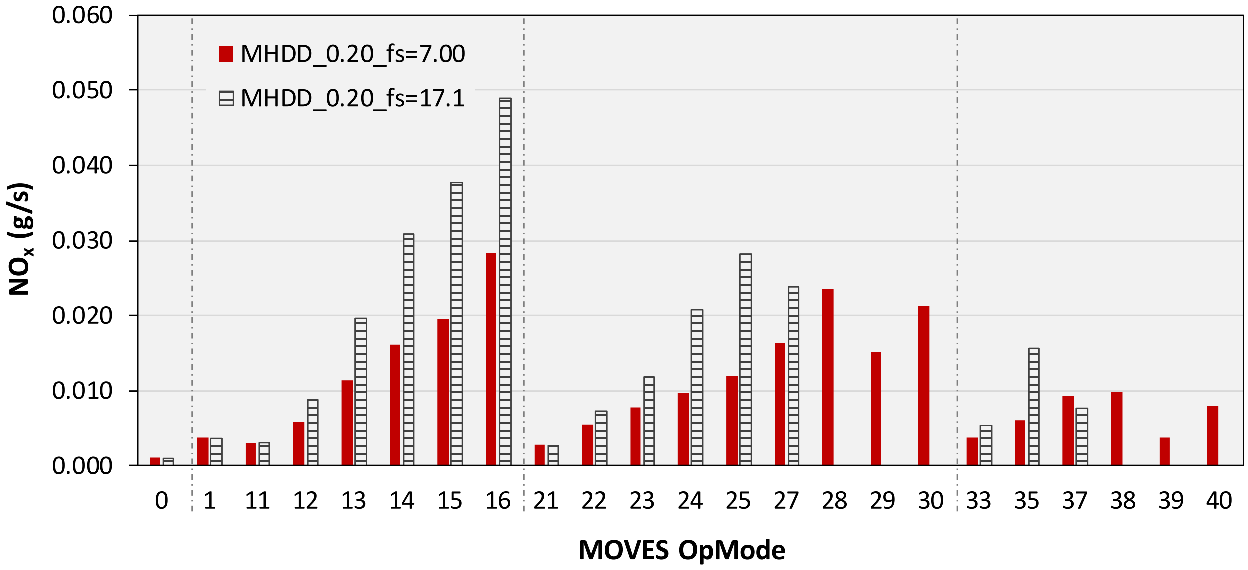

**Figure 2-14 Effect of MOVES2014 (17.1) and MOVES3 (7.00) $f_{scale}$ Value on OpMode Coverage for $NO_x$ Emission Rates for Medium Heavy-Duty Vehicles in the $NO_x$ FEL = 0.20 Group**

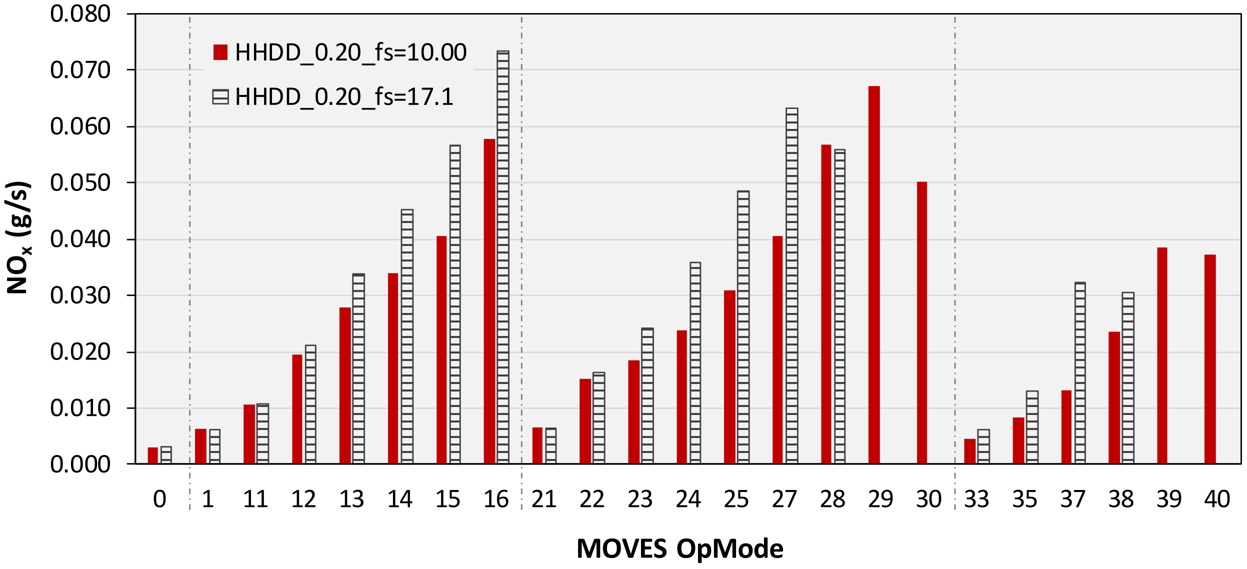

**Figure 2-15 Effect of MOVES2014 (17.1) and MOVES3 (10.00) $f_{scale}$ Value on OpMode Coverage for $NO_x$ Emission Rates for Heavy Heavy-Duty Vehicles in the $NO_x$ FEL = 0.20 Group**

#### ***2.1.1.5.5*** *HD Incorporation of Tier 3 Standards for LHD2b3*

In addition to regulating light-duty vehicles, the Tier 3 vehicle emission standard[38] also applies to chassis-certified light heavy-duty diesel vehicles, which with the new MOVES4 definition, includes all of regclass 41 (LHD2b3). In addition, we updated the T&M assumptions in MOVES4 for regclass 41 by reflecting the 50,000 miles warranty requirement for LHD vehicles, and the 150,000 useful life mileage for Tier 3 LHD2b3 vehicles (see Section B.1). For these LHD2b3 diesel vehicles, we estimate reductions in the $NO_x$ zero-mile emission rates attributable to the Tier 3 standards beginning in 2018. We did not estimate Tier 3 reductions in the THC, CO, and $PM_{2.5}$ emission rates as discussed in subsequent sections.

For diesel vehicles in the LHD2b3 regulatory class, we estimate that the Tier 3 $NO_x$ standard results in a different percent reduction of start and running emissions. We applied a greater portion of the reduction to running emissions and a smaller reduction to start emissions. These reductions were phased-in over the same schedule as for gasoline vehicles, as detailed in Table 2-8. The derivation of the phase-in assumptions is discussed in the MOVES2014 heavy-duty exhaust report.[35]

**Table 2-8 Phase-in Assumptions for Tier 3 $NO_x$ Standards for Light Heavy-Duty 2b3 Diesel Vehicles**

| Model Year | Phase-in fraction (%) | Reduction in Running Emission Rate (%)[1] | Reduction in Start Emission Rate (%)[1] |
|---|---|---|---|
| 2017 | 0 | 0.0 | 0.0 |
| 2018 | 49 | 30.1 | 11.2 |
| 2019 | 62 | 38.1 | 14.2 |
| 2020 | 75 | 46.1 | 17.2 |
| 2021 | 87 | 53.5 | 19.9 |
| 2022 | 100 | 61.5 | 22.9 |

Note:

[1] These reductions are based on comparison of Tier 3 standards against Tier 2 standards.

In generating the reduced rates for running operation, the starting point (or pre-Tier 3 baseline) are the LHD2b3 rates for MY2017. The ending point, representing full Tier 3 control, was model year 2022. The MY 2022 rates were calculated by multiplying the rates for MY2017 by 0.3855. This fraction reflects the percent reduction in running emission rates for MY2022 as shown in Table 2-8.

In addition to tightening emission standards, the Tier 3 regulations require an increase in the regulatory useful life from 120,000 miles to 150,000 miles. We used the Tampering and Mal-maintenance (T&M) methodology presented in Appendix B to estimate the emissions impact of the lengthened useful life, and to estimate different age effects for Tier 3 LHD2b3 vehicles as shown in Table B-3. For the phase-in model years, we calculated a weighted average of the Model Year 2017 and Model Year 2022 emission rates using the Tier 3 phase-in, as shown in Equation 2-16.

$$\begin{aligned}\mathrm{LHD2b3\ ER_{MY}} &= (\mathrm{LHD2b3\ ER}_{2017}) \times (1 - \mathrm{Tier\ 3\ Phasein}_{MY}) \\ &\quad + (\mathrm{LHD2b3\ ER}_{2022}) \times (\mathrm{Tier\ 3\ Phasein}_{MY})\end{aligned} \qquad \textbf{Equation 2-16}$$

Where:

$\mathrm{LHD2b3\ ER_{MY}}$ = the LHD2b3 diesel emission rate for each process (start/running), age, operating mode, and model year between 2018 and 2021.

Equation 2-16 is also used to estimate the impact of the lengthened Tier 3 useful life standard on $NO_x$, $PM_{2.5}$, THC, and CO emissions.

Tier 3 also allows fleet-wide averaging with electric vehicles as explained in the MOVES adjustments report.[63] While this averaging is allowed for LHD2b3s, it is not modelled in MOVES.

The reduction in $NO_x$ grams per mile from the Tier 3 rulemaking across model years is displayed in Figure 2-25.

#### *2.1.1.6 2027-2060 Model Years*

In MOVES4, we updated the MY 2027 and later emission rates for the LHD45, MHD, HHD and Urban Bus regulatory classes to account for the impact from the HD2027 standards. The HD2027 standards include duty-cycle standards, off-cycle standards and changes to warranty and useful life requirements. This section describes the methodology to derive the new zero-mile $NO_x$ emission rates for running emissions. Temperature adjustments for running and extended idle $NO_x$ emissions are described in the MOVES temperature report.[63]

We first estimated the effects of the duty-cycle standards and the off-cycle standards separately, as discussed in Sections 2.1.1.6.1 and 2.1.1.6.2, 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 as discussed in 2.1.1.6.3. The effects of aging are described in Section 2.1.1.7.

#### *2.1.1.6.1 Emission Rates Based on Duty-Cycle Standards*

The HD2027 $NO_x$ heavy-duty compression ignition duty-cycle exhaust emission standards for MY2027+ are shown in Table 2-9. The duty-cycle standards include three separate tests: Federal Test Procedure (FTP), Supplemental Emission Test - Ramped Modal Cycle (SET-RMC) and low load cycle (LLC). We used the 2027+ 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 LLC standard in MOVES, we used the FTP standard to model the impact of the standards on low-power operation.

**Table 2-9 Heavy-duty Compression Ignition Duty-Cycle $NO_x$ Standards for the HD2027 Rule**

| **Regulatory Classes** | **FTP (g/hp-hr)** | **SET-RMC (g/hp-hr)** | **LLC (g/hp-hr)** |
|---|---|---|---|
| LHD | 0.035 | 0.035 | 0.05 |
| MHD | 0.05 | 0.05 | 0.065 |
| HHD | 0.05 | 0.05 | 0.065 |

$$\mathrm{R_{duty}} = \frac{\text{HD2027 FTP and SET RMC standard}}{\text{MY2010-2026 standard}} \qquad \textbf{Equation 2-17}$$

Equation 2-17 through 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 standards. The term $R_{duty}$ is the ratio between the new emission standards and the MY 2010-2026 FTP and SET-RMC duty-cycle standards (0.2 g/hp-hr).

$$\mathrm{R_{duty}} = \frac{\text{HD2027 FTP and SET RMC standard}}{\text{MY2010} - \text{2026 standard}} \qquad \textbf{Equation 2-17}$$

$R_{duty}$ ranges between 17 and 25 percent as shown in Table 2-10.

**Table 2-10 $R_{duty}$ Ratios Calculated for the HD2027 Standards**

| Regulatory Classes | FTP and SET standard (g/hp-hr) | $R_{duty}$ |
|---|---|---|
| LHD | 0.035 | 17.5% |
| MHD, HHD | 0.05 | 25% |

To estimate the effect of the new engine dynamometer duty-cycle standards on in-use emissions, we looked at this relationship for the previous change in $NO_x$ standards. The 2010 0.2 g/hp-hr $NO_x$ emission standard[39] is the most recent previous 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 pre-2010 heavy-duty $NO_x$ standard with the 2010 standard. Equation 2-18 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 pre-2010 standard, and the percent change in the 2010 standard FTP standards relative to the pre-2010 standard.[g] In other words, $R_{in\_use}$ is the ratio between the relative change in in-use emissions compared to the relative change in the FTP duty-cycle emission standard. This ratio is operating mode specific and the ratio computed for HHD is applied to MHD and LHD45.

$$\mathrm{R_{in\_use}} = \frac{\text{\% Change in the in} - \text{use emission rates from 2010 compliant vehicles}}{\text{\% Change in the 2010 FTP standard}} \qquad \textbf{Equation 2-18}$$

The percent change in in-use emission rates from vehicles certified to the 2010 standard (the numerator in Equation 2-18) was estimated using Equation 2-19. For each operating mode, the MOVES emission rates for HHD vehicles certified to the 2010 0.2 g/hp-hr standard (the numerator) were calculated from 93 MY 2010-2015 HHD vehicles with a certified engine family emission limit (FEL) below the 0.2 g/hp-hr $NO_x$ emissions level and tested as part of the Heavy-Duty In-Use Testing program.[21] 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.  Because data was sparse for LHD and MHD, the HHD data ratios were also used for LHD and MHD.

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[g] 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.

$$\begin{aligned}&\text{\% Change in the in\_use emission rates from 2010 compliant vehicles}\\&\quad=\frac{\text{Emission rate from HHD 2010 compliant vehicles}}{\text{HHD MY 2006 MOVES emission rate}}-1\end{aligned}$$ **Equation 2-19**

The percent change from Equation 2-19 was calculated separately for each MOVES operating mode to evaluate the effectiveness of the 2010 standard across different ranges of in-use operating conditions, as shown in Figure 2-16 and Table 2-11. 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 2-20 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 2-18. The 2004-2006 $NO_x$ emission standard was estimated as 1.68 g/hp-hr, assuming that $NO_x$ emissions consist of 70 percent of the combined NMHC (Non-Methane Hydrocarbons) plus $NO_x$ standard, consistent with the assumption used in MOVES3[40]. The percent change associated with the standard change is plotted as a horizontal line in Figure 2-16 to compare to the in-use emission rate reductions.

$$\text{Percent Change in the 2010 FTP standard}=\frac{0.2}{(70\%\times 2.4)}-1=-88.1\%$$ **Equation 2-20**

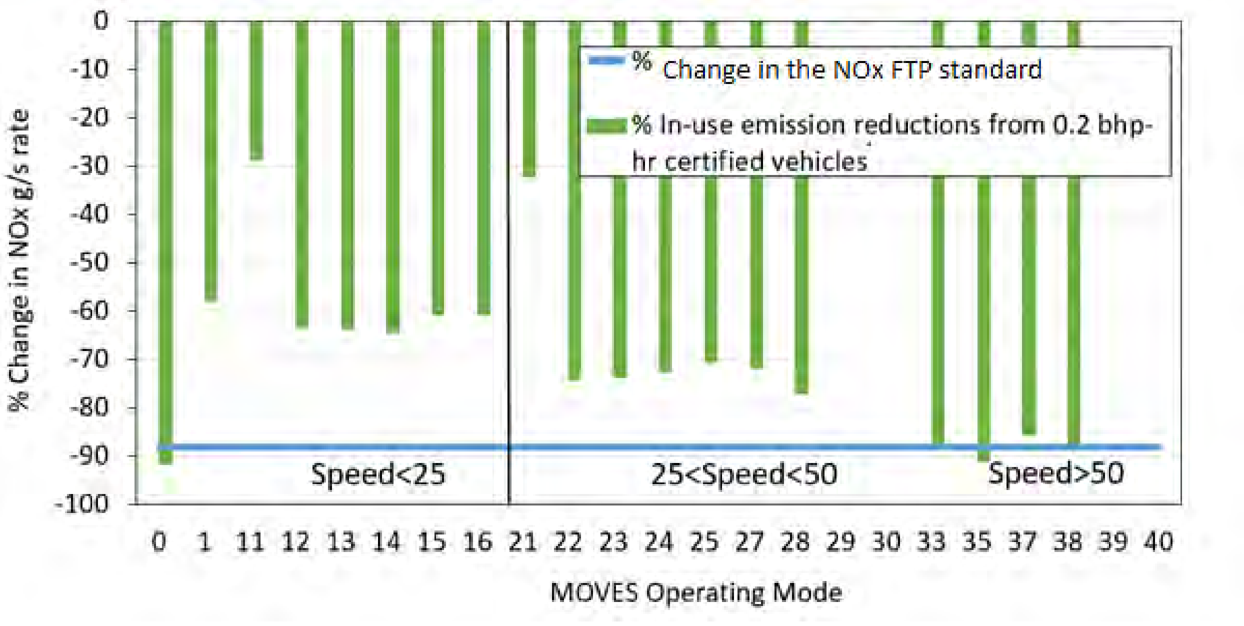

**Figure 2-16 Percent change in in-use emission rates for 2010 standard (0.2 g/hp-hr) compliant HHD vehicles, compared to the percent change in the 2010 duty-cycle standard across MOVES operating modes**

Table 2-11 displays the $R_{in\_use}$ as calculated by Equation 2-18. For operating modes with $R_{in\_use}$ values greater than one, the observed in-use emissions are less than would be expected due to the change in FTP emission standard. Operating modes with $R_{in\_use}$ values less than one see less impact than implied by the change in the FTP emissions standards.

**Table 2-11 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 (%) | $R_{in\_use}$ [c] |
|---|---|---|---|---|
| 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 MY 2006 HHD emission rates in MOVES3 and later versions. Note that the $f_{scale}$ for model year 2010 and later is 10 for HHD, 7 for MHD, and 5 for LHD45 and LHD2b3.

[b] For operating modes lacking data, we used the same $R_{in\_use}$ for the closest operating mode.

[c] $R_{in\_use}$ is calculated based HHD data, but also applied to LHD45 and MHD.

Equation 2-21 is used to estimate the percentage reduction to $NO_x$ running emissions from the change in the duty-cycle standard for each operating mode.

$$\mathrm{R_{duty\_in\_use}} = \left(1 - \mathrm{R_{duty}}\right) \times \mathrm{R_{in\_use}} \qquad \textbf{Equation 2-21}$$

Where:

$R_{duty\_in\_use}$= the percent emission reductions in the in-use running $NO_x$ emissions estimated from changing the FTP duty-cycle standard.

Equation 2-22 is used to estimate the age 0-3 heavy-duty diesel $NO_x$ running emission rates from the changes in the duty-cycle standards. The same calculations were applied to estimate rates for all the heavy-duty diesel regulatory classes.[h]

$$\mathrm{ER}_{\mathrm{duty\_in\_use}} = \left(1 - \mathrm{R}_{\mathrm{duty\_in\_use}}\right) \times \mathrm{ER}_{\mathrm{MOVES\_baseline}} \qquad \textbf{Equation 2-22}$$

Where:
$ER_{duty\_in\_use}$= the MOVES running $NO_x$ emission rates for the control scenarios based on reduction in the duty-cycle standard
$R_{duty\_in\_use}$= the percent emission reductions in running $NO_x$ emissions estimated from changing to FTP duty-cycle standard
$ER_{MOVES\_baseline}$= the MOVES baseline running $NO_x$ emission rates for each regulatory class

The estimated HHD MOVES running $NO_x$ emission rates for the HD2027 standards, estimated based solely on the duty-cycle standards in Table 2-9, are shown in Figure 2-17.

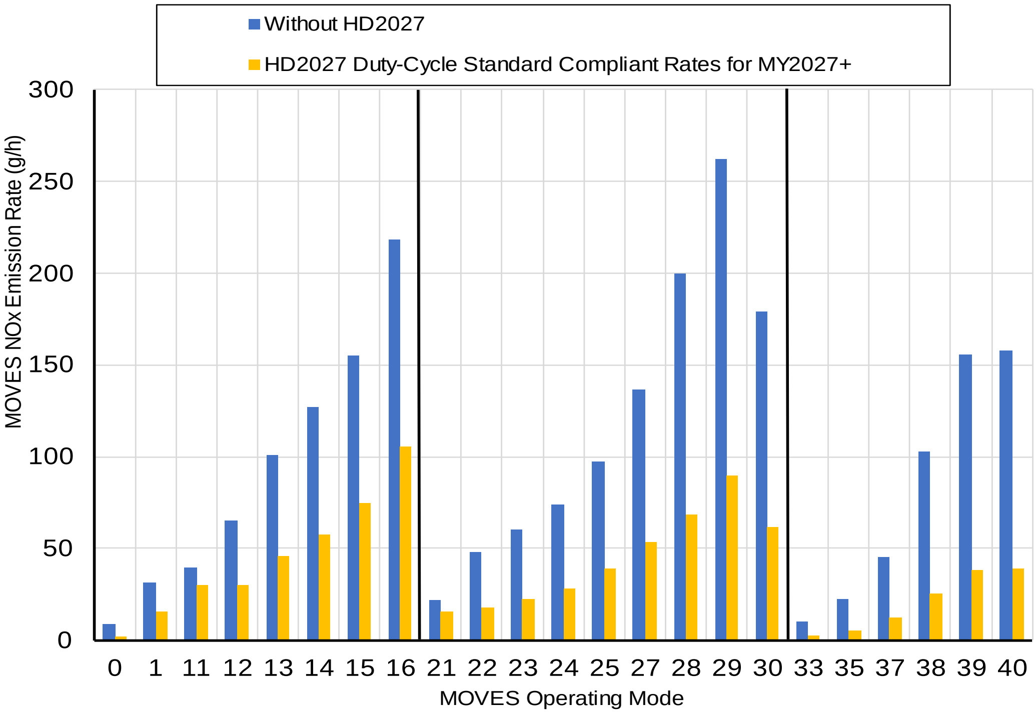

**Figure 2-17 Duty-cycle-based running $NO_x$ emissions, $ER_{duty\_in\_use}$, for HHD diesel for the HD2027 standards**

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[h] 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 1-4. Changing the $f_{scale}$ values does change the definition of vehicle operation in the other operating modes. However, the $R_{in\_use}$ values are relatively constant for the positive power operating modes within each speed range as observed in Table 2-11. In calculating the results shown in Figure 2-16, we deemed it was not necessary to attempt to account for the $f_{scale}$ differences when applying the $R_{in\_use}$ values.

#### *2.1.1.6.2 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 HD2027 off-cycle standards for heavy-duty diesel vehicles. Table 2-12 presents the calculated off-cycle standards used to develop MOVES inputs. The off-cycle standards include requirements for operating conditions in two bins: idle bin (less than 6 percent of maximum power) and non-idle load bin. In developing inputs to MOVES, we assumed manufacturers will comply with the optional idle standard in all off-cycle idle operation. We then developed the off-cycle standards using the procedures as described below. These calculations are detailed here for HHD, but we used the same approach for MHD and LHD45.

In modeling the HD2027 off-cycle standards in MOVES4, we incorporated the impact of the compliance margin EPA used in setting the off-cycle standards. The in-use compliance margin of approximately 40% of the standards, accounted for a number of in-use factors, including test procedure variability, production and engine variability, fuel and diesel exhaust fluid (DEF) quality, aftertreatment aging due to severe-service operation, and aftertreatment packaging to name a few. When manufactures design engines, they must include similar margin to ensure each of their engines meet the standards, which results in the average fleet emissions being below the standards.

**Table 2-12 Calculated Off-Cycle $NO_x$ Standards based on the HD2027 Standards**

| **Regulatory Class** | **Off-cycle Bin** | **Off-Cycle $NO_x$ Standards (g/hr for idling, g/hp-hr for non-idle operation)** |
|---|---|---|
| LHD | Idle | 9 for MY2027-2028; 13.5 for MY2029+ [A] |
| | Non-idle | 0.052 for MY2027-2028, 0.051 for MY2029+ [B] |
| MHD | Idle | 9 for MY2027-2028; 13.5 for MY2029+ [A] |
| | Non-idle | 0.065 for MY2027-2028; 0.064 for MY2029+ [B] |
| HHD | Idle | 9 for MY2027-2028; 13.5 for MY2029+ [A] |
| | Non-idle | 0.065 for MY2027-2028; 0.064 for MY2029+ [B] |

[A] The optional idle standards were 10 g/hr in the HD2027 final standards. However, MOVES uses the values in the table to specifically account for the compliance margin to the off-cycle standards.

[B] The non-idle standards in the table are different from the HD2027 final standards values (0.058 g/hp-hr and 0.073 g/hp-hr for LHD and MHD/HHD/Urban bus, respectively). They are now based on the modeling of off-cycle standards compliance margin in MOVES4.

In order to apply these off-cycle standards to MOVES operating modes, we first converted the standards to a fuel consumption (i.e., $CO_2$ emissions) basis. We calculated the optional idle $NO_x$ g/hr standard in units of $NO_x$ g/$CO_2$ kg using Equation 2-23 and the resulting values are displayed in Table 2-13.

$$\text{Optional Idle } \frac{\mathrm{NO_X}}{\mathrm{CO_2}} \text{ standard } \left(\frac{\mathrm{g}}{\mathrm{kg}}\right) = \left[\text{Optional Idle } \mathrm{NO_X} \text{ standard } \left(\frac{\mathrm{g}}{\mathrm{hr}}\right)\right] \Big/ \left[\text{Idle } \mathrm{CO_2} \left(\frac{\mathrm{kg}}{\mathrm{hr}}\right)\right]$$

**Equation 2-23**

Where $Idle\ CO_2 \left(\frac{kg}{hr}\right)$= the MOVES average $CO_2$ (kg/hr) emission rate for HHD diesel vehicles for MOVES idle (operating mode 1). We assume the $CO_2$ rates are unaffected by the HD2027 standard.

**Table 2-13 Calculation of Optional Idle $NO_x$ /$CO_2$ Standard (g/kg)**

| Optional Idle $NO_x$ standard (g/hr) | Average HHD Idle (Operating Mode=1) $CO_2$ emission rate (kg/hr) | Optional Idle $NO_x$ /$CO_2$ standard (g/kg) |
|---|---|---|
| 9 for MY2027-2028; 13.5 for MY2029+ | 7.68 | 1.17 for MY2027-2028;<br>1.13 for MY2029+ |

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 2-14 in Columns (F) for HHD vehicles for the final standards.

In Table 2-14, Column (B) lists the MOVES $CO_2$ emission rate for Model Year 2027 HHD diesel vehicles for each MOVES operating mode. Column (C) lists the mean power for each operating mode bin as calculated from the Heavy-Duty In-Use Testing data, which is the same data set that was used to derive the MOVES $CO_2$ emission rates (see Section 2.1.4.3).[21] The percent load, Column (D), is calculated for each operating mode bin using Equation 2-24.

$$\text{Percent Load}_{\text{OpMode=i}} = \frac{\text{Mean Power}_{\text{OpMode= i}}}{\text{Mean Power}_{\text{OpMode=40}}}$$

**Equation 2-24**

$$\text{Percent Load}_{\text{OpMode=i}} = \frac{\text{Mean Power}_{\text{OpMode= i}}}{\text{Mean Power}_{\text{OpMode=40}}}$$

**Equation 2-24**

Where $i$= one of the 23 MOVES running exhaust operating modes from 0 to 40
$Mean\ Power_{OpMode=\ i}$= the mean power for each of the MOVES operating modes shown in Column C.
$Mean\ Power_{OpMode=40}$= 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)) as defined in the rule, where percent load less than 6 percent of maximum power is defined as idle and above 6 percent of maximum power is non-idle load.

**Table 2-14 Calculation of the Off-cycle $NO_x$ Standard Compliant Emission Rate for HHD Diesel Vehicles for the HD2027 Standards**

| 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 2027-2028 off-cycle compliant emission rate (g/hr) | MY 2029+ off-cycle compliant emission rate (g/hr) |
| 0 | 4.92 | 6.04 | 1.3% | Idle | 5.76 | 5.57 |
| 1 | 7.68 | 8.10 | 1.7% | Idle | 9.00 | 8.70 |
| 11 | 13.42 | 1.04 | 0.2% | Idle | 15.72 | 15.19 |
| 12 | 21.69 | 28.90 | 6.2% | Non-idle | 1.88 | 1.85 |
| 13 | 37.31 | 75.16 | 16.1% | Non-idle | 4.89 | 4.81 |
| 14 | 52.20 | 121.18 | 26.0% | Non-idle | 7.88 | 7.76 |
| 15 | 68.68 | 166.98 | 35.8% | Non-idle | 10.85 | 10.69 |
| 16 | 110.42 | 282.24 | 60.5% | Non-idle | 18.35 | 18.06 |
| 21 | 13.92 | -1.61 | -0.3% | Idle | 16.31 | 15.76 |
| 22 | 32.99 | 34.43 | 7.4% | Non-idle | 2.24 | 2.20 |
| 23 | 44.71 | 77.71 | 16.7% | Non-idle | 5.05 | 4.97 |
| 24 | 59.82 | 121.62 | 26.1% | Non-idle | 7.91 | 7.78 |
| 25 | 77.03 | 167.82 | 36.0% | Non-idle | 10.91 | 10.74 |
| 27 | 102.53 | 230.56 | 49.4% | Non-idle | 14.99 | 14.76 |
| 28 | 142.09 | 327.41 | 70.2% | Non-idle | 21.28 | 20.95 |
| 29 | 181.90 | 403.76 | 86.5% | Non-idle | 26.24 | 25.84 |
| 30 | 212.63 | 470.01 | 100.7% | Non-idle | 30.55 | 30.08 |
| 33 | 28.36 | 34.76 | 7.4% | Non-idle | 2.26 | 2.22 |
| 35 | 71.87 | 145.03 | 31.1% | Non-idle | 9.43 | 9.28 |
| 37 | 106.93 | 227.23 | 48.7% | Non-idle | 14.77 | 14.54 |
| 38 | 148.35 | 323.23 | 69.3% | Non-idle | 21.01 | 20.69 |
| 39 | 183.17 | 396.00 | 84.9% | Non-idle | 25.74 | 25.34 |
| 40 | 196.42 | 466.62 | 100.0% | Non-idle | 30.33 | 29.86 |

Finally, the off-cycle $NO_x$ standard compliant emission rate in Column (F) was calculated based on the power classification and the stringency of the off-cycle standard. For operating modes classified as idle, we multiplied the MOVES $CO_2$ emission rate in Column (B) by the $NO_x/CO_2$ off-cycle idle standard calculated in Table 2-13 using Equation 2-25.

$$\begin{aligned}&\text{Idle Emission Rate}\\&\quad= \text{MOVES MY 2027 HHD CO}_2\text{ Emission Rate }\left(\frac{\text{kg}}{\text{hr}}\right)\\&\quad\times \text{Voluntary Idle }\frac{NO_X}{\text{CO}_2}\text{in}_{\text{use}}\text{standard }\left(\frac{\text{g}}{\text{kg}}\right)\end{aligned}$$

**Equation 2-25**

For the operating modes classified as non-idle load, we multiplied the off-cycle (g/hp-hr) standard in Table 2-12 for the corresponding power classification by the mean power (Column C), as shown in Equation 2-26.

$$\begin{aligned}&\text{Non}-\text{idle Emission Rate}\\&\quad=\text{Mean Power(hp)}\ \times\text{In\_use standard}\left(\frac{\text{g}}{\text{hp}\cdot\text{hr}}\right)\end{aligned}$$ **Equation 2-26**

The estimated off-cycle $NO_x$ standard compliant emission rates for heavy heavy-duty diesel vehicles are shown in Figure 2-18. Similarly, we applied Equation 2-24 through Equation 2-26 to estimate the off-cycle standard compliant emission rates for the other MOVES regulatory classes using corresponding $CO_2$ rates and the mean power for those vehicles.

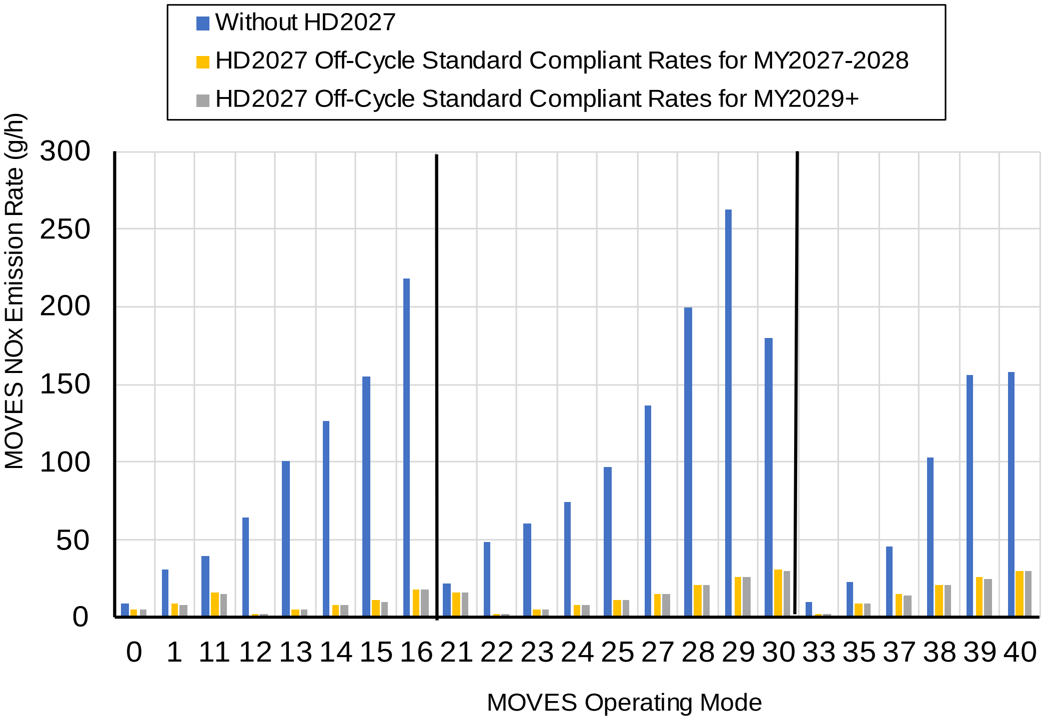

**Figure 2-18 Base $NO_x$ rates and off-cycle $NO_x$ standard compliant emission rates for HHD diesel**

#### *2.1.1.6.3 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 2-19 shows the HHD duty-cycle and off-cycle standards for MY 2027+ across MOVES operating modes. The duty-cycle standard is estimated to constrain emissions in four operating modes (operating modes 0, 21, 35 and 37), while the off-cycle standard constrains emissions in the remaining operating modes.

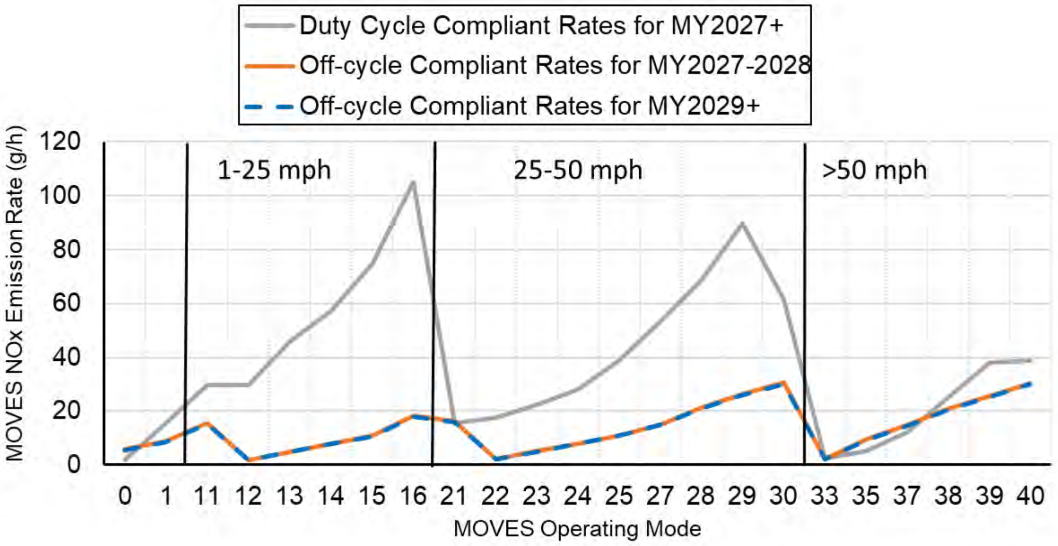

**Figure 2-19 Comparison of Running NO$_x$ emission rates for diesel-fueled HHD compliant with the duty-cycle and off-cycle standards**

Because manufacturers will need to simultaneously 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 off-cycle standards is selected for operating mode 12, but the emission rate based on the duty-cycle standards is selected for operating mode 35). Figure 2-20, Figure 2-21 and Figure 2-22 present the estimated emission rates for HHD, MHD, and LHD45 diesel vehicles that meet both the final duty-cycle and off-cycle standards, respectively.

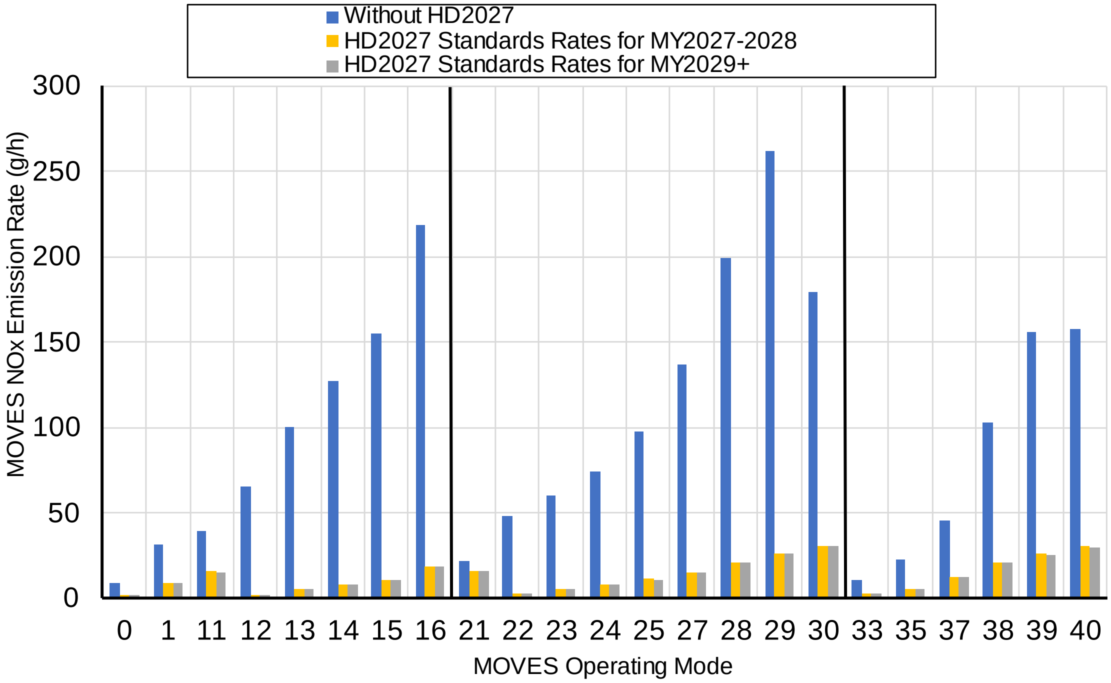

**Figure 2-20 Estimated zero-mile NO$_x$ emission rates for HHD diesel vehicles due to the HD2027 duty-cycle and off-cycle standards**

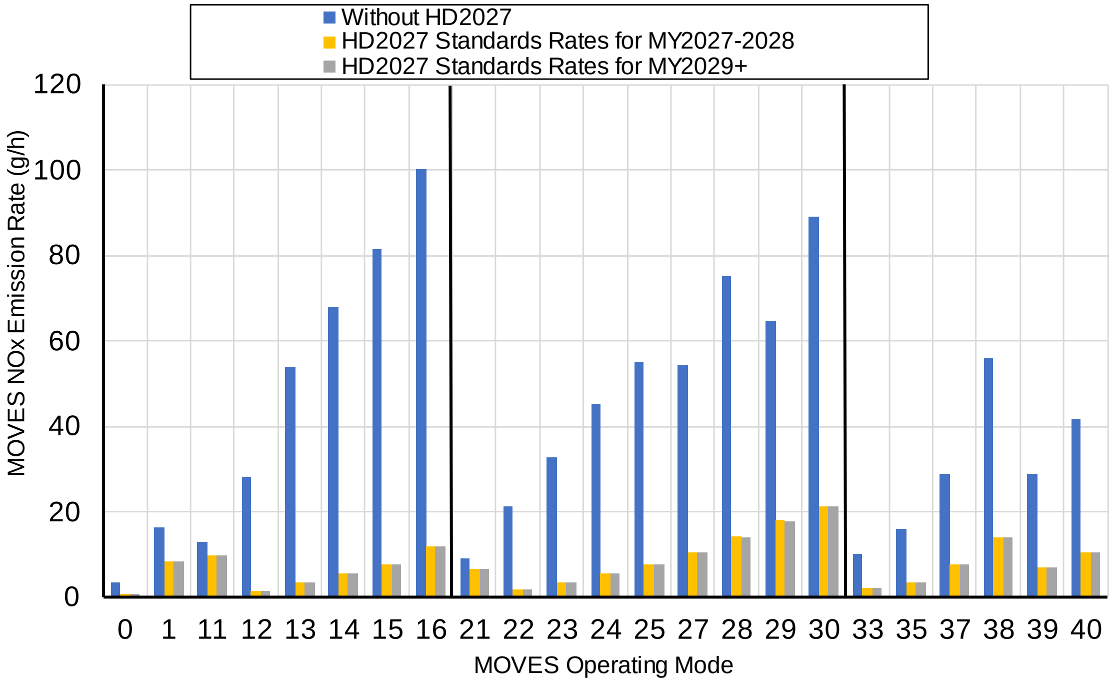

**Figure 2-21 Estimated zero-mile NO$_x$ emission rates for MHD diesel vehicles due to the HD2027 duty-cycle and off-cycle standards**

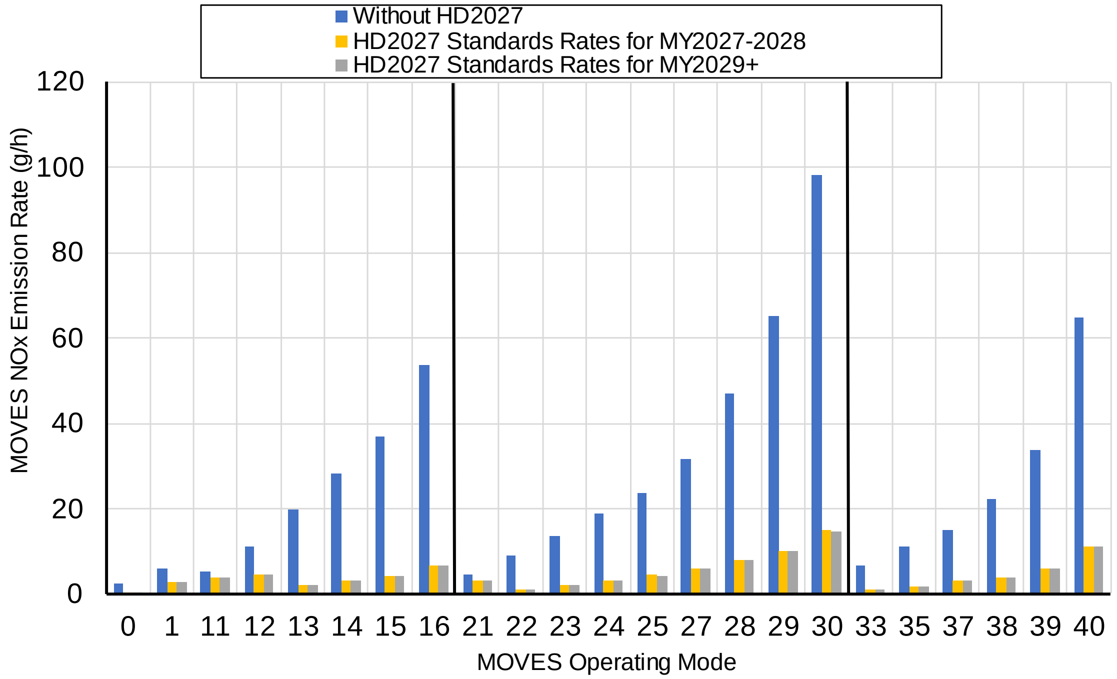

**Figure 2-22 Estimated zero-mile $NO_X$ emission rates for LHD45 diesel vehicles due to the HD2027 duty-cycle and off-cycle standards**

#### *2.1.1.7 Tampering and Mal-maintenance*

MOVES accounts for the fleet-average increase in emissions with vehicle age. For heavy-duty diesel vehicles, the increase with age is modeled in the development of the emission rates by applying tampering & mal-maintenance (T&M) adjustment factors to age zero rates. We assume that the T&M effects are the dominant cause of emission increases with age in heavy-duty diesel vehicles. No effort has been made to explicitly model emission increases due to normal wear and tear (e.g. catalyst degradation, sensor deterioration from properly maintained vehicles) from heavy-duty diesel vehicles.

Table 2-15 shows the percent increases due to T&M adjustment factors for aggregate $NO_x$ emissions by regulatory class and model year group. As described in Appendix B, the T&M adjustment factors in Table 2-15 are calculated by combining information regarding the assumed frequency rate of an equipment failure at the useful life of the engine with the estimated emission impact of the equipment failure.

**Table 2-15 $NO_x$ T&M adjustment factor (percent) by regulatory class**

| Model years | LHD2b3 trucks (%) | LHD45 trucks (%) | MHD, HHD, Urban Bus (%) |
|---|---|---|---|
| 1994-1997 | 0 | 0 | 0 |
| 1998-2002 | 0 | 0 | 0 |
| 2003-2006 | 0 | 0 | 0 |
| 2007-2009 | 3.8 | 3.84 | 0 |
| 2010-2012 | 55.9 | 77.9 | 77.9 |
| 2013-2026 | 58.6 | 58.6 | 58.6 |
| 2027-2028 | 58.6 | 329.7 | 324.0 (MHD),<br>410.5 (HHD),<br>433.7 (Urban Bus) |
| 2029-2060 | 58.6 | 331.6 | 325.6 (MHD),<br>416.3 (HHD),<br>440.6 (Urban Bus) |

We also apply an age effect; that is, we assume that emissions begin to deteriorate at the age vehicles pass the warranty requirements and increase to the full T&M adjustment factors at the age the vehicles reach the useful life mileage requirement (Figure B-1). Because we expect the warranty period for the HHD, MHD, and Urban Buses will be reached within the first three years (Table B-1), the T&M adjustments factors are applied starting with the age 0-3 group for these vehicles. Similarly, the T&M adjustments factors are applied starting in the age 4-5 group for the LHD45 and LHD2b3 vehicles.

The emission rates described in Sections 2.1.1.4 through Section 2.1.1.6 are assumed to represent new or "zero-mile" emission rates. The 2007-2009 LHD emission rates are derived from the 2003-2006 HDIUT data as discussed in Section 2.1.1.4.6. The MY 2010 and later heavy-duty emission rates are also based on the HDIUT data which tested newer and well-maintained vehicles. We then account for the emission increases with age by multiplying the MY 2007-2009 LHD emission rates, and MY-2010-and-later emission rates by a function of the corresponding T&M adjustment factors and age effects (Equation 8-3). The MOVES emission rates for regulatory classes with the same zero-mile emission rates (Table 2-16) are different due to the T&M $NO_x$ effects (Table 2-15) and phase-in of T&M effects by age (Table B-4).

The T&M adjustments for $NO_x$ are zero for some of the model year groups because these vehicles lack the heavy-duty advanced aftertreatment systems that we assume are most affected by tampering and mal-maintenance, as discussed more in Appendix B.

The LHD vehicles have different T&M $NO_x$ increases than HHD, MHD, and Urban Bus vehicles due to the penetration of lean $NO_x$ trap (LNT) aftertreatment. For MY 2007-2009 we assumed that there was a 25 percent penetration of LNT-equipped vehicles within both LHD2b3 and LHD45 regulatory classes, with the remaining 75% having no $NO_x$ aftertreatment equipment. Subsequent certification data shows that LNT was not actually used in LHD45 vehicles, however, we have not updated this assumption, or the T&M adjustment factors, for MY 2007-2009 because the resulting LHD45 2007-2009 emission rates compare well to the HDIUT data for 2007-2009 vehicles.[34] For MY 2010-2012, we assumed a 25 percent penetration of LNT and 75 percent of selective catalytic reduction (SCR) $NO_x$ aftertreatment system within the LHD2b3 regulatory class. We assume that all heavier heavy-duty vehicles (LHD45, MHD, HHD, Urban bus) have 100 percent penetration of SCR systems starting in model year 2010. For model years 2027+, the $NO_x$ standard is much more stringent and we assume that aftertreatment systems are much more effective in reducing emissions. As detailed in Section B.7, we also assume the converse—that aftertreatment failure in a MY2027 vehicle would bring $NO_x$ emissions to the same level as estimated for a MY 2010 vehicle's engine-out emissions without any reductions from aftertreatment system.

The T&M values for model year 2010 and later vehicles also account for implementation of OBD. For LHD2b3 trucks, OBD systems were assumed to be fully implemented in MY 2010. For the other HD regulatory classes (LHD45, MHD, HHD), we assumed there would be a phase-in period from MY 2010 to 2012 where one-third of those trucks were equipped with OBD systems. In MY 2013 and later, all trucks have OBD systems. These OBD adoption rates have been incorporated into the tampering and mal-maintenance emission increases in Table 2-15 based on the assumptions and calculations detailed in Appendix B.

Figure 2-23 displays the $NO_x$ rates in gram per mile by age and regulatory class for model year 2015 vehicles. Due to faster mileage accumulation, the HHD trucks tend to reach their useful life quicker than other heavy-duty vehicles, with the maximum emission rates by the 4-5 age group. In contrast Urban Buses do not reach the useful life until the age 10-14 group. The gram per mile (g/mile) emission rates were calculated outside the model by using operating mode distributions and average speeds for each regulatory class estimated from a national MOVES run. The emission rates showed here do not include any adjustments to the rates due to fuel effects or humidity that are applied during MOVES run, however they do incorporate differences due to activity.[i]

Despite the significant T&M adjustment factors for MY 2010+ heavy-duty diesel vehicles, the fully-aged $NO_x$ emissions of MY 2010+ vehicles are significantly lower than the emission rates of MY 2009 and earlier vehicles. As shown in Figure 2-25, the age 0-3 MY 2009 $NO_x$ g/mile emission rates are over 100% higher than the MY 2010 vehicle emission rates, while the T&M adjustment factors are less than 100% (Table 2-15). Thus, MOVES estimates that, on average, a fully-aged MY 2010 heavy-duty truck has lower $NO_x$ emissions than a new MY 2009 heavy-duty truck.

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[i] For example, the MY 2015 $NO_x$ emission rates by operating mode for LHD2b3 and LHD45 diesel vehicles are the same, but Figure 2-17 shows different gram per mile emission rates due to vehicle and activity differences, including heavier weights of LHD45 vehicles (source mass), and because the two regulatory classes are distributed differently among the source types in MOVES, which have different operating mode distributions. See the MOVES Population and Activity Report**Error! Bookmark not defined.** for more information. The zero-mile HHD and Urban Bus $NO_x$ emission rates by operating mode are equivalent. However, the emission rates in the age groups: 0-3, 4-5, 6-7, and 8-9 are different because they have a different phase-in of the T&M effects. The difference between HHD and Urban Bus in grams per mile for ages 10+ are due to differences in the operating mode distributions and average speeds.

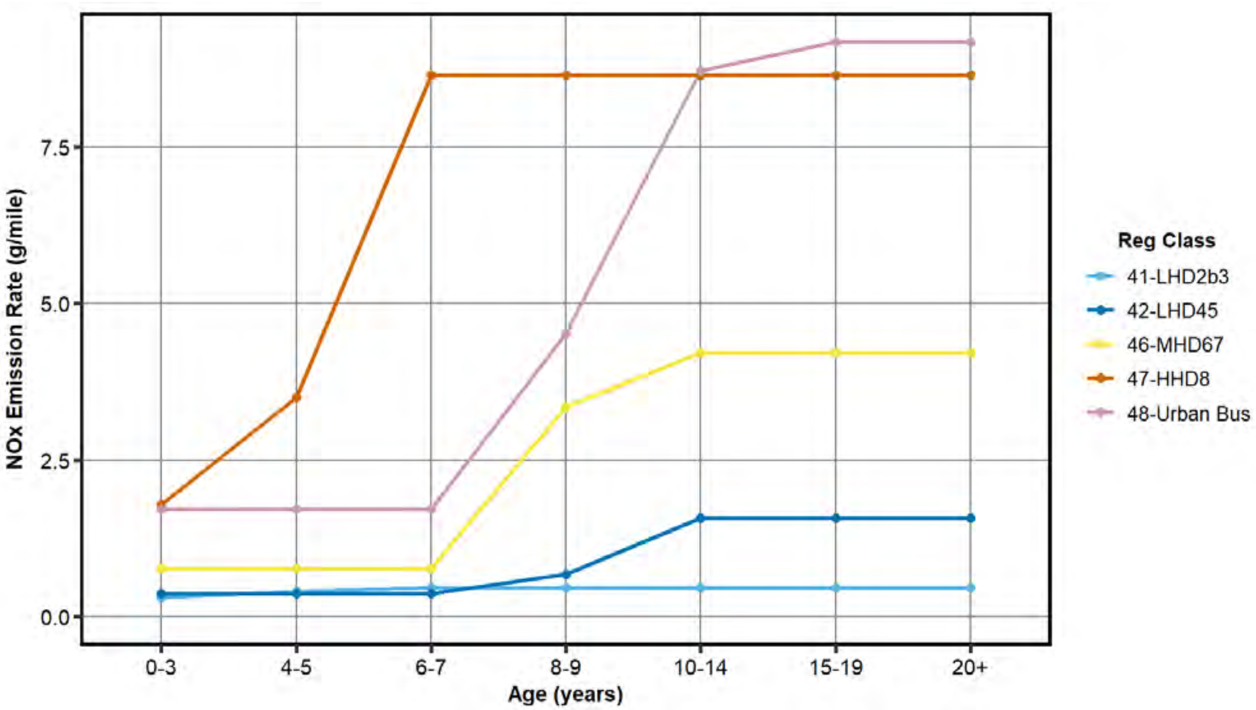

**Figure 2-23 Base Heavy-duty Diesel $NO_x$ Running Emission Rates (g/mile) by Age for Model Year 2015 by Regulatory Class Estimated using Nationally Representative Operating Mode Distribution**

#### *2.1.1.8 Summary and Model Year Trends*

Table 2-16 summarizes the methods used to estimate emission rates for each regulatory class and model year group combination. The emission rates in MOVES are based on the analysis of ROVER, Consent Decree testing data, and HDIUT data. Using the HDIUT data, we updated the HHD, MHD, LHD, and Urban Bus rates for MY 2010+ vehicles in MOVES3. Rates for MY 2027+ were updated in MOVES4.

**Table 2-16 Summary of Methods for Heavy-Duty Diesel NO$_x$ Emission Rate Development for Each Regulatory Class and Model Year Group**

| Model year group | HHD (regClass 47) | MHD (regClass 46) | Urban Bus (regClass 48) | LHD45 (regClass 42) | LHD2b3 (regClass 41) |
|---|---|---|---|---|---|
| 1960-1989, 1990 | HHD 1991-1997 rates proportioned to ratio of certification levels | Same rates as HHD | Urban Bus 1991-1997 rates proportioned using ratio of HHD certification levels | LHD 1991-1993 rates proportioned to LHD certification levels | |
| 1991-1997 | Data analysis[a,c], with adjustments for Low-NO$_x$ rebuilds | Same rates as HHD | Data analysis[a] | LHD 1999-2002 rates proportioned to 1991-1997 FTP standards per Table 2-1 | |
| 1998 | Data analysis[a,c], with adjustments for Low-NO$_x$ rebuilds | Same rates as HHD | Urban Bus 1999-2002 rates proportioned using ratio of HHD 1998 rates to HHD 1999-2002 rates | Same rates as 1999-2002 | |
| 1999-2002 | Data analysis[a,c] | Data analysis[a] | Data analysis[a] | MHD data analyzed with 2.06 $f_{scale}$ | |
| 2003-2006 | Data analysis[a,c] | Data analysis[a,c,] | Data analysis[a] | Data analysis [b] | |
| 2007-2009 | Data analysis[b] | MHD 2003-2006 rates proportioned to FTP standards per Table 2-1[c] | Urban Bus 2003-2006 rates proportioned to FTP standards per Table 2-1 | Percent reductions from the MOVES2010 LHD 2003-2006 rates (Section 2.1.1.4.6)[c] | |
| 2010 - 2018 | HHD data analysis[b] with MY specific production volume weighting | MHD data analysis[b] with MY specific production volume weighting | Same as HHD except T&M adjustment factors specific to Urban Bus | LHD data analysis[b] with MY specific production volume weighting; T&M specific to LHD45 | LHD data analysis[b] with MY specific production volume weighting; T&M specific to LHD2b3 & Tier 3 reductions starting in MY 2018 |
| 2019-2026 | Same as HHD MY 2018 | Same as MHD MY 2018 | Same as Urban Bus MY 2018 | Same as LHD45 MY 2018 | Same baseline as LHD2b3 MY 2018 with Tier 3 reduction phase-in from MY 2019-2022 |
| 2027-2060 | Revised rates based on HD2027 standards | Revised rates based on HD2027 standards | Revised rates based on HD2027 standards | Revised rates based on HD2027 standards | Same as 2019-2026 rates |

Notes:

[a] Analysis based on ROVER and Consent Decree testing data

[b] Analysis based on HDIUT data

[c] Confirmed by HDIUT and/or Houston Drayage Program data

The role of the model year groups, representing a rough surrogate for technology or standards, can be seen in Figure 2-24, which shows $NO_x$ emission rates for 0-3 age group by model year and regulatory class estimated in grams per mile (g/mile) using nationally representative operating mode distributions and average speeds. The MOVES model estimates drastic reductions in $NO_x$ emissions from pre-1990 technologies to modern 2027 and later model year engines. Some of the differences in the emission rates for the 0-3 age group are caused by different phase-in of T&M adjustment factors, which began to be applied in the first age group for HHD, MHD, and Urban Bus regulatory classes (Section 2.1.1.5.5). Because the nationally representative operating modes are different across model years and regulatory classes, some of the differences between model years and the regulatory classes are due to activity differences and not the emission rates by operating mode.[i]

The figure also shows $NO_x$ emissions for “gliders”, which are trucks with a new chassis and cab assembly and equipped with a rebuilt engine typically without an exhaust aftertreatment system. These emissions are of similar magnitude to emission rates from the model year 2000 HHD vehicles as discussed in Section 2.5. In MOVES4, zero population of gliders is estimated starting MY2020+.

Figure 2-25 shows the model year trend for $NO_x$ in gram per mile for the 2007 and later model years. The reduction in LHD2b3 emission rates due to the phase-in of the Tier 3 standards between 2018 and 2022 is evident. All other heavy-duty emission rates by operating mode are unchanged from model year 2018-2026 until the HD2027 rule introduces additional reductions for MY2027+ as documented in Table 2-16. The slight reductions observed in the gram per mile emission rates for all heavy-duty vehicles (including gliders) in model years 2014 through 2027 are due to changes in the operating mode distribution from lower weights, lower rolling resistance, and improved aerodynamics of trucks implemented in the Phase 1 and Phase 2 Heavy-duty Greenhouse Gas Regulations as documented in the MOVES4 Population and Activity Report.[6]

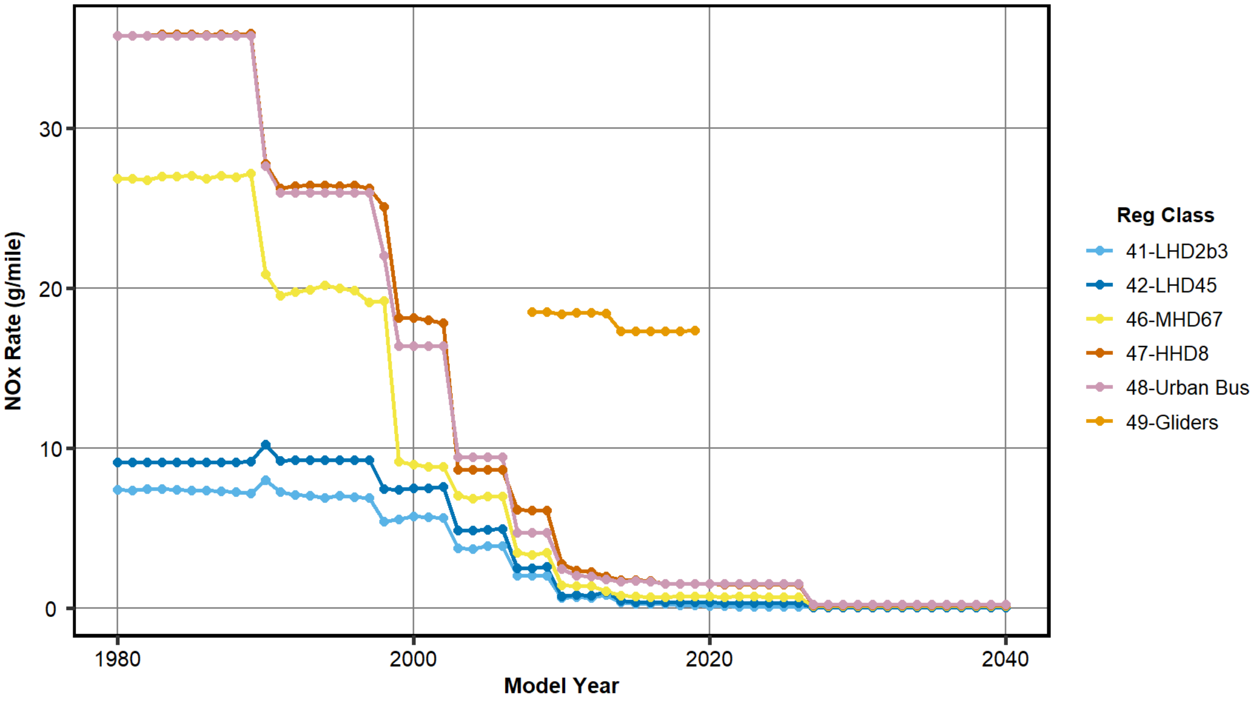

Figure 2-24 Base running emission rates for NO$_x$ from age 0-3 diesel heavy-duty vehicles averaged over a nationally representative operating mode distribution.

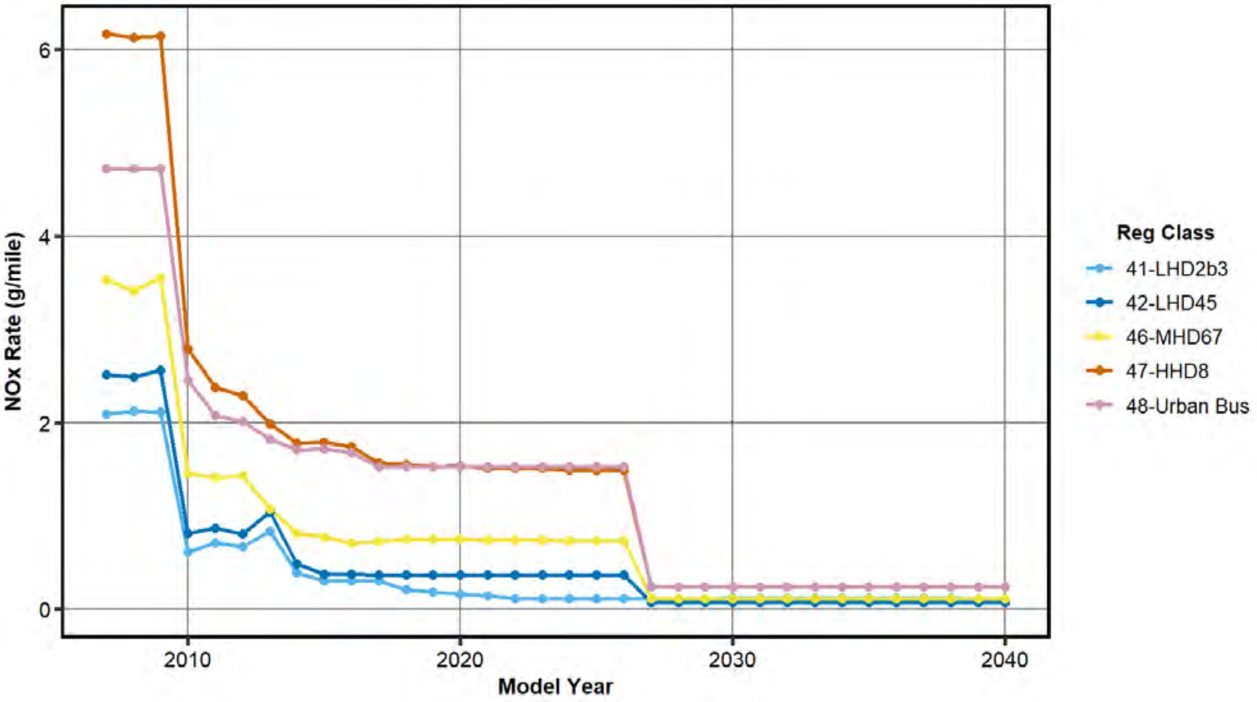

Figure 2-25 Base running emission rates for NO$_x$ from age 0-3 gasoline heavy-duty vehicles averaged over a nationally representative operating mode distribution for model years 2007 through 2040.

### 2.1.2 Particulate Matter ($PM_{2.5}$)

$PM_{2.5}$ refers to particulate matter with a mean aerodynamic diameter less than 2.5 microns. Particulate matter is a complex mixture of particles that are composed of one or many of the following substances: organic material, metals, elements, and ions, including sulfate. Measurements from which the MOVES $PM_{2.5}$ emission rates are based on are typically filter-based, which include the mass of all the chemical components in the particle-phase. MOVES reports PM emissions in terms of elemental carbon (EC) and the remaining non-elemental carbon PM (nonECPM).

As described above for $NO_x$, the heavy-duty diesel $PM_{2.5}$ emission rates in MOVES are a function of: (1) fueltype, (2) regulatory class, (3) model year group, (4) operating mode, and (5) age group. We classified heavy-duty diesel exhaust PM emission data into the following model year groups for purposes of emission rate development. These groups are generally based on the introduction of emissions standards for heavy-duty diesel engines. They also serve as a surrogate for continually advancing emission control technology on heavy-duty engines. For example, MY 2010 and beyond is defined as a separate group even though the PM standard is unchanged from the previous group MY 2007-2009. This is because, starting with MY 2010, the wide adoption of SCR systems and improvements in DPFs likely resulted in a shift in tailpipe $PM_{2.5}$emissions. Other, secondary reasons include wider availability of $PM_{2.5}$ data in the HDIUT data set (section 2.1.1.1) for MY 2010-2011 and the $f_{scale}$ updates to all HD regClasses for MY 2010 and later (see section 2.1.1.4.2 and Appendix G). Table 2-17 shows the model year group ranges and the applicable brake-specific emissions standards.

**Table 2-17 Model Year Groups Used for Analysis Based on the PM Emissions Standard**

| Model Year Group Range | PM Standard (g/bhp-hr) |
|---|---|
| 1960-1987 | No transient cycle standard |
| 1988-1990 | 0.60 |
| 1991-1993 | 0.25 |
| 1994-1997 | 0.10 |
| 1998-2006 | 0.10 |
| 2007-2009 | 0.01 |
| 2010+ | 0.01 |

Section 1.2.1 and Section 2.1.2.2 discuss the derivation of the MY 1960-2009 and 2010-2060 heavy-duty diesel $PM_{2.5}$ emission rates, respectively. The discussion of the tampering and mal-maintenance factors applied to emissions in both model year groups are discussed in Section 2.1.2.3.

#### *2.1.2.1 1960-2009 Model Years*

The $PM_{2.5}$ data from was analyzed in several steps to obtain MY 1960-2009 $PM_{2.5}$ emission rates. First, STP operating mode bins were calculated from the chassis dynamometer data from the CRC E55/59. Second, continuous $PM_{2.5}$ data measured by the TEOM was normalized to gravimetric PM filters. Third, MOVES $PM_{2.5}$ emission rates were calculated for the STP operating mode bins for the available regulatory class and model year combinations. Then, steps were taken to estimate missing operating modes, regulatory classes, and model years from the E55/59 program. In addition, we estimate the EC/PM fraction and adjust the emission rates to account for tampering and mal-maintenance. The E55/59 data and analysis steps are explained in detail in the following subsections.

##### *2.1.2.1.1 Data Sources*

All of the data used to develop the MOVES $PM_{2.5}$ emission rates for MY 1960-2009 was generated based on the CRC E-55/59 research program.[41] The following description in the "*Compilation of Diesel Emissions Speciation Data – Final Report*"[42] provides a good summary of the program:

> The objective of the CRC E55/59 test program was to improve the understanding of the California heavy-duty vehicle emissions inventory by obtaining emissions from a representative vehicle fleet, and to include unregulated emissions measured for a subset of the tested fleet. The sponsors of this project include CARB, EPA, Engine Manufacturers Association, DOE/NREL, and SCAQMD. The project consisted of four segments, designated as Phases 1, 1.5, 2, and 3. Seventy-five vehicles were recruited in total for the program, and recruitment covered the model year range of 1974 through 2004. The number and types of vehicles tested in each phase are as follows:
>
> - Phase 1: 25 heavy heavy-duty (HHD) diesel trucks
> - Phase 1.5: 13 HHD diesel trucks
> - Phase 2: 10 HHD diesel trucks, 7 medium heavy-duty (MHD) diesel trucks, 2 MHD gasoline trucks
> - Phase 3: 9 MHD diesel, 8 HHD diesel, and 2 MHD gasoline
>
> The vehicles tested in this study were procured in the Los Angeles area, based on model years specified by the sponsors and by engine types determined from a survey. WVU measured regulated emissions data from these vehicles and gathered emissions samples. Emission samples from a subset of the vehicles were analyzed by Desert Research Institute for chemical species detail. The California Trucking Association assisted in the selection of vehicles to be included in this study. Speciation data were obtained from a total of nine different vehicles. Emissions were measured using WVU's Transportable Heavy-Duty Vehicle Emissions Testing Laboratory. The laboratory employed a chassis dynamometer, with flywheels and eddy-current power absorbers, a full-scale dilution tunnel, heated probes and sample lines and research grade gas analyzers. PM was measured gravimetrically. Additional sampling ports on the dilution tunnel supplied dilute exhaust for capturing unregulated species and PM size fractions. Background data for gaseous emissions were gathered for each vehicle test and separate tests were performed to capture background samples of PM and unregulated species. In addition, a sample of the vehicles received

Tapered Element Oscillating Microbalance (TEOM) measurement of real time particulate emissions.

The HHDDTs were tested under unladen, 56,000 lb., and 30,000 lb. truck load weights. The driving cycles used for the HHDDT testing included:

- AC50/80;
- UDDS;
- Five modes of an HHDDT test schedule proposed by CARB: Idle, Creep, Transient, Cruise, and HHDDT_S (a high-speed cruise mode of shortened duration);
- The U.S. EPA Transient test.

The CARB HHDDT test cycle is based on California truck activity data and was developed to improve the accuracy of emissions inventories. It should be noted that the transient portion of this CARB test schedule is similar but not the same as the EPA certification transient test.

The tables below provide a greater detail on the CRC E-55/59 data used in the analysis. Both the number of tests and number of vehicles by model year group and regulatory class (MHD, HHD) are provided in Table 2-18.

**Table 2-18 Vehicle and Test Counts by Regulatory Class and Model Year Group**

| Regulatory Class | Model Year Group | Number of tests | Number of vehicles |
|---|---|---|---|
| MHD | 1960 - 1987 | 82 | 7 |
| | 1988 - 1990 | 39 | 5 |
| | 1991 - 1993 | 22 | 2 |
| | 1994 - 1997 | 39 | 4 |
| | 1998 - 2006 | 43 | 5 |
| | 2007 - 2009 | 0 | 0 |
| HHD | 1960 - 1987 | 31 | 6 |
| | 1988 - 1990 | 7 | 2 |
| | 1991 - 1993 | 14 | 2 |
| | 1994 - 1997 | 22 | 5 |
| | 1998 - 2006 | 171 | 18 |
| | 2007 - 2009 | 0 | 0 |

Counts of tests are provided by test cycle in Table 2-19.

**Table 2-19 Vehicle Test Counts by Test Cycle**

| Test Cycle | Number of tests |
|---|---|
| CARB-T | 71 |
| CARB-R | 66 |
| CARB-I | 42 |
| UDDS_W | 65 |
| AC5080 | 42 |
| CARB-C | 24 |
| CARBCL | 34 |
| MHDTCS | 63 |
| MHDTLO | 23 |
| MHDTHI | 24 |
| MHDTCR | 29 |

###### *2.1.2.1.2 Calculate STP from Second-By-Second Data*

For each second of operation on the chassis-dynamometer the instantaneous scaled tractive power ($STP_t$) was calculated using Equation 1-6, and then subsequently classified to one of the 23 operating modes defined above in Table 1-4.

The values of coefficients *A*, *B*, and *C* are the road-load coefficients pertaining to the heavy-duty vehicles as determined through previous analyses for EPA's Physical Emission Rate Estimator (PERE).[43] The chassis dynamometer cycles used in E55/59 include the impact of speed, acceleration, and loaded weight on the vehicle load, but grade effects are not included and the grade value is set equal to zero in Equation 1-6.

Note that this approach differs from the $NO_x$ emission rates analysis described in Section 2.1.1.3, since the particulate data was collected on a chassis dynamometer from vehicles lacking electronic control units (ECU). We have not formally compared the results of the two methods of calculating STP. However, on average, we did find the operating-mode distributions to be similar between the two calculation methods for a given vehicle type. For example, we found that the maximum STP in each speed range was approximately the same.

###### *2.1.2.1.3 Compute Normalized TEOM Readings*

The TEOM readings were obtained for a subset of tests in the E-55/59 test program. Only 29 vehicles had a full complement of 1-Hz TEOM measurements. However, the continuous particulate values were modeled for the remaining vehicles by West Virginia University, and results were provided to EPA. In the end, a total of 56 vehicles and 470 tests were used in the analysis out of a possible 75 vehicles. Vehicles and tests were excluded if the total TEOM $PM_{2.5}$ reading was negative or zero, or if corresponding full-cycle filter masses were not available. Table 2-20 provides vehicle and test counts by vehicle class and model year. The MHD (Class 6 and Class 7) trucks tested in the study included seven Class 6 and eleven Class 7 vehicles, representing only a limited model years.

Table 2-20 Vehicle and Test Counts by Heavy-Duty Class and Model Year

| Model Year | HDD Class 6/7(MHD) | | HDD Class 8 (HHD) | |
|---|---|---|---|---|
| | No. Vehicles | No. Tests | No. Vehicles | No. Tests |
| 1969 | - | - | 1 | 6 |
| 1974 | 1 | 10 | - | - |
| 1975 | - | - | 2 | 10 |
| 1978 | - | - | 1 | 5 |
| 1982 | 1 | 5 | - | - |
| 1983 | 1 | 10 | 1 | 6 |
| 1985 | 1 | 28 | 1 | 10 |
| 1986 | 1 | 3 | 1 | 4 |
| 1989 | 2 | 11 | 1 | 4 |
| 1990 | 1 | 12 | 1 | 3 |
| 1992 | 1 | 11 | 1 | 11 |
| 1993 | 1 | 11 | 1 | 3 |
| 1994 | 1 | 9 | 3 | 15 |
| 1995 | 2 | 24 | 3 | 13 |
| 1998 | 2 | 20 | 3 | 28 |
| 1999 | - | - | 3 | 43 |
| 2000 | 2 | 18 | 5 | 44 |
| 2001 | 1 | 5 | 2 | 21 |
| 2004 | - | - | 4 | 29 |
| 2005 | - | - | 1 | 6 |

Since the development of MOVES emission rates is cycle independent, all available cycles/tests which met the above requirements were utilized. As a result, 488,881 seconds of TEOM data were used. The process required that each individual second-by-second TEOM rate be normalized to its corresponding full-cycle filter mass, available for each combination of vehicle and test. This step was necessary because individual TEOM measurements are highly uncertain and vary widely in terms of magnitude (extreme positive and negative absolute readings can occur). Kinsey et al. (2006)[44] demonstrated that time-integrated TEOM measurements compare well with gravimetric filter measurements of diesel-generated particulate matter. Equation 2-27 shows the normalization process for a particular one second TEOM measurement.

$$PM_{\text{normalized},i,j} = \frac{PM_{\text{filter},j}}{\sum^{j} PM_{\text{TEOM},i}} PM_{\text{TEOM},j,i} \qquad \textbf{Equation 2-27}$$

Where:

$i$ = an individual 1-Hz measurement (g/sec),
$j$ = an individual test on an individual vehicle,
$PM_{TEOM,j,i}$ = an individual TEOM measurement on vehicle $j$ at second $i$,
$PM_{filter,j}$ = the total $PM_{2.5}$ filter mass on vehicle $j$,
$PM_{normalized,i,j}$ = an estimated continuous emission result ($PM_{2.5}$) emission result on vehicle $j$ at second $i$.

###### *2.1.2.1.4 Compute Average Rates by MOVES Operating Mode*

After normalization, the data were classified into the 23 operating modes defined in Section 1.6 by regulatory class and model-year group. Mean average results, and standard deviation for $PM_{2.5}$ emission values were computed in terms of g/hour for each operating mode. In cases where the vehicle and TEOM samples were sufficient for a given mode (based on the number of points within each operating mode bin), these mean values were adopted as the MOVES emission rates for total $PM_{2.5}$.

###### *2.1.2.1.5 Populating Missing and High-Power Operating Modes*

As detailed in Appendix E, a log-linear regression was performed on the existing $PM_{2.5}$ data against STP to fill in emission rates for missing operating mode bins. Similar to the $NO_x$ rates for MY 2009 and older vehicles, emission rates were extrapolated for the highest STP operating modes.

###### *2.1.2.1.6 LHD and Urban Bus Emission Rates*

The $PM_{2.5}$ emission rates for LHD and Urban Buses are based on the available TEOM data collected on MHD and HHD vehicles. We believe this is reasonable because the certification standards in terms of brake horsepower-hour (bhp-hr) are the same for LHD, MHD, and HHD regulatory classes.

The following steps were conducted to adjust the emissions estimated from the MHD and HHD regulatory classes because the data were not analyzed for the $f_{scale}$.used for LHD. The emission rates of pre-2010 LHD (LHD2b3 and LHD45 (regClassID 41 and 42) are based on an $f_{scale}$ of 2.06 as discussed in Section 1.5, whereas MHD and HHD are based on an $f_{scale}$ of 17.1. The $PM_{2.5}$ emission rates for the pre-2010 LHD regulatory classes are derived from the VSP-based MHD $PM_{2.5}$ emission factors derived from the E55/59 TEOM data as analysed for MOVES2009.[45]

With VSP-based emission rates, the power of the vehicle is scaled to the mass of the individual tested vehicle. Because LHD have lower vehicle weights and power outputs than the MHD and HHD vehicles, we scaled the VSP-emission rates down to the power requirements of the LHD vehicles. To estimate the LHD2b3 and LHD45 $PM_{2.5}$ emission rates, we multiplied the VSP-based MHD $PM_{2.5}$ emission rates by a factor of 0.46 obtained from the MOBILE6.2 heavy-duty conversion factors[46], which accounts for the lower power requirements per mile (bhp-hr/mile) of light heavy-duty trucks versus MHD trucks. This scaling factor estimates VSP-based emissions rates for LHD vehicles. We approximated the STP-based MOVES emission rates for LHD vehicles using these VSP-based rates.[j] Equation 2-28 used to derive the $PM_{2.5}$ emission rates for LHD regulatory class is shown below:

$$LHDPM_{2.5}\ emission\ rate = 0.46\ \times MHD\ (VSP_{based})PM_{2.5}\ emission\ rate \qquad \textbf{Equation 2-28}$$

---

[j] When this approximation was conducted in MOVES2010, the $f_{scale}$ of 2.06 matched the average mass of LHD vehicles for the source types. This approximation need to be revisited now that we have updated the mass of LHD vehicles in MOVES to range from 3.5 to 7.8 metric tons.

Despite the uncertainty used in this approach, the representative $PM_{2.5}$ gram per mile emission rates show reasonable trends (see Figure 2-33). LHD2b3 and LHD45 emission rates for pre-2010 model years are lower than the MHD and HHD emission rates, but higher than the Urban Bus emission rates.

Urban Bus emission rates are generally assumed to be the same as the HHD emission rates. However, they have different emission deterioration effects as discussed in Appendix B.1. Also, for some model year groups, the Urban Buses are subject to a different emission standard, so we adjust the emission rates before deterioration by applying a ratio of the EPA certification standards. Table 2-21 displays the model years for which the Urban Bus regulatory class has different PM emission standards from other heavy-duty compression-ignition engines. For these model years (1991-2006), the Urban Bus PM emission rates were set equal to the HHD emission rates multiplied by the ratio in emission standards before applying deterioration. The gram per mile emission rates for Urban Bus presented in Figure 2-33 show expected trends, with lower emission rates than the other regulatory classes starting in MY 1991 through 2006.

**Table 2-21 Urban Bus PM Standards in Comparison to Heavy-Duty Highway Compression Engine Standards**

| Engine Model Year | Standard for Heavy-Duty Highway Compression-Ignition Engines (g/bhp-hr) | Standard for Urban Buses (g/bhp-hr) | Ratio in standards |
|---|---|---|---|
| 1991-1993[a] | 0.25 | 0.1 | 0.4 |
| 1994-1995 | 0.1 | 0.07 | 0.7 |
| 1996-2006 | 0.1 | 0.05 | 0.5 |

Note:

[a] The 0.1 g/bhp-hr US EPA Urban Bus standard began with model year 1993. In California, the 0.1 g/bhp-hr Urban Bus standard began in 1991. MOVES assumes all Urban Buses met the stricter CA standard beginning in 1991.

##### *2.1.2.1.7 Model Year 2007-2009 Vehicles (with Diesel Particulate Filters)*

The heavy-duty diesel emission regulations were made considerably more stringent for $PM_{2.5}$ emissions starting in model year 2007 – even considering the phase-ins and average banking and trading program, the emission standard fell by a factor of ten from 0.1 g/bhp-hr to 0.01 g/bhp-hr. This increase in regulatory stringency required the use of diesel particulate filter (DPF) systems on heavy-duty diesels. As a result, the $PM_{2.5}$ emission performance of diesel vehicles has improved dramatically.

At the time of analysis (originally done for MOVES2014, but carried over to MOVES3 and MOVES4 for the 2007-2009 vehicles), no continuous $PM_{2.5}$ emissions data were available on the 2007-2009 model-year vehicles. However, heavy and medium heavy-duty diesel $PM_{2.5}$ data were available from the EPA engine certification program on model years 2003 through 2007. These data provided a snapshot of new engine emission performance before and after the introduction of particulate trap technology in 2007 and made it possible to determine the relative improvement in $PM_{2.5}$ emissions from model years 2003 through 2006 to model year 2007. This same relative improvement was applied to the existing, operating mode-based, 1998-2006 model year $PM_{2.5}$ running emission rates to estimate in-use rates for MY 2007-2009 vehicles.

An analysis of the certification data is shown in Table 2-22 below. It suggests that the particulate trap reduced $PM_{2.5}$ emissions by a factor of 27.7. This factor is considerably higher than the relative change in the certification standards (i.e., a factor of 10). The reason for the difference is that the new trap-equipped vehicles certify at emission levels which are much lower than the standard, and thus, create a much larger compliance margin than previous technologies could achieve.

As an additional check on the effectiveness of the trap technology, EPA conducted some limited in-house testing of a Dodge Ram truck, and carefully reviewed the test results from the CRC Advanced Collaborative Emission Study (ACES) phase-one program, designed to characterize emissions from diesel engines meeting 2007 standards. The results from these studies demonstrated that the effectiveness of working particulate traps is very high.[47]

**Table 2-22 Average Certification Results for Model Years 2003-2007**

| **Certification Model Year** | **Mean (g/bhp-hr)[a]** | **St. Dev.** | ***n*** |
|---|---|---|---|
| 2003 | 0.084 | 0.014 | 91 |
| 2004 | 0.088 | 0.013 | 59 |
| 2005 | 0.085 | 0.014 | 60 |
| 2006 | 0.085 | 0.014 | 60 |
| 2007 | 0.003 | 0.002 | 21 |

Note: [a] Average ratio from MYs 2003-2006 to MY 2007 is 27.7.

#### *2.1.2.1.8 Elemental Carbon and Non-Elemental Carbon Emission Factors*

Particulate matter from conventional (pre-2007) diesel engines is largely composed of elemental carbon. Elemental carbon is often used synonymously with soot and black carbon. Black carbon is important because of its negative health effects and its environmental impacts as a climate forcer.[48] Elemental carbon from vehicle exhaust is measured with filter-based measurements using thermal optical methods. Continuous surrogate measures of elemental carbon can also be made with photoacoustic instruments.

MOVES models Total $PM_{2.5}$ emissions by vehicle operating mode using elemental carbon (EC) and non-elemental particulate matter carbon (NonECPM), as shown in Equation 2-29.

$$\mathrm{PM}_{2.5} = \mathrm{EC} + \mathrm{NonECPM} \qquad \textbf{Equation 2-29}$$

By having emission rates for EC and nonECPM for each operating mode, the MOVES design permits the EC fraction of PM (EC/PM) to vary for each operating mode. In practice, the data used to develop EC and nonECPM emission rates does not support such fine resolution, and the EC/PM is the same across all the running exhaust operating modesexcept for the idle operating mode.

For pre-2007 diesel trucks, we developed EC and nonECPM emission rates by applying EC/PM fractions to the modal-based emission rates. For the idle operating mode (opModeID 1), we applied an EC/PM fraction of 46.4 percent from the $PM_{2.5}$ speciation profile developed from the idle mode from the UDDS tests from the E55/59 program. For all the other operating modes within the running emission process, we used an EC/PM fraction of 79.0 percent from the $PM_{2.5}$ speciation profile developed from the transient mode of the UDDS tests from the E55/59 program. The development of the pre-2007 $PM_{2.5}$ speciation profiles from the E55/59 program are documented in the Onroad Speciation Report.[1]

For 2007-2009 DPF-equipped diesel engines, we used the EC/PM fraction of 9.98 percent measured in Phase 1 of the Advanced Collaborative Emissions Study (ACES) Report.[47] Diesel particulate filters preferentially reduce elemental carbon emissions, resulting in the low percentage of elemental carbon emissions. The average EC/PM fraction is based on four engines run on the 16-hour cycle which composes several different operating cycles. Because the fraction is based upon a range of driving conditions, we applied the constant 9.98 percent EC/PM fraction across all operating modes for the 2007+ diesel emissions rates, including the idle operating mode (opModeID 1).

Figure 2-26 and Figure 2-27 show the operating mode trend for $PM_{2.5}$ with the EC and nonECPM fractions. As with $NO_x$, the highest operating modes in each speed range will rarely be attained due to the power limitations of heavy-duty vehicles and the high $f_{scale}$ used for these model years, but are included in the figures for completeness. At high speeds (greater than 50 mph; operating modes ≥ 30), the overall $PM_{2.5}$ rates are lower than the other speed ranges. For pre-2007 model years (Figure 2-26), the $PM_{2.5}$ rates are dominated by EC (except for the idle operating mode, opModeID 1). With the introduction of DPFs in model year 2007 (Figure 2-27), we model the large reductions in overall $PM_{2.5}$ rates and the smaller relative EC contribution to PM emissions. Figure 2-35 shows the $PM_{2.5}$ gram per mile emission rates separated into the elemental carbon and non-elemental carbon fractions for HHD vehicles across model years.

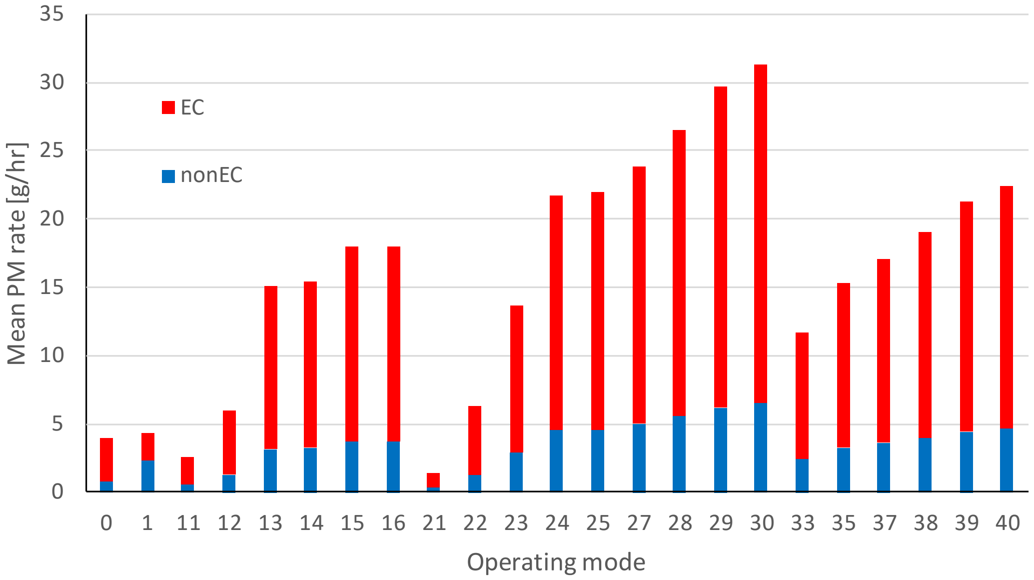

**Figure 2-26 MHD Diesel $PM_{2.5}$ Emission Rates for MY 2006 (age 0-3) by Operating Mode**

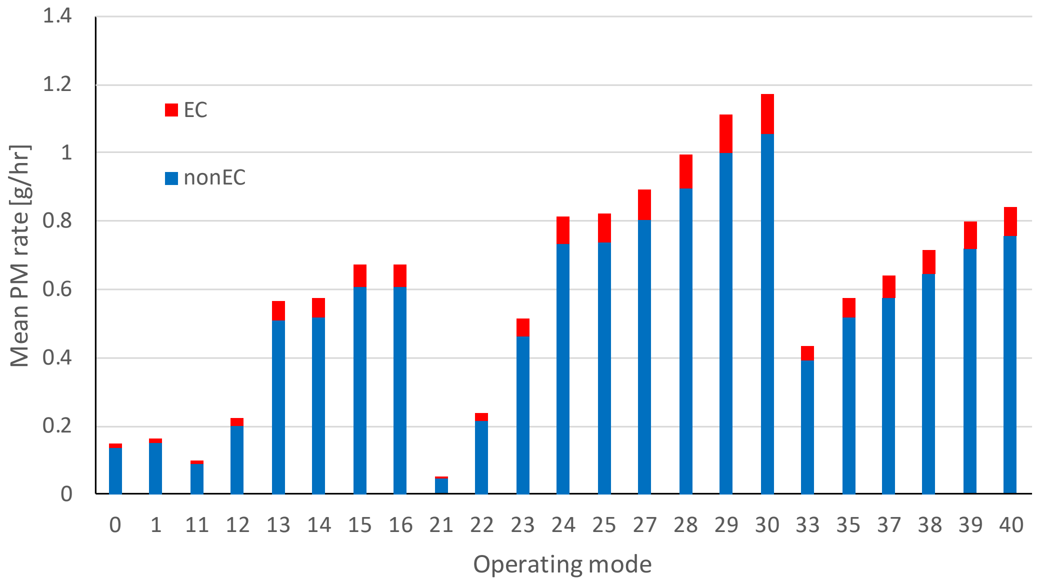

**Figure 2-27 MHD Diesel $PM_{2.5}$ Emission Rates for MY 2007 (age 0-3) by Operating Mode**

### *2.1.2.2 2010-2060 Model Years*

The MY 2010+ HDIUT data set described in Section 2.1.1.1 and Table 2-2 was used to update $PM_{2.5}$ emissions rates for MY 2010+ vehicles. Operating modes (Table 1-4) were assigned to the 1 hz data using the method to calculate STP described in Section 2.1.1.3, and the updated $f_{scale}$ values developed for the 2010+ MY $NO_x$ analysis described in Section 2.1.1.4.2 and Appendix G.

#### *2.1.2.2.1 Estimating Base Rates*

As compared to the $NO_x$, THC, and CO data, the $PM_{2.5}$ emissions data reported from the HDIUT program had many missing, negative and zero values. When the $PM_{2.5}$ emissions data are distributed over the $NO_x$ FEL groups, the number of vehicles with valid measurements (non-zero or non-negative) by regulatory class and model year group was very limited as shown in Table 2-23. The number of vehicles with valid measurements for each model year group and regulatory class are significantly smaller than the total number of vehicles tested, with the exception of the HHD 2014-2015 model year group.

**Table 2-23. HDIU Vehicles with Valid $PM_{2.5}$ Measurements By Regulatory Class, Model Year Group and $NO_x$ FEL Group**

| | | Valid Measurements by $NO_x$ FEL Group | | | Total Valid | Total Vehicles Tested |
|---|---|---|---|---|---|---|
| Reg Class | Model Year Group | 0.2 | 0.35 | 0.5 | | |
| LHD | 2010-2013 | 52 | 0 | 4 | 56 | 64 |
| | 2014-2016 | 19 | 0 | 2 | 21 | 32 |
| MHD | 2010-2013 | 20 | 6 | 6 | 32 | 55 |
| | 2014-2015 | 17 | 6[1] | 6[1] | 29 | 51 |
| HHD | 2010-2013 | 57 | 9 | 26 | 92 | 139 |
| | 2014-2015 | 48 | 4 | 0 | 52 | 55 |

Note:

[1] Due to an absence of MHD 2014-2015 vehicles certified to 0.35 and 0.5 $NO_x$ in the HDIUT, we replicated the HDIUT MHD 2010-2013 vehicles certified to 0.35 and 0.5 $NO_x$ FEL to the 2014-2015 model year group.

When evaluating the data by operating mode, the data are even more sparse. Table 2-23 shows the total number of vehicles tested by model year group and regulatory class that had valid (positive) $PM_{2.5}$ emissions data in at least one operating mode. However, the number of vehicles with valid measurements is less when the data is evaluated by operating mode. Table 2-24 shows the minimum and maximum range of valid vehicle measurements by individual operating modes. The operating modes with the smallest number of valid measurements tended to be for the high-power operating modes (opModeID 29, 30, 39 and 40). The highest number of valid measurements tend to be for the high speed (>50 mph) at moderate power (opModeID 33, 35, 37, and 38).

We addressed the issue of data sparsity in the $PM_{2.5}$ emissions data by not using $NO_x$ FEL based grouping and production volume weighting. By aggregating the data across $NO_x$ FEL groups, there was sufficient data to divide the data into the two model year groups used for the $NO_x$ analysis: MY 2010-2013 and 2014-2015/2016. Note that for the current HDIUT dataset, LHD includes MY 2016 vehicles, but MHD and HHD only include up to MY 2015.

**Table 2-24. Range of Valid Vehicle Measurements by Operating Mode by Regulatory Class and Model Year Group**

| | Model Year Group | Total Valid Vehicle Measurements (in at least one operating mode) | Minimum Valid Vehicle Measurements for any operating mode | Maximum Valid Vehicle Measurements for any operating mode |
|---|---|---|---|---|
| LHD | 2010-2013 | 56 | 11 | 52 |
| | 2014-2016 | 21 | 3 | 18 |
| MHD | 2010-2013 | 32 | 4 | 27 |
| | 2014-2015 | 29 | 3 | 26 |
| HHD | 2010-2013 | 92 | 17 | 83 |
| | 2014-2015 | 52 | 4 | 45 |

The operating mode-based $PM_{2.5}$ emission rates were estimated using Equation 2-30 and Equation 2-31, which are similar to Equation 2-13 and Equation 2-14 used for the development of $NO_x$ emission rates except the FEL grouping factor is removed. Zero or negative emission rates are as treated as missing values. Despite the sparseness of the data by operating mode, due to the revised $f_{scale}$ factors for 2010 and later vehicles (2.1.1.5.4), in general, there was no need for estimating rates for missing high power operating modes.[k]

$$ER_{pol,OM,C,MYG,veh} = \frac{\sum_{sec} ER_{pol,OM,C,MYG,veh,sec}}{sec_{count}}$$ **Equation 2-30**

$$ER_{pol,OM,C,MYG} = \frac{\sum_{veh} ER_{pol,OM,C,veh}}{veh_{count}}$$ **Equation 2-31**

Where:

C = Regulatory class (LHD, MHD, HHD, and Urban Bus)
ERx,y,z = Emission rate in mass/time. The subscripts show the categorization
MYG = Model year group (2010-2013 or 2014-2016)
MY = Model year
OM = running exhaust emissions operating mode
pol = Pollutant ($PM_{2.5}$ )
sec; $sec_{count}$ = a second of data (for a given *veh* and *OM*); number of seconds in that category
veh; $veh_{count}$ = a vehicle (in the class); number of vehicles in that category

Similar to $NO_x$, the $PM_{2.5}$ rates for LHD2b3 and LHD45 are identical and based on the combined LHD class vehicles in HDIUT, while the MHD rates are based on MHD class vehicles, and HHD and Urban Bus rates are based on HHD class vehicles.

Because we did not use production volume weighting by $NO_x$ FEL, the $PM_{2.5}$ emission rates are the same for each model year within the two model year groups. The 2014-2015 model year group sample contains a higher penetration of HHD vehicles certified to the 0.2 $NO_x$ FEL group, than the 2010-2013 model year HHD group (Table 2-23) which is consistent with the trend in production volumes (Figure 2-12). The LHD vehicles had a similar proportion of vehicles certified to the 0.2 and 0.35 $NO_x$ FELs within the 2010-2013 and 2014-2016 model year groups. The $PM_{2.5}$ emission rates decrease for each of the regulatory classes between the MY 2010-2013 and 2014 and later model years as observed in Figure 2-34.

There was no valid HDIUT PM data for 2014-2015 MY MHD vehicles within the 0.35 and 0.50 FEL groups. Because there are 2014-2015 MY MHD vehicles certified to these higher levels in the production volume data (Figure 2-12), we supplemented the 2014-2016 MY MHD data with data from the MY 2010-2013 MHD vehicles in the 0.35 and 0.5 FEL groups. As such, the MHD vehicles have a similar proportion of vehicles certified to the 0.35 and 0.5 $NO_x$ FEL Groups within the 2010-2013 and 2014-2015 model year groups.

Figure 2-28 through Figure 2-30 display the average $PM_{2.5}$ emission rates by regulatory class, model year group, and operating mode. The error bars are the 95% confidence intervals of the mean, calculated by treating the mean emission rates from each vehicle within each operating mode

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[k] The MHD 2010-2013 vehicles were an exception, missing data in operating modes 29, 30, and 40. Using the methods outlined in Appendix I.3 the emission rates in operating mode 29 and 30 were set equal to 28, and 40 was set equal to 39.

as an independent random variable. While the average $PM_{2.5}$ emission rates by individual operating mode bin and regulatory class generally are not significantly different between the 2010-2013 and 2014-2016 model year groups, when you look across the operating modes, there is a fairly consistent decrease in $PM_{2.5}$ emission rates in the 2014-2016 compared to the 2010-2013 model year groups. The observed decrease in $PM_{2.5}$ emission rates in the 2014+ model year emission rates is consistent with the decrease in extended idle $PM_{2.5}$ emissions observed with the full-phase in of SCR engines[1] (Section 2.3.2.2).

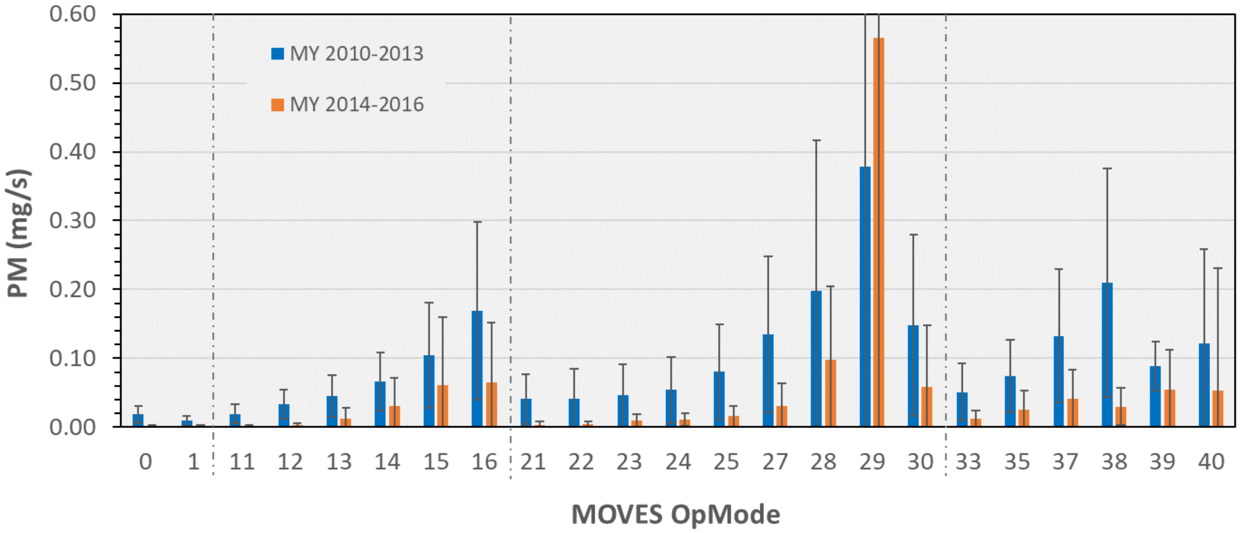

**Figure 2-28 $PM_{2.5}$ Emissions by Operating Mode for LHD Model Year Groups 2010-2013 and 2014-2016**

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[1] As discussed in Section 2.3.2.2, we believe the reduction in THC and $PM_{2.5}$ with the SCR systems is because the SCR aftertreatment classification is a surrogate for the combined engine control and aftertreatment system used with SCR equipped trucks that have a large impact on THC emissions. With the use of SCR, engines can be calibrated to run leaner, producing lower engine-out $PM_{2.5}$. Additionally, SCR systems rely on oxidation catalysts and/or catalyzed DPFs to convert NO to $NO_2$, which also reduces $PM_{2.5}$ tailpipe emissions.

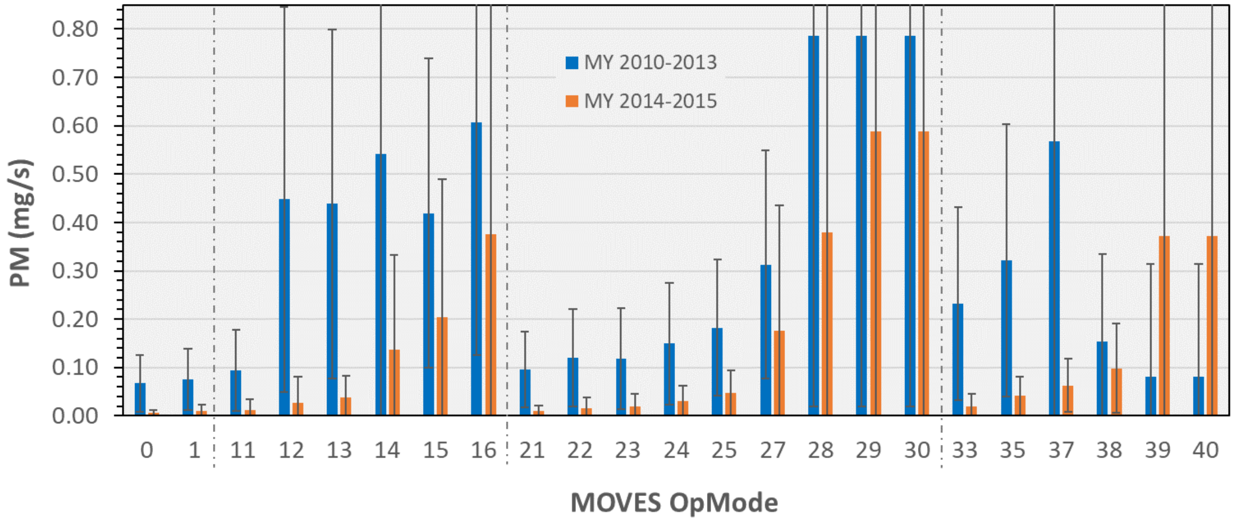

Figure 2-29 $PM_{2.5}$ Emissions by Operating Mode for MHD Model Year Groups 2010-2013 and 2014-2015

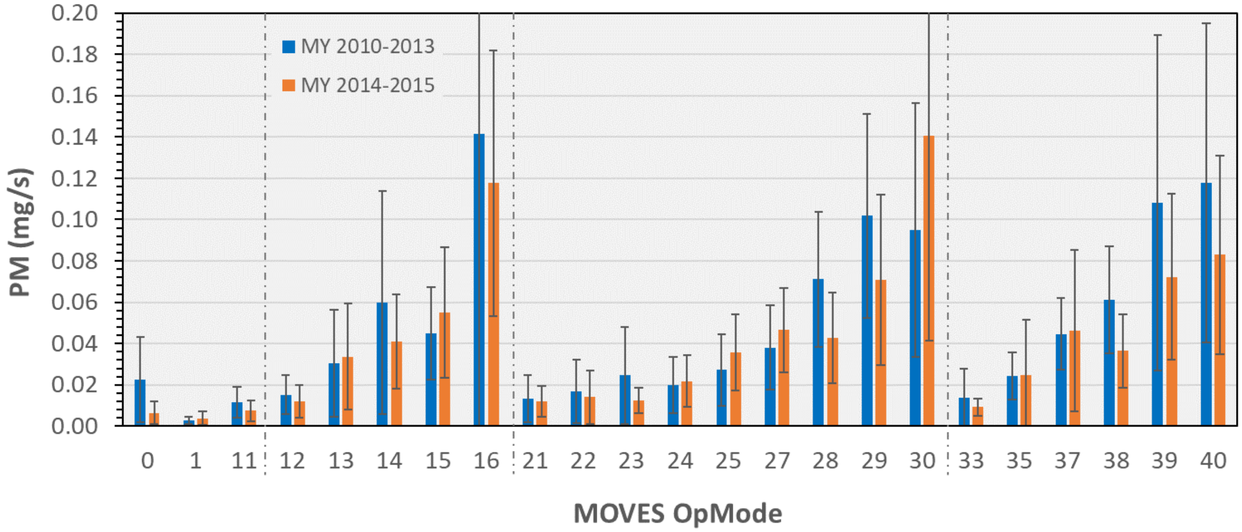

Figure 2-30 $PM_{2.5}$ Emissions by Operating Mode for HHD Model Year Groups 2010-2013 and 2014-2015

As observed in Figure 2-28 through Figure 2-30, the $PM_{2.5}$ emission rates are highest for the MHD vehicles, followed by the HHD, and then the LHD vehicles. The corresponding uncertainty of the MHD rates is also largest compared to the other rates. We do not have a reason to suspect the accuracy of the HDIUT $PM_{2.5}$ measurements from the MHD vehicles, and we can only speculate on the reasons the MHD emission rates would be higher than the other regulatory classes. For example, the fraction of vehicles produced in the less stringent 0.35 and 0.5 $NO_x$ FEL groups is higher for the MHD than most of the other regulatory class and model year combinations, but not all (Table 2-23).

Because much of the HDIUT PM data are missing or reported as zero, and given the additional uncertainty regarding the MHD rates, we compared our HDIUT-based $PM_{2.5}$ rates against values reported in the literature. As shown in Figure 2-34, the MOVES age 0-3 $PM_{2.5}$ rate ranges from 3 to 7 mg/mile for MY 2010-2014 HHD and LHD vehicles with the MHD significantly higher at 26 mg/mile and from 2 to 7 mg/mile for all HD MY 2014+ vehicles. Other studies have reported $PM_{2.5}$ rates in the range of 1-7 mg/mi for MY 2010+ vehicles equipped with DPF and SCR and certified to $NO_x$ standard of 0.20 g/bhp-hr.[49,50,51] The rates from the MOVES run and other studies are dependent on driving cycle, however, since the MOVES rates are generally within the range of reported values, we believe it is reasonable to use the HDIUT-based $PM_{2.5}$ data for the update for all regulatory classes.

The MY 2014-2016 emission rates are applied to all future model yearsfor each regulatory class. The Tier 3 rulemaking sets PM FTP emission standards for Class 2b and Class 3 of 8 mg/mile and 10 mg/mile respectively.[52] Because the age 0-3 LHD2b3 MOVES emissions rates are well below the Tier 3 standard, we do not estimate a reduction in zero-mile $PM_{2.5}$ rates with the phase-in of Tier 3 in MY 2018 and later vehicles as we do for $NO_x$ emissions. For $PM_{2.5}$, the MOVES LHD2b3 rates are in compliance with the 3 mg/mile standard as shown in Figure 2-34 However, we do incorporate different aging effects due to the extended useful life in the Tier 3 program as discussed below in Section 2.1.2.3.2.

#### *2.1.2.2.2 Elemental Carbon and Non-Elemental Carbon Emission Rates*

The EC (9.98 percent) and non-EC (90.02 percent) fractions for MY 2010 and later are unchanged from MY 2007-2009 analysis described in section 2.1.2.1.8. As discussed in the Speciation Report[1], the ACES Phase 1 is deemed to be an appriorate source of the EC/PM fractions for 2010+ engines which continue to use DPF technology along with other selective catalyctic converters for controlling $NO_x$. One of the reasons why we deemed applying the ACES Phase 1 PM speciation preferable to using the ACES Phase 2 profile (which is tested on MY 2011 diesel engines and aftertreatment systems) is because the ACES Phase 2 program did not include DPF regeneration events that can have a large impact on PM composition, as discussed in the MOVES speciation report.[1]

#### *2.1.2.2.3 DPF Regeneration Events*

The MOVES 3 emission rates include active DPF regeneration effects because the HDIUT data set includes active regeneration activity, but MOVES does not model active regeneration explicitly. To do this, we would like to have detailed information on the frequency and emission effect of real world regeneration events by operating mode and regulatory class. Until we have that kind of data and see a need for that detail in MOVES, we assume that the emission rates in MOVES for MY 2010+ HD vehicles reasonably capture the average effect of active DPF regeneration events.

To assess the amount of active regeneration activity in the HDIUT data, we examined the ECU codes. Modern DPFs have catalyzed substrate that allow them to undergo passive regeneration when the vehicle is operating at high-speeds and/or high-loads such that the exhaust temperature is sufficient to induce the regeneration. The passive regeneration events are "silent" and happen in the background without any regeneration code in the ECU data. On the other hand, active regeneration events happen when the ECU actively raises the temperature in the exhaust so that the soot captured in the DPF can be combusted. One way to increase the temperature is to inject additional fuel which gets burned off and raises the temperature. These events can raise the $PM_{2.5}$

concentrations considerably, but may only occur infrequently. We analyzed the “Regen_Signal” column in the quality-assured 1 hz emissions data files for 77 vehicles in the HHD 0.20 $NO_x$ FEL group to estimate the frequency and count of regeneration events. It is our understanding that the “Regen_Signal” flag only accounts for active regen events. There were 11 vehicles with the Regen_Signal set to “Y” and the regen events totaled 60,576 seconds, which is about 18% of the data from just those 11 vehicles and 3% of the data from all 77 vehicles. Future work could evaluate whether the active regeneration observed in the HDIUT data is consistent with other studies and whether the $PM_{2.5}$ second-by-second measurements accurately capture the elevated $PM_{2.5}$ concentrations that occur during active regeneration events.[m]

#### 2.1.2.3 Tampering and Mal-maintenance

Tampering refers to intentional disabling or modifying the vehicle engine, control systems, and/or exhaust aftertreatment systems that results in increased emissions. Mal-maintenance refers to lack or improper maintenance of the engine and aftertreatment, including neglecting to repair broken or mal-functioning engine and aftertreatment parts, which also increases emissions. MOVES uses the same methodology to apply tampering and mal-maintenance (T&M) adjustment factors to both the pre-2010 and 2010 and later $PM_{2.5}$ emission rates

We followed the same tampering and mal-maintenance methodology and analysis for $PM_{2.5}$ as we did for $NO_x$, as described in Appendix B. We account for the emission increases with age by multiplying the zero-mile emission rates by T&M adjustment factors and scaled aged effects (Equation 8-3). The MOVES T&M adjustment factors on $PM_{2.5}$ emissions over the fleet’s useful life are shown in Table 2-25 and derived in Appendix B.8. The value of 89 percent for 2010-2012 model years reflects the projected effect of heavy-duty on-board diagnostic deterrence/early repair of T&M effects. It is an eleven percent improvement from model years which do not have OBD (i.e., 2007-2009). The 67 percent value for 2013+ is driven by the assumed full-implementation of the OBD in 2013 and later trucks, which assumes a 33 percent decrease in T&M emission effects.

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[m] As discussed in the MOVES speciation report[1], the $PM_{2.5}$ composition can change significantly during regeneration events. Second-by-second $PM_{2.5}$ measurements made with a photoacoustic or optical method are dependent on the properties of the $PM_{2.5}$ composition

**Table 2-25 Tampering and Mal-maintenance Adjustment Factors for $PM_{2.5}$ over the Useful Life[2]**

| Model Year Group | Increase in $PM_{2.5}$ Emissions (%) |
|---|---|
| Pre-1998 | 85 |
| 1998 - 2002 | 74 |
| 2003 – 2006 | 48 |
| 2007 – 2009 | 100 |
| 2010 – 2012[1] | 89 (HHD, MHD, LHD45, and Bus)<br>67 (LHD2b3) |
| 2013+ | 67 |

Note:

[1] LHD2b3 achieve full OBD adoption in MY 2010. HHD, MHD, LHD45, and Bus are at partial (33%) and full OBD adoption in MY 2010-2012 and MY 2013, respectively.

[2] Useful life varies by regulatory class (Table B-4)

#### *2.1.2.3.1 1960-2009 Model Years*

The CRC E-55/59 emissions data set used for the pre-2010 emission rates was collected during a limited calendar year period, yet MOVES requires data from a complete range of model year/age combinations. For example, for the 1981 through 1983 model year group, the primary dataset contained data which was in either the 15-to-19 or the 20+ age groups. However, for completeness, MOVES must have emission rates for these model years for age groups 0-3, 4-5, 6-7, etc. In populating the emission rates in MOVES, we used the age group that had the most data in each regulatory class and model year group combination. Then, we used the T&M methodology discussed in the previous section to model age and model year group combinations.

One criticism of the T&M approach is that it may double count the effect of T&M on the fleet because the primary emission measurements, and base emission rates, were made on in-use vehicles that may have had maintenance issues during the testing period. This issue would be most acute for the 2007 and later model year vehicles where all of the deterioration is subject to projection. However, for 2007 and later model year vehicles, the base emission rates start at low levels, and represent vehicles that are considered to be free from the effects of T&M.

Figure 2-31 shows the estimated $PM_{2.5}$ emission rates from MY 2006 heavy-duty diesel vehicles, accounting for the effect of tampering and mal-maintenance. The different ages at which each regulatory class reaches full useful life can be observed as the age when the emissions reach their maximum value. The age 0-3 emission rates for the 2006 and earlier model year were extrapolated using the T&M adjustment factors since the majority of these engines were older than three years when tested in the E-55/59 program.

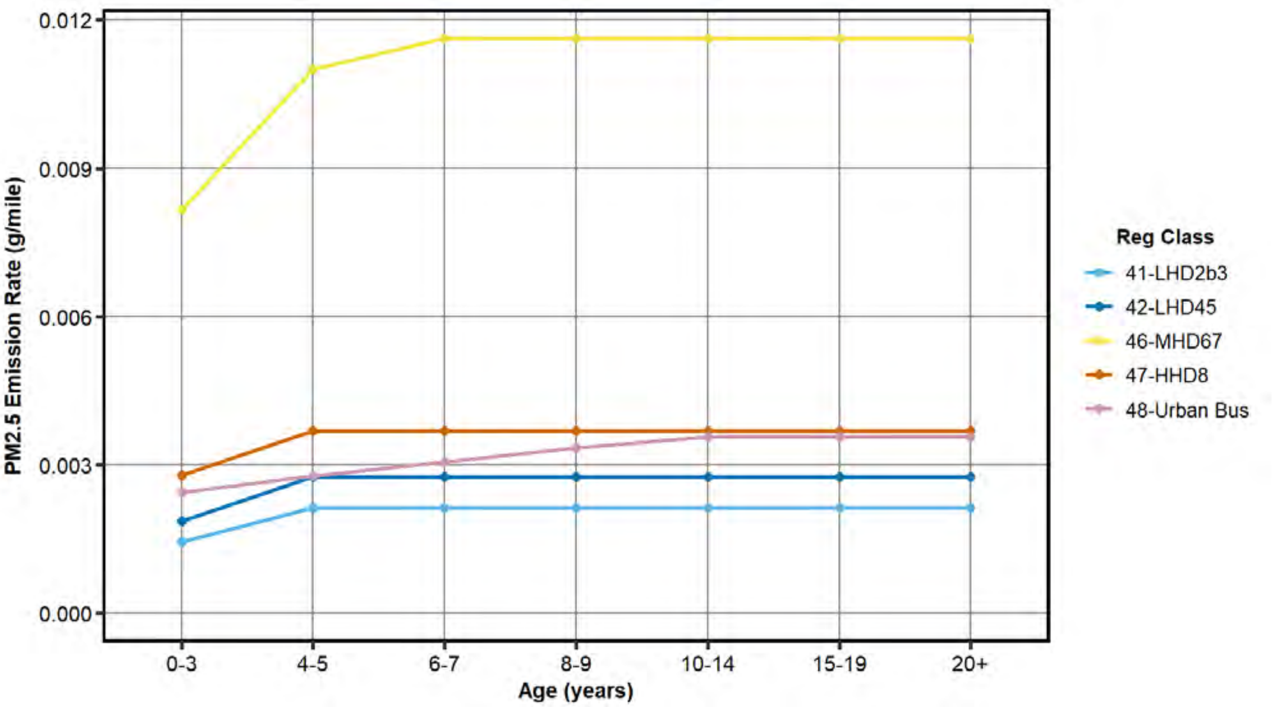

**Figure 2-31 Heavy-duty Diesel $PM_{2.5}$ Emission Rates (g/mile) by Age Group and Regulatory Class for Model Year 2006 using Nationally Representative Operating Mode Distribution**

###### *2.1.2.3.2 2010-2026 Model Years*

As mentioned in Section 2.1.1.1, the vehicles in HDIUT program are generally well-maintained and therefore, are used to represent zero-mile emission rates in MOVES. As such, we apply the T&M adjustment factors shown in Table 2-25 and scaled age effects (Table B-4) to estimate emission rates for the different ages. As shown in Table B-4, there are different age effects for Tier 2 and Tier 3 LHD2b3 vehicles. We used Equation 2-27 to estimate a weighted average of the $PM^{2.5}$ emission rates during the Tier 3 phase-in (Model year 2017-2022) as discussed in 2.1.1.5.5.

Note that for regulatory class LHD45, MHD, HHD and Urban Bus, the $PM_{2.5}$ emission rates in the MOVES database for all age groups for MY 2013+ have lower T&M age adjustments than their counterpart rates for MY 2010-2012 due to the HD OBD phase-in (see Section 2.1.2.3 and Appendix B).

Figure 2-32 shows the impact of tampering and mal-maintenance on $PM_{2.5}$ emission rates by vehicle age for MY 2015 heavy-duty vehicles. Again, the rate at which emissions increase toward their maximum varies by regulatory class.

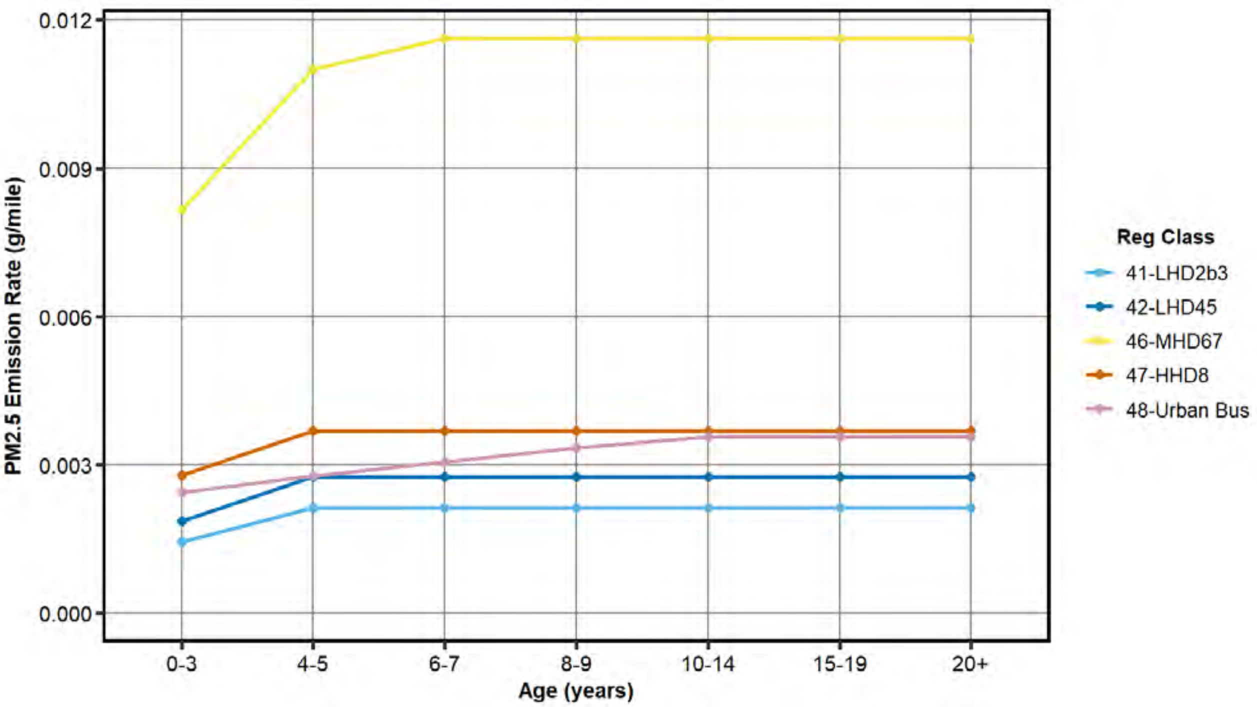

**Figure 2-32 Heavy-duty Diesel $PM_{2.5}$ Emission Rates (g/mile) by Age Group and Regulatory Class for Model Year 2015 using Nationally Representative Operating Mode Distribution**

#### *2.1.2.3.3 2027-2060 Model Years*

The T&M approach for model years 2027 through 2060 is similar to the approach for 2010 through 2026, but since the HD2027 standards set longer warranty period and useful life requirements (as shown in Table B-2) for diesel heavy-duty vehicles starting with the 2027 model year, we adjusted the T&M effects and the resulting $PM_{2.5}$ emission rates to account for those changes.

### *2.1.2.4 Model Year Trends*

Figure 2-33 displays the $PM_{2.5}$ rates by model year and regulatory class for 0-3 age group estimated in grams per mile (g/mile) using nationally representative operating mode distributions and average speeds. MOVES models a very large decrease in $PM_{2.5}$ emission rates starting in model year 2007 (decrease on order of ~10 to 40 times), when all regulatory classes are assumed to have implemented diesel particulate filters, with the exception of gliders (Section 2.5). As discussed in Section 2.1.1.8, some of the variation between regulatory classes is also due to differences in the application of T&M adjustment factors and differences in the operating mode distributions and average speeds.

Figure 2-34 provides resolution to the model year changes in $PM_{2.5}$ emission rates for the 2007 and later model years. Further reductions in $PM_{2.5}$ emissions are observed for each regulatory class between the 2007-2009 and the 2014 and later emission rates. The higher rates for MY 2010 and later MHD vehicles stem directly from the HDIUT data as shown in Figure 2-29 and discussed in Section 2.1.2.2.1. The minor variation in the gram per mile emission rates within the 2010-2013 and 2014+ model year groups by model year and regulatory class are due to differences in operating mode distributions. Finally, there is a small change in $PM_{2.5}$ rates beginning in MY2027 due to warranty period provisions of the HD2027 rule.

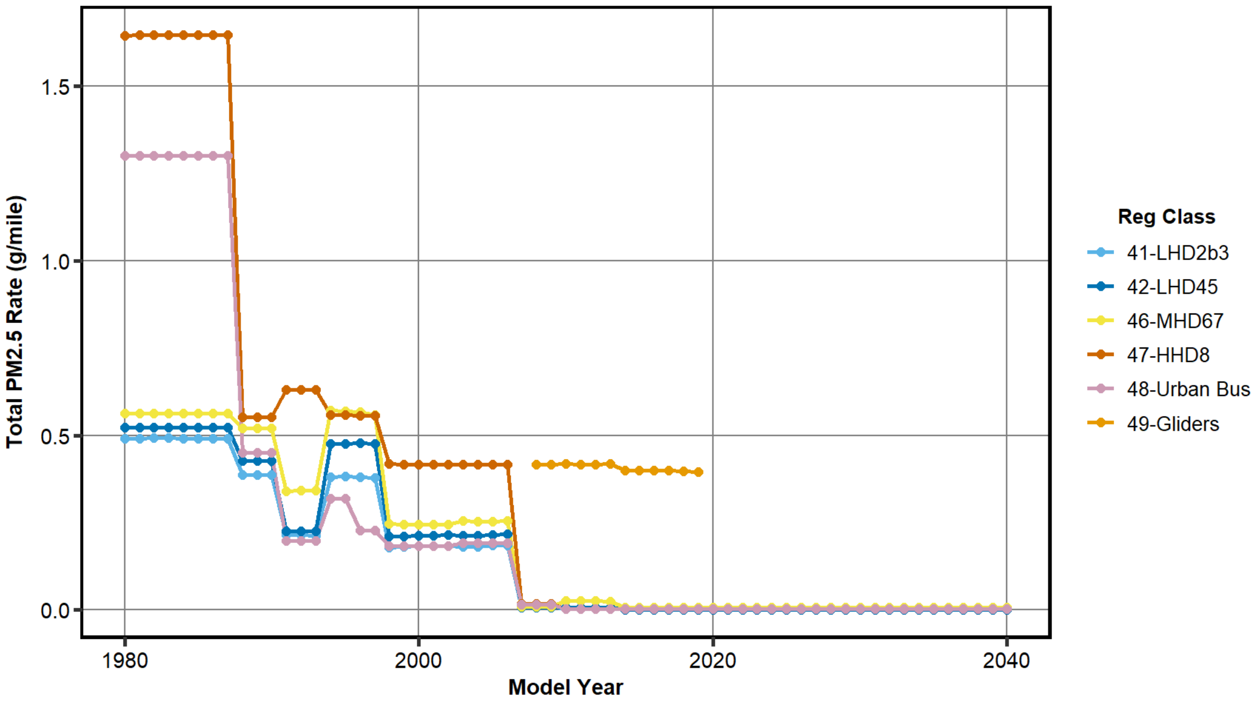

**Figure 2-33. Base running emission rates for $PM_{2.5}$ from age 0-3 diesel heavy-duty vehicles averaged over a nationally representative operating mode distribution.**

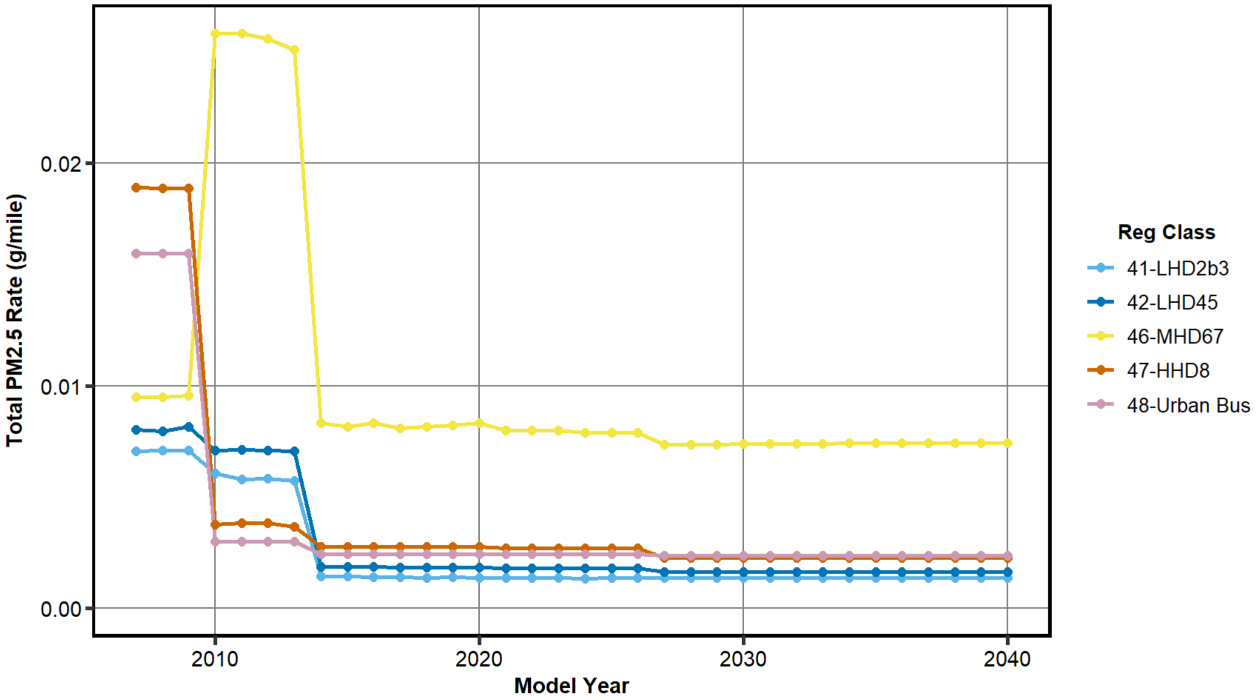

**Figure 2-34 Base running emission rates for $PM_{2.5}$ from age 0-3 diesel heavy-duty vehicles for MY 2007-2040 averaged over a nationally representative operating mode distribution.**

Figure 2-35 shows the $PM_{2.5}$ emission rates separated into elemental carbon (EC) and non-elemental carbon (nonEC) fractions for age 0-3 HHD diesel vehicles using nationally representative operating mode distributions and average speeds. The EC fraction stays constant until model year 2007, when it is reduced to less than ~10 percent due the implementation of diesel particulate filters.

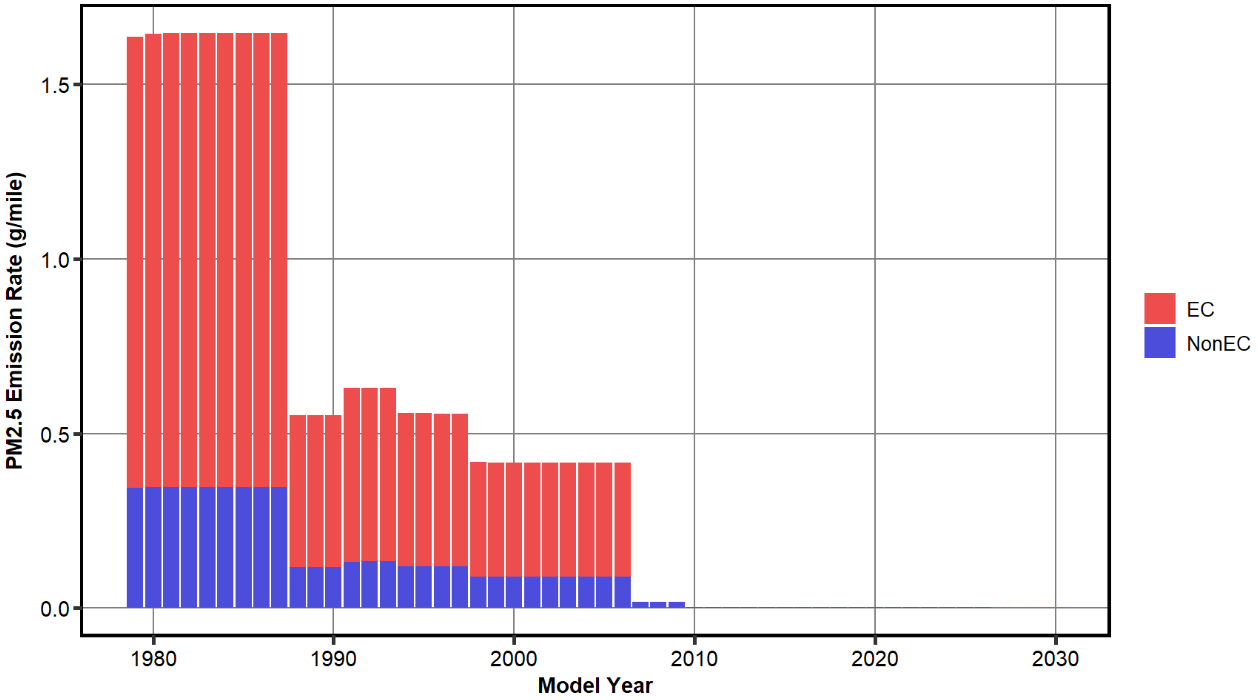

**Figure 2-35 Heavy Heavy-duty (HHD) Diesel $PM_{2.5}$ Emission Rates by Elemental Carbon (EC) and Non-Elemental Carbon (nonEC) Fraction for the 0-3 Age Group by Model Year using Nationally Representative Operating Mode Distributions**

### *2.1.3 Total Hydrocarbons (THC) and Carbon Monoxide (CO)*

While diesel engine emissions of THC and CO are important, they are not the largest contributors to mobile source THC and CO emission inventories. Regulations of non-methane hydrocarbons (NMHC), combined with the common use of diesel oxidation catalysts have yielded reductions in both THC and CO emissions from later model year heavy-duty diesel engines. As a result, data collection efforts typically do not focus on THC or CO from heavy-duty engines, and less data is available. As discussed in Section 1.1, this report discusses the derivation of total hydrocarbons (THC), from which MOVES estimates other hydrocarbons and organic gaseous pollutants.

#### *2.1.3.1 1960-2009 Model Years*

We used emissions data combined with emissions standards to develop appropriate model year groups. Since standards did not change frequently in the past for either NMHC or CO, we created fewer model year groups than we did for $NO_x$ and PM. The MOVES THC and CO model year groups are:

- 1960-1989
- 1990-2006
- 2007-2009

##### *2.1.3.1.1 Data Sources*

The heavy-duty diesel THC and CO emission rate development followed a methodology that resembles the light-duty methodology[9], where emission rates were calculated from 1-hz data produced from chassis dynamometer testing. Data sources were all heavy-duty chassis test programs:

1. **CRC E-55/59[41]: As** mentioned earlier, this program represents the largest volume of heavy-duty emissions data collected from chassis dynamometer tests. All tests were used, not just those using the TEOM. Overall, 75 trucks were tested on a variety of drive cycles. Model years ranged from 1969 to 2005, with testing conducted by West Virginia University from 2001 to 2005.
2. **Northern Front Range Air Quality Study (NFRAQS)[53]:** This study was performed by the Colorado Institute for Fuels and High-Altitude Engine Research in 1997. Twenty-one HD diesel vehicles from model years 1981 to 1995 selected to be representative of the in-use fleet in the Northern Front Range of Colorado were tested over three different transient drive cycles.
3. **New York Department of Environmental Conservation (NYSDEC)[54]:** NYSDEC sponsored this study to investigate the nature and extent of heavy-duty diesel vehicle emissions in the New York Metropolitan Area. West Virginia University tested 25 heavy heavy-duty and 12 medium heavy-duty diesel trucks under transient and steady-state drive cycles.
4. **West Virginia University:** Additional historical data collected on chassis dynamometers by WVU is available in the EPA Mobile Source Observation Database.

The pre-2010 onroad data used for the $NO_x$ analysis was not used since THC and CO were not collected in the MEMS program, and the ROVER program used the less accurate non-dispersive infrared (NDIR) technology instead of flame-ionization detection (FID) to measure HC. To keep THC and CO definitions and data sources consistent, we only used chassis test programs which measured THC using a FID exclusively for the analysis. Time-series alignment was performed using a method similar to that used for light-duty chassis test data.

**Table 2-26 Numbers of Vehicles by Model Year Group, Regulatory Class, and Age Group**

| Model year group | Regulatory class | Age group | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | 0-3 | 4-5 | 6-7 | 8-9 | 10-14 | 15-19 | 20+ |
| 1960-2002 | HHD | 58 | 19 | 16 | 9 | 16 | 6 | 7 |
| | MHD | 9 | 6 | 5 | 4 | 12 | 15 | 6 |
| | LHD45 | 2 | | | 1 | | | |
| | LHD2b3 | 6 | | | | | | |
| | Bus | 26 | | | 1 | 3 | | |
| 2003-2006 | HHD | 6 | | | | | | |
| 2007-2009 | HHD, MHD, LHD45, LH2b3, Bus | No vehicles for this model year group. Rates for this model year group are based on MY 2003-2006 with 80 percent reduction. | | | | | | |

#### *2.1.3.1.2 1960-2006 Model Years*

Similar to the analysis done for $PM_{2.5}$, for each second of operation on the chassis dynamometer, the instantaneous scaled tractive power ($STP_t$) was calculated using Equation 1-6 and the second was subsequently classified to one of the 23 operating modes defined in Table 1-4. We used the same track-load coefficients, A, B, and C pertaining to heavy-duty vehicles that were used in the $PM_{2.5}$ analysis.

Using the methods introduced in the $NO_x$ analysis, we averaged emissions by vehicle and operating mode. We then averaged across all vehicles by model year group, age group, and operating mode. In populating the emission rates in MOVES, we used the age group that had the most data in each regulatory class and model year group combination. These age groups are shown in Table 2-27. We then used the T&M effects discussed in Section 2.1.3.3 to extrapolate the emission rates for each age group. For missing operating modes, we extrapolated using STP as was discussed for $NO_x$ in Section 2.1.1.4.2. For the 1960-2002 group, data for the HHD and Urban Bus regulatory classes were combined because they have the same CO and NMHC emission standards, although they have separate age effects as discussed in Section 2.1.3.3.

**Table 2-27 Age Groups for which THC and CO Emission Rates are Populated Directly Based on the Data**

| Regulatory class | Model year group | Age group |
|---|---|---|
| HHD/Urban Bus | 1960-2002 | 0-3 |
| MHD | 1960-2002 | 15-19 |
| LHD2b3 | 1960-2002 | 0-3 |
| HHD | 2003-2006 | 0-3 |

With limited data on LHD45 vehicles, we applied the LHD2b3 emissions data to all LHD vehicles. We also applied the LHD emission rates from 1960-2002 to the LHD 2003-2006 model year group. For 2003-2006 MHD and Urban Bus regulatory classes emission rates, we applied the HHD 2003-2006 emission rates.

Figure 2-36 and Figure 2-37 show the rates for MHD and HHD for MY 2002 for THC and CO, respectively, based on the methods described above. The THC and CO mean emission rates increase with STP, though there is much higher uncertainty than for the $NO_x$ rates (Figure 2-1). This pattern could be due to the smaller data set or may reflect a less direct correlation of THC and CO to STP as is observed for the 2010 and later model year rates.

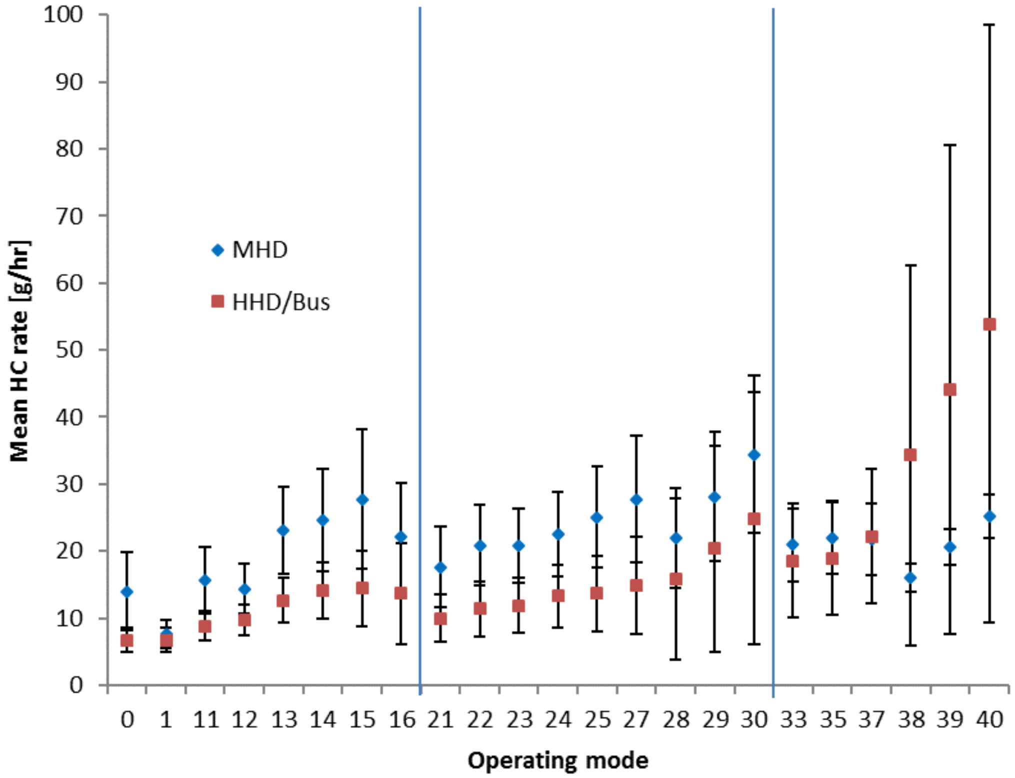

Figure 2-36 THC Emission Rates [g/hr] by Operating Mode for Model Year 2002 and Age Group 0-3. Error Bars Represent the 95 Percent Confidence Interval of the Mean

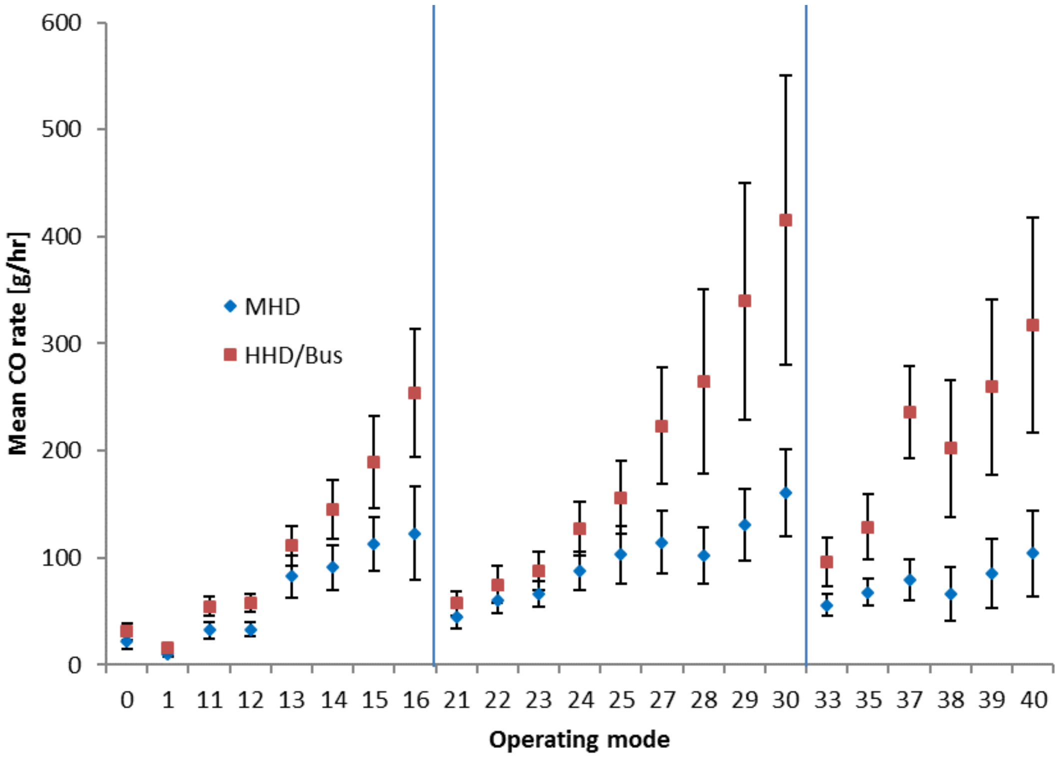

Figure 2-37 CO Emission Rates [g/hr] by Operating Mode for Model Year 2002 and Age Group 0-3. Error Bars Represent the 95 Percent Confidence Interval of the Mean

##### *2.1.3.1.3 2007-2009 Model Years*

With the increased use of diesel oxidation catalysts (DOCs) in conjunction with DPFs, we assumed an 80 percent reduction in zero-mile emission rates for both THC and CO for 2007-2009 model years. The derivation of the T&M effects for 2007-2009 model years are presented in Table 2-28 and discussed in Appendix Section B.9. As shown in Figure 2-48, the CO emission rates developed using this assumption are significantly lower than the model year 2010 and later emission rates that were developed based on the HDIUT data, and should be re-evaluated in future versions of MOVES.

#### *2.1.3.2 2010-2060 Model Years*

We used the MY 2010+ HDIUT data set, using the same vehicles as used for $NO_x$ and described in Section 2.1.1.1 and Table 2-2. The HDIUT dataset includes vehicles in the HHD, MHD, LHD45, LHD2b3 and Urban Bus regulatory classes. The HDIUT emission measurements are made using instruments that conform to the requirements described in 40 CFR Part 1065, which require the use of a flame ionization detector (FID) for measuring total hydrocarbons (THC)[55] and a non-dispersive infrared (NDIR) analyzer for carbon monoxide (CO)[56]

The THC and CO emission rates have more uncertainty than the $NO_x$ emission rates, which suggests a less direct correlation of THC and CO to STP. Nevertheless, we followed the analysis methodology used for MY 2010+ $NO_x$ rates as described in Sections 1.6 (calculation of STP and assignment of operating modes), 2.1.1.5 (calculation of mean emission rates), 2.1.1.5.1 ($NO_x$ FEL groups) and Appendix G (selection of $f_{scale}$). Figure 2-38 and Figure 2-39 display the HHD THC and CO emission rates estimated from the HDIUT data by the $NO_x$ FEL Groups used to develop the MY 2010-2013 emission rates. Comparisons of the THC and CO emission rates by $NO_x$ FEL Groups for the LHD and MHD regulatory classes are provided in Appendix H. These comparisons show that there are significant differences among the emission rates in different $NO_x$ FEL groups for THC emissions. The THC emission rates in the 0.2 and 0.35 $NO_x$ FEL group are lower than the THC emission rates from the vehicles in the 0.5 $NO_x$ FEL groups for each regulatory class, with the differences being the most significant for MHD (Appendix H.1.2) and especially HHD (Figure 2-38). For CO, there is not a consistent trend among the different $NO_x$ FEL groups and regulatory classes. Regardless, we have analyzed the CO emission rates using the $NO_x$ FEL groups for consistency.

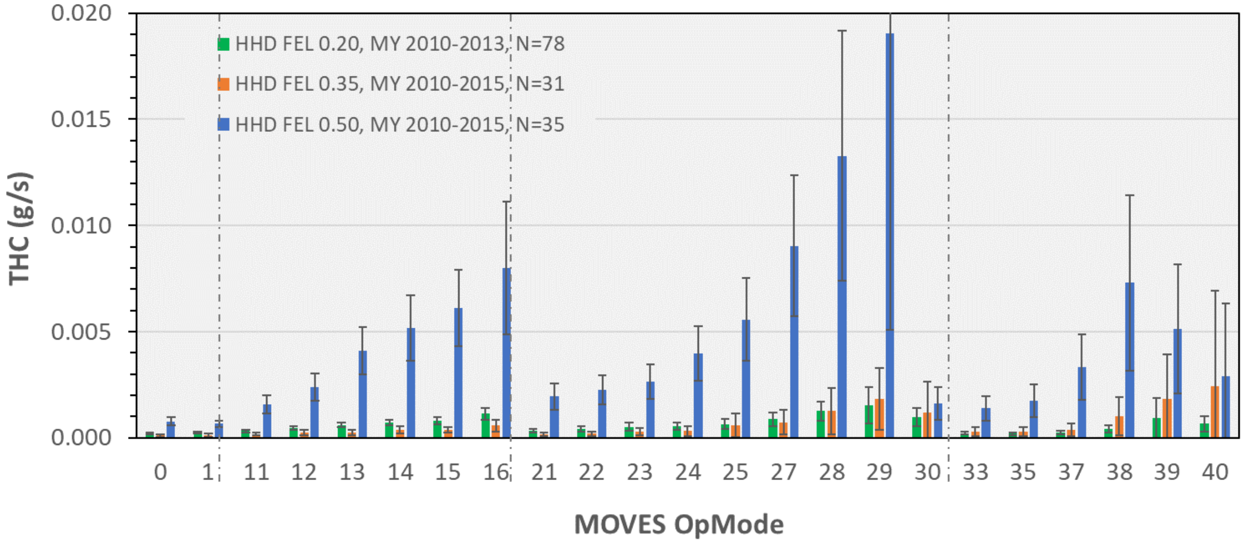

**Figure 2-38 Average HHD THC Emission Rates by Operating Mode for the 0.2 $NO_x$ FEL for MY 2010-2013 and the 0.35 and 0.5 $NO_x$ FEL for MY 2010-2015. Error Bars are 95% Confidence Intervals of the Mean**

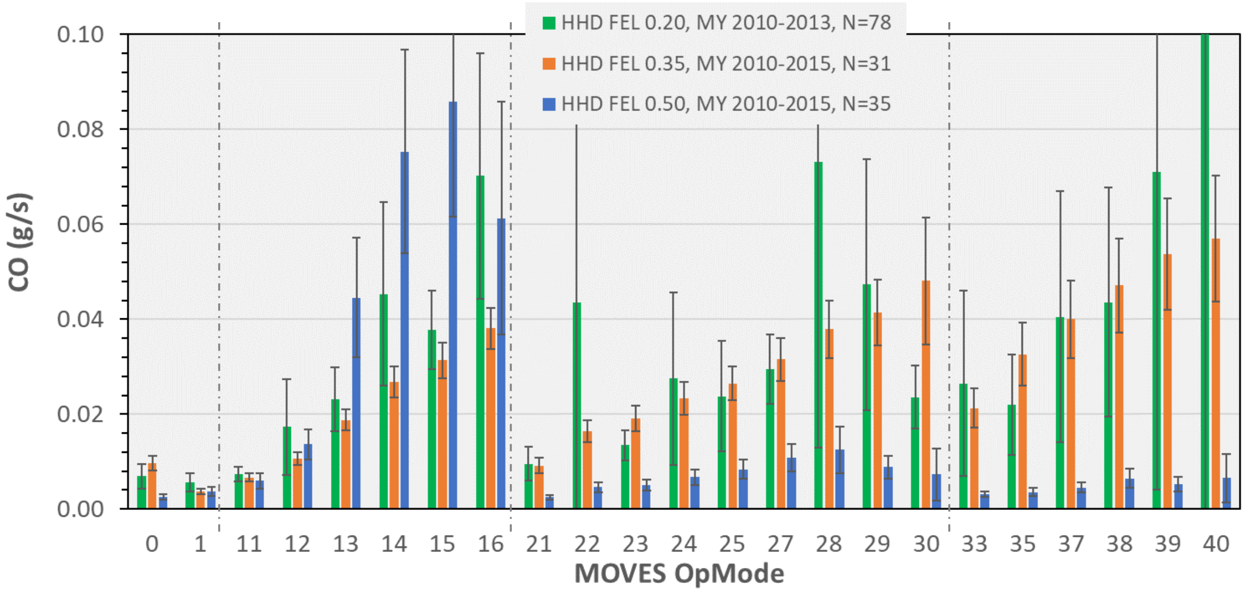

**Figure 2-39 Average HHD CO Emission Rates by Operating Mode for the 0.2 $NO_x$ FEL for MY 2010-2013 and the 0.35 and 0.5 $NO_x$ FEL for MY 2010-2015. Error Bars are 95% Confidence Intervals of the Mean**

Figure 2-40 and Figure 2-41 display the production-weighted average emission rates for THC and CO emissions for model year 2013 HHD trucks. Production-weighted averages are calculated for each model year between model year 2010 and 2018 using the production volumes displayed in Figure 2-12.

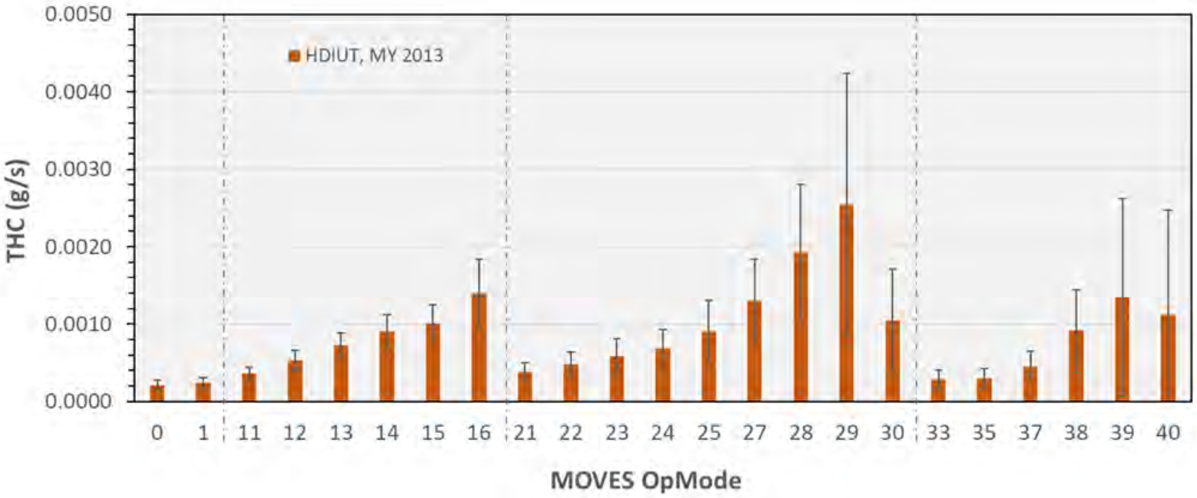

**Figure 2-40 THC Emissions by Operating Mode from HHD Trucks for Model Year 2013. Error Bars represent the 95 percent confidence interval of the Mean**

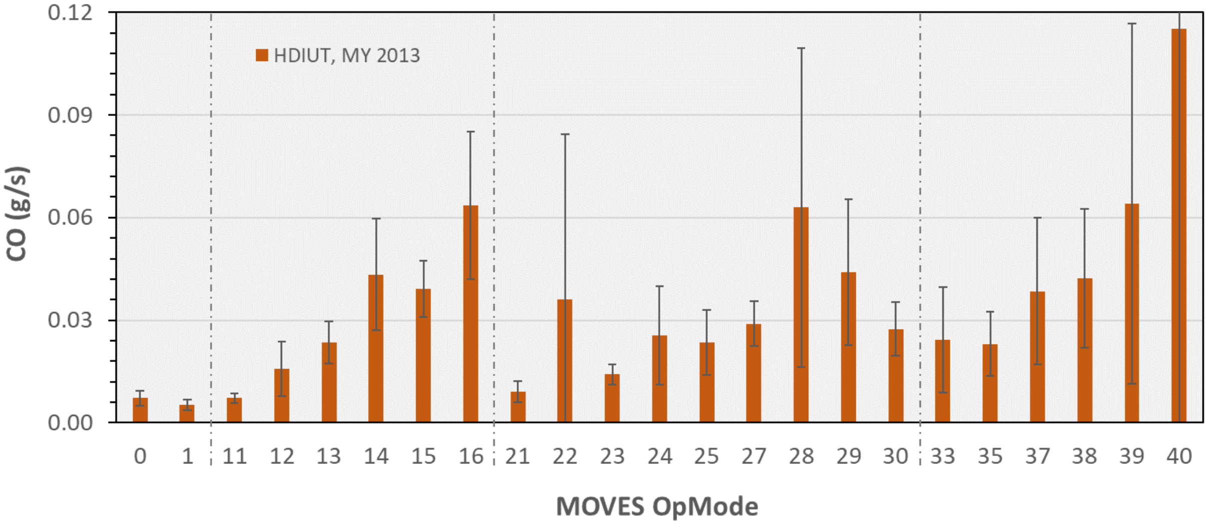

**Figure 2-41 CO Emissions by Operating Mode from HHD Trucks for Model Year 2013. Error Bars represent the 95 percent confidence interval of the Mean**

Figure 2-42 and Figure 2-43 display the comparison of the MY 2010-2013 and MY 2014-2015 groups within the HHD 0.2 $NO_x$ FEL Groups. In general, the newer vehicles (MY 2014-2015) have lower THC and CO emission rates than the corresponding MY 2010-2013 emission rates. Similar model year trends are observed for LHD THC emissions, and MHD THC and CO emissions in Appendix H. As discussed in Section 2.1.1.5.2 regarding $NO_x$ emissions, we attribute the model year differences within the 0.2 $NO_x$ FEL Group to improved emission control hardware and engine and aftertreatment operation.

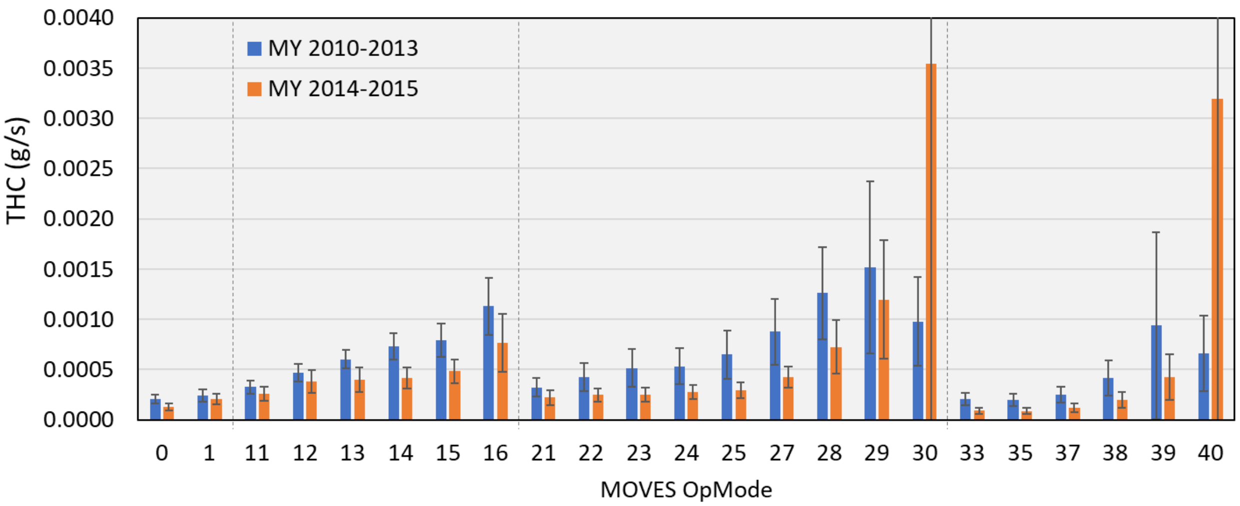

**Figure 2-42 THC emission rates for the MY 2010-2013 and MY 2014-2015 vehicles in the HHD 0.20 $NO_x$ FEL Group**

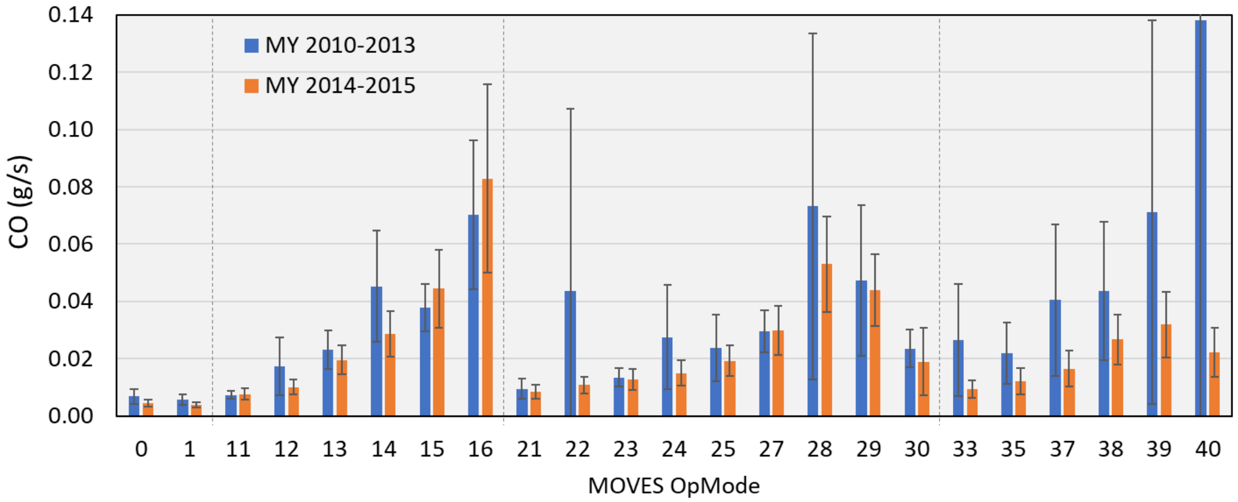

**Figure 2-43 CO emission rates for the MY 2010-2013 and MY 2014-2015 vehicles in the HHD 0.20 $NO_x$ FEL Group**

LHD2b3 and LHD45 emission rates are based on the vehicles with “LHD” service class in the HDIUT data set, which only contains engine-certified LHD45 vehicles. Urban Bus emission rates are based on HHD vehicles in the HDIUT data set. MHD and HHD emission rates are based on the emission rates from those vehicle classes. The

HDIUT data set predominantly contains vehicles in the 0-3 age group with only a handful vehicles in the 4-5 age group. Since the HDIUT data is measured and submitted by the manufacturer and the test vehicles are required to be free of any tampering or mal-maintenance, we can safely assume that they represent zero-mile vehicles for the purpose of assigning base rates and applying the tampering and mal-maintenance effects.

A comparison of HDIUT-based THC and CO emission rates for MY 2010+ heavy-duty vehicles by regulatory class are shown in Figure 2-47 and Figure 2-48, respectively. The THC rates, generally low for diesel vehicles, are comparable to MY 2007-2009 rates for both MHD and HHD. However, for CO, the HHD rates for MY 2010+ are significantly higher compared to MY 2007-2009, but are comparable to the pre-2007 data which are based on emission measurements. The variation in the 2010-2018 rates reflects the model year variation in the production volume by $NO_x$ FEL group, and use of the different 0.2 FEL $NO_x$ model year group between 2010-2013 and 2014 and later.

In the 2017 review of a draft version of this report, we received a comment that single-cell-NDIR-based CO measurements suffer from severe drift that is not corrected by zero and span checks because the calibration gases are dry, while vehicle tailpipe exhaust gases are not dry. Based on the HDIUT data, it is not possible for us to determine if MY 2010+ CO emission rates are affected by the alleged drift in the CO measurements. We looked at the CO emissions for each of 93 vehicles in the HHD 0.20 FEL group (from the 2010-2016 selection years) and confirmed the high average CO rate is not due to a few outliers. Further, the CO emission rate for the MHD and LHD vehicles is significantly lower (see Figure 2-48). Based on the available data and trends, we are unable to confirm whether or not the high CO emissions for the HHD vehicles is real or an artifact of CO sensor drift. In Section 2.1.5, we demonstrated that the fleet-average heavy-duty CO emission rate estimates from MOVES compare well with measurements from heavy-duty exhaust plume capture and tunnel measurement campaigns conducted in 2015 and 2017, which increased our confidence that the CO emission rates measured from HDIUT are reasonable. Thus, we decided to accept the reported HDIU CO emission rates as valid.

As discussed in 2.1.1.5.5, we did not reduce the LHD2b3 zero-mile THC and CO emission rates due to the implementation of the Tier 3 standard. For LHD2b3 2010 and later vehicles, the MOVES emissions rates are based on LHD45 vehicles measured in the HDIU program, as described above. The surrogate LHD45 emission rates, for THC, CO, and $PM_{2.5}$emissions, imply that current levels on the FTP cycle are substantially below the Tier 3 standards. For example, when MOVES rates are used to simulate FTP cycle for NMHC, the result is a rate of approximately 0.05 grams per mile, while the simulated FTP estimate for CO is less than 1.0 gram/mile. However, we did account for the lengthened useful life standard required by the Tier 3 standard in the Tampering & Mal-maintenance standards as discussed in the next section.

#### *2.1.3.3 Tampering and Mal-maintenance*

For all model years, we applied tampering and mal-maintenance effects to adjust emissions from the measured age to all age groups, lowering emissions for younger ages and raising them for older ages, using the methodology described in Appendix B. We applied the tampering and mal-maintenance effects shown below in Table 2-28 to CO and THC.

For MY2027+ LHD45, MHD, HHD vehicles, we adjusted the T&M effects in estimating the emission rates for CO and THC to account for the longer warranty period and useful life requirements in HD2027 standards (as shown in Table B-2).

**Table 2-28 Tampering and Mal-maintenance Effects for THC and CO over the Useful Life**

| Model years | Increase in THC and CO Emissions (%) |
|---|---|
| 1994-2003 | 300 |
| 2003 – 2006 | 150 |
| 2007 – 2009 | 150 |
| 2010 – 2012[1] | 29 (HHD, MHD, LHD45, and Bus)<br>22 (LHD2b3) |
| 2013-2026 | 22 |
| 2027+ | 22 |

Note:

[1] LHD2b3 achieve full OBD adoption in MY 2010. HHD, MHD, LHD45, and Bus are at partial (33%) and full OBD adoption in MY 2010-2012 and MY 2013, respectively.

While LHD2b3, LHD45 and MHD vehicles share the same pre-2010 MY fully deteriorated emission rates for THC and CO, they deteriorate differently as they age. Table B-4 estimates the degree of T&M that occurs by age by using the warranty and full useful life requirements for each heavy-duty regulatory class with the average mileage accumulation rates. We multiplied these increases by the T&M age-based adjustment factors shown in Table B-4 and applied the result to the zero-mile (or age 0) emissions rate to estimate the emissions rate by age group using Equation 8-3. As shown in Table B-4, there are different age effects for Tier 2 and Tier 3 LHD2b3 vehicles. We used Equation 2-27 to estimate a weighted average of the THC and CO emission rates during the Tier 3 phase-in (Model year 2017-2022) as discussed in Section 2.1.1.5.5.

Figure 2-44 and Figure 2-45 show THC and CO emission rates by age group for MY 2015. Due to our projections of T&M effects, there are large increases as a function of age. Additional data collection would be valuable to determine if real-world deterioration effects are consistent with those in MOVES.

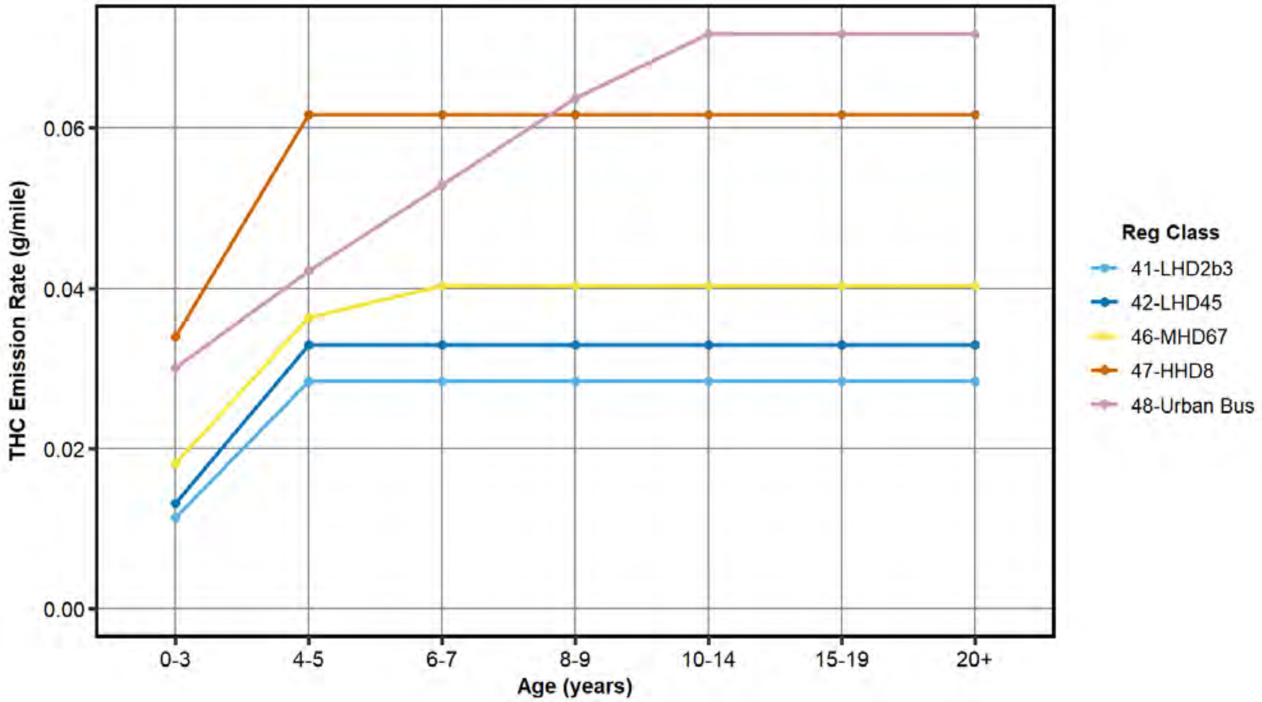

Figure 2-44 Heavy-duty Diesel THC Running Emission Rates (g/mile) by Age for Model Year 2015 by Regulatory Class Estimated using Nationally Representative Operating Mode Distribution

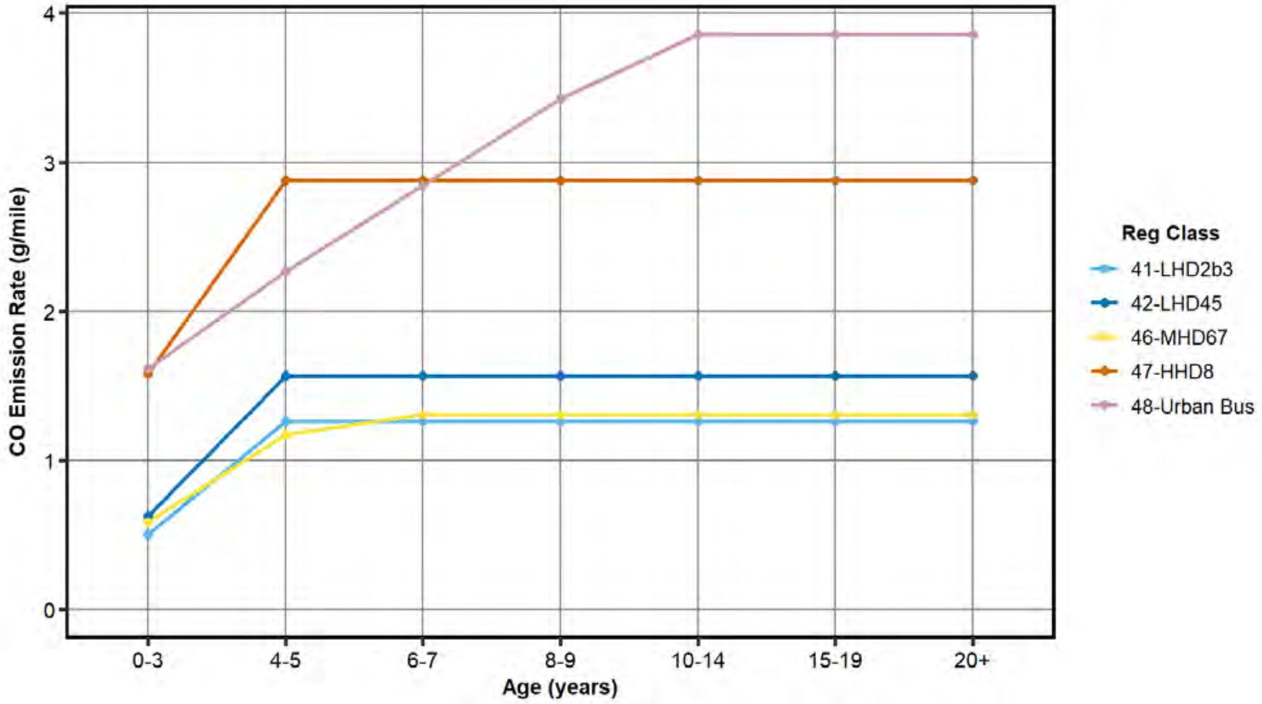

Figure 2-45 Heavy-duty Diesel CO Running Emission Rates (g/mile) by Age for Model Year 2015 by Regulatory Class Estimated using Nationally Representative Operating Mode Distribution

#### *2.1.3.4 Model Year Trends*

Figure 2-46 through Figure 2-48 display the THC and CO emission rates by model year and regulatory class for age group 0-3 estimated in grams per mile (g/mile) using nationally representative operating mode distributions and average speeds. As discussed in Section 2.1.1.8, some of the minor variation in the gram per mile emission rates within the model year groups and between regulatory classes are due to differences in operating mode distributions. Differences in the emission rates for age group 0-3 between regulatory classes are also due to different application of the T&M adjustment factors (Section 2.1.3.3). For example, as discussed in Section 2.1.3.1.3, the zero-mile MY 2003-2006 emission rates by operating mode are equivalent for HHD, MHD, and Urban Bus, but the T&M adjustment factors are applied differently for each regulatory class, and the operating mode distributions are difference, resulting in the differing gram per mile emission rates observed for 2003-2006 in Figure 2-46 and Figure 2-48.

The MY 2007–2009 emission rates reflect the use of diesel oxidation catalysts and are derived by reducing the CO and THC emissions in MY 2003-2006 by 80 percent and applying the model-year and regulatory class specific T&M adjustment factors. For MY 2010–2018, the significant variation in the emission rates by model year are due to the model year specific production volumes of the $NO_x$ FEL Group and the model year split of the 2010-2013 and 2014 and later 0.2 $NO_x$ FEL group (Section 2.1.1.5.2 and Section 2.1.3.2). For example, the spike in THC emissions observed in the 2010 model year HHD vehicles (Figure 2-47) is explained by the high THC emissions of the 0.5 $NO_x$ FEL group (Figure 2-38), and the high production volumes of the 0.5 $NO_x$ FEL engines in MY 2010 (~50% of the total HHD, see Figure 2-12).

Finally, there are small reductions in emission rates attributable to the longer warranty period and useful life requirements in the HD2027 rule.

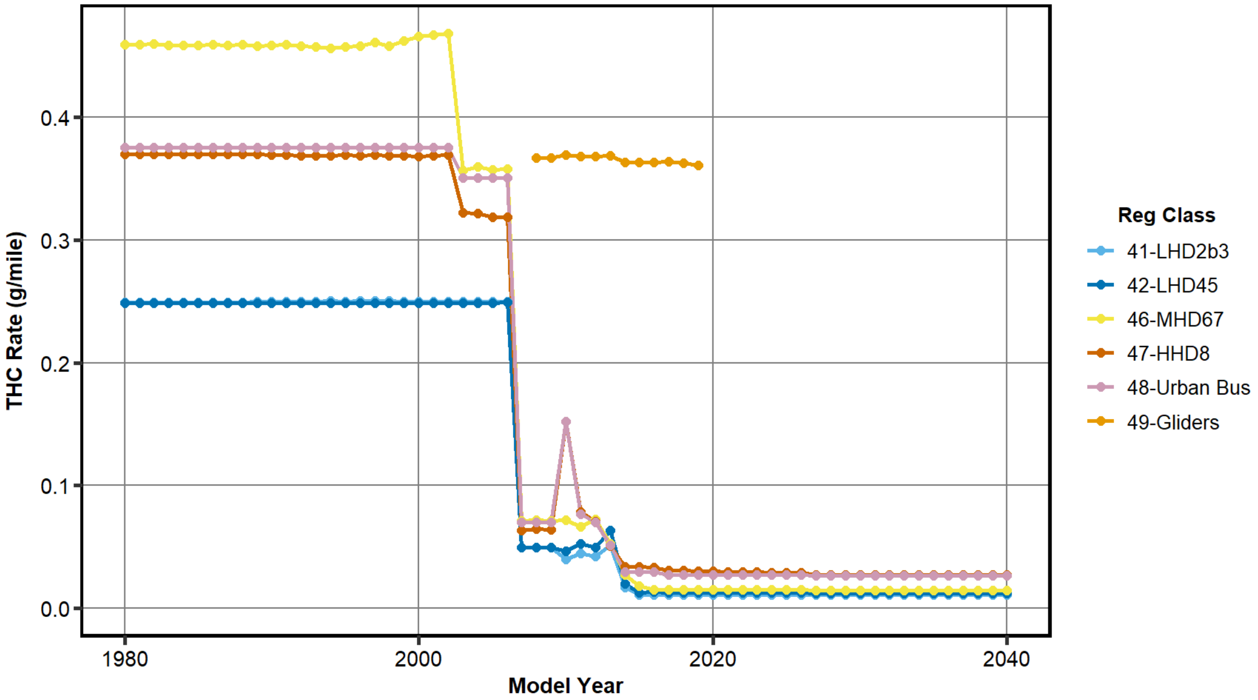

Figure 2-46 Base running emission rates for THC from age 0-3 diesel heavy-duty vehicles averaged over a nationally representative operating mode distribution.

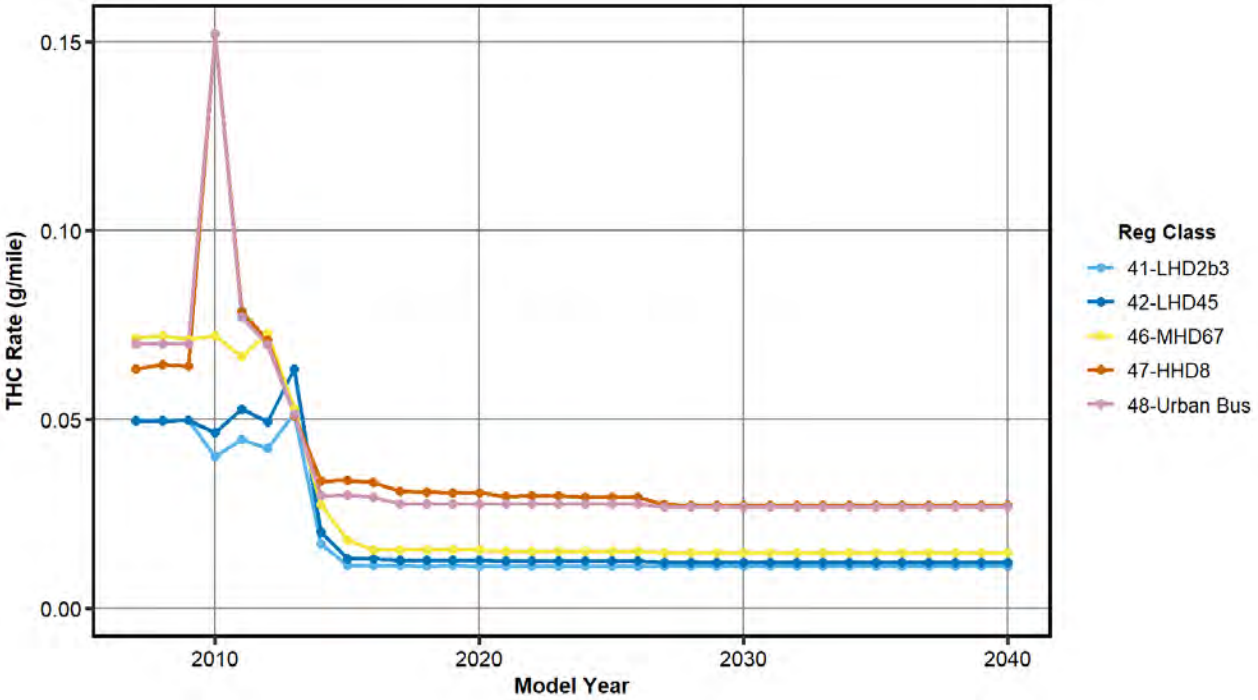

Figure 2-47 Base running emission rates for THC from age 0-3 diesel heavy-duty vehicles for MY 2007-2040 averaged over a nationally representative operating mode distribution.

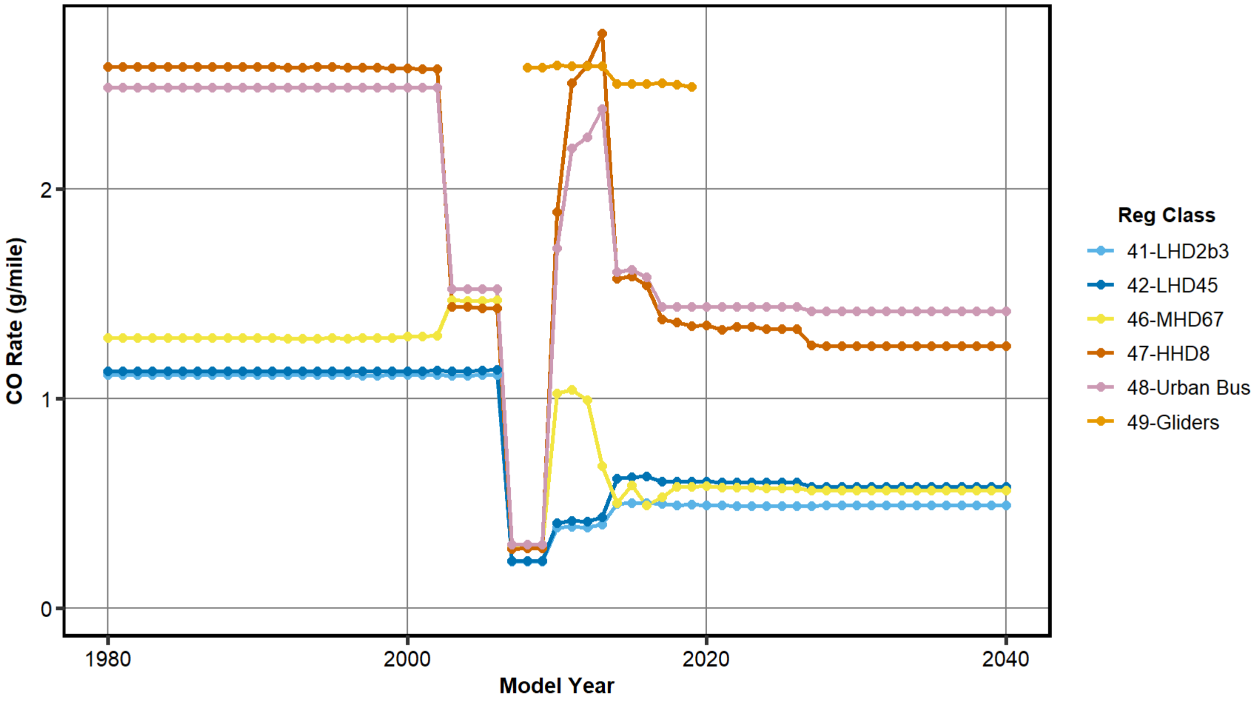

**Figure 2-48 Base running emission rates for CO from age 0-3 diesel heavy-duty vehicles averaged over a nationally representative operating mode distribution.**

## *2.1.4 Energy*

### *2.1.4.1 1960-2009 Model Years*

#### *2.1.4.1.1 LHD*

In MOVES4, the energy rates for LHD (LHD2b3 and LHD45) for pre-2010 MY diesel vehicles are unchanged from MOVES2010a. In MOVES2010, the energy rates for LHD2b3 regulatory class, along with the light-duty regulatory classes (regClassIDs 20 and 30), varied by fueltype, model year group, engine technology, and “size weight fraction” as discussed in the MOVES2010a energy updates report.[57] The energy rates in MOVES2010a were simplified to be a single set of energy rates for each regulatory class, fuel type and model year combination by weighting across engine size, engine technology, and vehicle weight according to the default population in the MOVES2010 sample vehicle population table. The resulting $CO_2$ (g/mile) emission rates and fuel economy values (miles per gallon) calculated from the energy rates using nationally representative operating mode distributions and average speeds are shown in Figure 2-52 and Figure 2-53. Because this approach uses highly detailed data, coupled with information on the vehicle fleet that varies for each model year, model year variability was introduced into the energy rates used in MOVES.

#### *2.1.4.1.2 MHD, Urban Bus, and HHD*

The data used to develop $NO_x$ rates was used to develop running-exhaust energy rates for the MHD, Urban Bus, and HHD vehicles. The energy rates were based on the same data (Section

2.1.1.1), STP structure and calculation steps as in the $NO_x$ analysis (Sections 2.1.1.3 and 2.1.1.4); however, unlike $NO_x$, we did not classify the energy rates by model year, regulatory class, or by age, because neither variable had a significant impact on energy rates or $CO_2$.

In MOVES, $CO_2$ emissions were used as the basis for calculating energy rates. To calculate energy rates (kJ/hour) from $CO_2$ emissions (Equation 2-32), we used a heating value (HV) of 138,451 kJ/gallon and $CO_2$ fuel-specific emission factor ($f_{CO2}$) of 10,180 g/gallon[58] for conventional diesel fuel.

$$\bar{r}_{energy} = \bar{r}_{CO_2} \frac{HV}{f_{CO_2}} \quad \textbf{Equation 2-32}$$

The energy rates for the MHD, Urban Bus, and HHD vehicle classes are shown in Figure 2-49. Compared to other emissions, the uncertainties in the energy rates are smaller, in part because there is no classification by age, model year, or regulatory class. Thus, the number of vehicles used to determine each rate is larger, providing for a greater certainty of the average mean energy rate.

Operating mode-based energy consumption rates are the same across MHD, Urban Bus, and HHD regulatory classes. However, the distribution of time spent in the operating mode varies between these regulatory classes based on differences in their activity and tractive power demand. Thus, the $CO_2$ (g/mile) emission rates and fuel economy values (miles per gallon) calculated from the energy rates using nationally representative operating mode distributions differ by regulatory class as shown in Figure 2-52 and Figure 2-53.

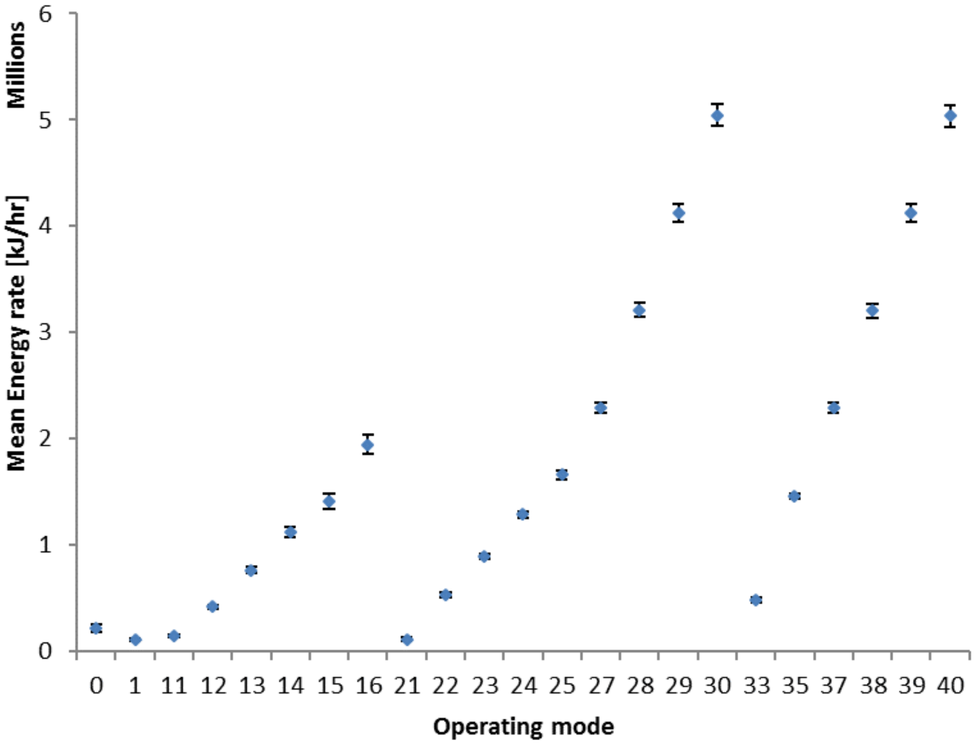

**Figure 2-49 Diesel running exhaust energy rates for MHD, HHD, and Urban Buses for 1960-2009 model years. Error bars represent the 95 percent confidence interval of the mean**

### *2.1.4.2 2010-2013 Model Years*

The MY 2010+ HDIUT dataset described in Section 2.1.1.1 and Table 2-2 included $CO_2$ emissions data, which was used to update the energy rates. The energy rates are derived using the $CO_2$ rates and the conventional diesel specific values for carbon content (0.0202 g/KJ) and a HV of of 138,451 kJ/gallon, yielding a $CO_2$ fuel-specific emission factor ($f_{CO2}$) of 10,255 g/gallon. MOVES uses these same values to calculate $CO_2$ emissions from the energy rates of vehicles using conventional diesel fuel – this methodology is described in the MOVES GHG and Energy Consumption report[3].

The 2010-2013 model year energy rates were calculated using the $NO_x$ FEL production volume and model year group splits used for estimating the MY 2010+ $NO_x$ rates as described in Section 2.1.1.5. The energy rates for the 0.2 $NO_x$ FEL group are based only on MY 2010-2013 vehicles. The energy rates for the 0.35 and 0.5 $NO_x$ FEL group were developed using vehicles sampled between 2010-2016 model years. Figure 2-50 shows the mean HHD $CO_2$ emission rates for the $NO_x$ FEL Groups used to estimate the MY 2010-2013 emission rates. As shown, $CO_2$ emission rates are a strong function of STP operating mode, and there is significantly less variability in the $CO_2$ emission rates between the sampled vehicles compared to other pollutants, as evidenced by the small confidence intervals. Even though there is little difference between the $CO_2$ emission rates among the different FEL groups, we used the FEL production volume and model years splits to estimate the $CO_2$ emissions, to be consistent with our analysis of the THC, CO, and $NO_x$ emission rates.

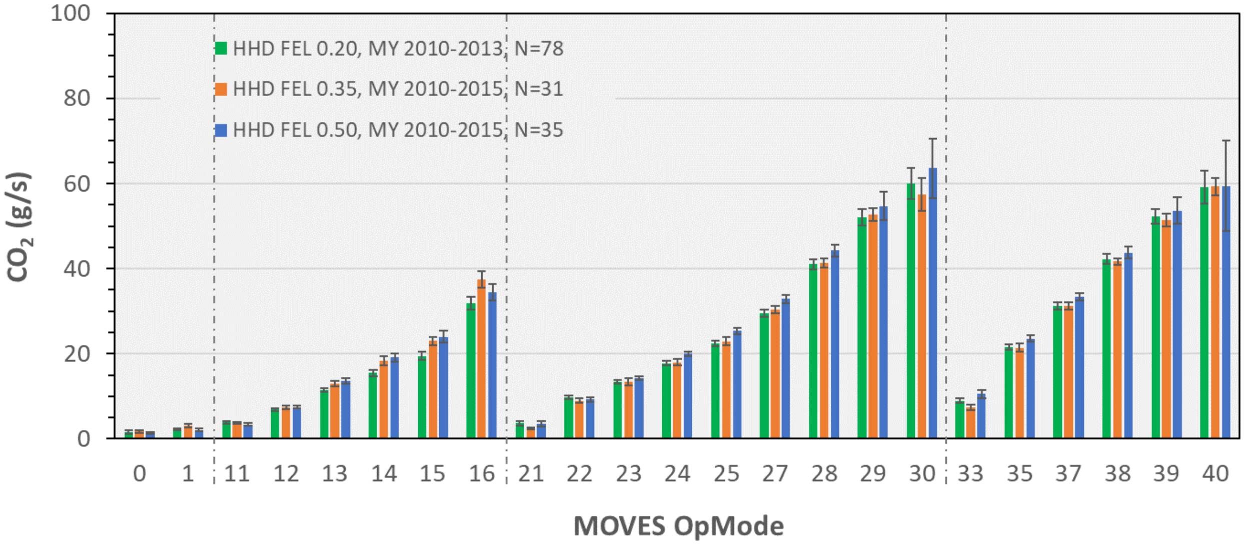

**Figure 2-50 Average HHD $CO_2$ Emission Rates by Operating Mode for the 0.2 $NO_x$ FEL for MY 2010-2013 and the 0.35 and 0.5 $NO_x$ FEL for MY 2010-2015. Error Bars are 95% Confidence Intervals of the Mean.**

As shown in Table 2-29, the majority of vehicles within the $NO_x$ FEL groups of 0.35 and 0.5 include MY 2010-2013 vehicles, for both HHD and MHD vehicles. As discussed in the next subsection, we expect improved energy efficiencies in MY 2014 and later vehicles due to the phase-in of the Phase 1 Heavy-duty Greenhouse Gas Emission Standards. Due to the small sample of vehicles in the 0.35 and 0.5 $NO_x$ FEL groups, we assume that the MY 2010-2016 energy rates are representative of both the MY 2010-2013 and the 2014-2016 model year groups.

**Table 2-29 HDIU Vehicles with Valid $CO_2$ Measurements By Regulatory Class, Model Year Group and $NO_x$ FEL Group**

| | | $NO_x$ FEL Group | | | Total Valid | Tested Vehicles |
|---|---|---|---|---|---|---|
| Reg Class | Model Year Group | 0.2 | 0.35 | 0.5 | | |
| LHD | 2010-2013 | 52 | 0 | 10 | 62 | 64 |
| | 2014-2016 | 27 | 0 | 5 | 32 | 32 |
| MHD | 2010-2013 | 21 | 23 | 9 | 53 | 55 |
| | 2014-2015 | 19 | 0 | 0 | 19 | 19 |
| HHD | 2010-2013 | 78 | 26 | 35 | 139 | 139 |
| | 2014-2015 | 44 | 5 | 0 | 49 | 55 |

Using this method, the energy rates for each model year are unique based on $NO_x$ FEL based production volume weighting, as can be observed in the model year variability among the MY 2010-2013 $CO_2$ (g/mile) emission rates and fuel economy values (miles per gallon) shown in Figure 2-52 and Figure 2-53.

#### *2.1.4.3 2014-2060 Model Years*

##### *2.1.4.3.1 LHD45, MHD, Urban Bus, and HHD Energy Rates*

In developing the MY 2014-2060 running energy rates for LHD45, MHD, Urban Bus, and HHD, we also used the $NO_x$ FEL groups, model year groups, and production volume weights as discussed in the previous section (Section 2.1.4.2). The MY 2014-2018 running energy rates were calculated as a weighted average using the MY 2014-2015/2016 rates from the 0.2 $NO_x$ FEL group, and the MY 2010-2016 rates from the 0.35 and 0.5 $NO_x$ FEL groups. Although the 0.35 and 0.5 $NO_x$ FEL groups contain measurements from MY 2010-2013 vehicles (Table 2-29), applying the MY-specific production volume weighting of the FEL groups means that the MY 2014-2018 emission rates are primarily or entirely based on the data from the MY 2014-2015/2016 vehicles in the 0.2 $NO_x$ FEL group. The MY 2014-2018 running energy rates developed in this step are considered the "baseline" – the reductions in energy rates expected from the Medium- and Heavy-Duty Greenhouse Gas (GHG) Phase 1 Rule[59] were applied to the "baseline" energy rates as described below.

MOVES accounts for the improved fuel efficiency achieved by the HD GHG Rulemakings in two ways. First, the running, start, and extended idle rates for total energy consumption are reduced to be consistent with the HD GHG rules. Second, the truck weights and road-load coefficients are updated to reflect the lower vehicle curb weights through lightweighting of materials, lower resistance tires, and improved aerodynamics of the vehicle chassis. Vehicle weights and road-load coefficients are discussed in the Population and Activity Report.[6]

The HD GHG Phase 1 rule[59] was implemented starting with 2014 model year and increased in stringency through model year 2018. The reductions in start and running energy rates reflect the improvements expected from improved energy efficiency in the powertrain. The estimated reductions for heavy-duty diesel energy rates from the HD GHG Phase 1 rule are shown in Table 2-30.

However, the MY 2014-2016 running energy rates were not adjusted for the HD GHG Phase 1 rulemaking because the impact of Phase 1 is assumed to be included in the measurements from the MY 2014-2015/2016 vehicles sampled from the HDIUT program. Instead, we renormalized the Phase 1 GHG reductions using the MY 2014-2016 as the baseline using Equation 2-33.

$$Renormalized\ Phase\ 1\ reductions\ in\ year_i = 1 - \frac{1-(reductions\ in\ year_i)}{1-(Average\ reductions\ in\ 2014\ thru\ 2016)} \quad \textbf{Equation 2-33}$$

For example, the renormalized reductions for LHD and MHD in 2017-2020 are calculated as:

$$Renormalized\ Phase\ 1\ reductions\ for\ LHD\ and\ MHD\ in\ 2017\ thru\ 2020 = 1 - \frac{1-(9\%)}{1-(5\%)} = 1 - \frac{91\%}{95\%} = 1 - 96\% = 4\% \quad \textbf{Equation 2-34}$$

We applied the renormalized reductions to estimate the MY 2017 and later running energy rates, as shown in Table 2-30. As discussed in Section 2.2.4, because the start energy rates were not updated with more data from model year 2014-2016 vehicles, the reduction in energy consumption from starts due to HD GHG Phase 1 rule was modeled by directly using the reductions estimated from the rule.

**Table 2-30 Estimated Reductions in Diesel Engine Energy Consumption Rates from the HD GHG Phase 1 Program[60]**

| Regulatory Class | Fuel | Model Years | Estimated Reduction from the MY 2013 Baseline *(applied to starts)* | Renormalized Reductions to MY 2014-2016 Energy Rates *(applied to running)* |
|---|---|---|---|---|
| HHD and Urban Bus | Diesel | 2014-2016 | 3% | - |
| | | 2017-2020 | 6% | 3% |
| LHD and MHD | Diesel | 2014-2016 | 5% | - |
| | | 2017-2020 | 9% | 4% |

MOVES3 incorporated the Medium- and Heavy-Duty GHG Phase 2 rule.[61] We updated MOVES4 to reflect Phase 2 as implemented. The Phase 2 program begins in 2021 and phases in through model year 2027. These Phase 2 standards continue indefinitely after model year 2027. The programs break the diverse truck sectors into three distinct categories, including:

- Line haul tractors and trailers (combination trucks source types in MOVES)
- Heavy-duty pickups and vans (passenger truck and light-commercial trucks)
- Vocational trucks (buses, refuse trucks, motorhomes, single-unit trucks)

The Phase 2 Rule set separate standards for engines and vehicles and ensured improvements in both. It also set separate standards for fuel consumption, $CO_2$, $N_2O$, $CH_4$ and HFCs.[n]

Because the Phase 2 rulemaking set different standards for vocational vehicles and tractor-trailers and because single-unit vocational vehicles and tractor-trailers are mapped to the same regulatory classes (MHD and HHD) under the default MOVES framework for emission rates, we modeled changes in running energy rates due to Phase 2 using the EmissionRateAdjustment table. The EmissionRateAdjustment table includes the following data fields, many of which are shared with the EmissionRate table:

1) polProcessID (primary key)
2) sourceTypeID (primary key)
3) regClassID (primary key)
4) fuelTypeID (primary key)
5) beginModelYearID (primary key)
6) endModelYearID (primary key)
7) emissionRateAdjustment
8) dataSourceID

Table 2-31 summarizes the energy rate reductions stored in the EmissionRateAdjustment table which are applied to the running rates in MOVES4 for MY 2021 and later heavy-duty diesel vehicles.

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[n] HFCs are not modeled in MOVES, and the $N_2O$ and $CH_4$ standards are not considered technology forcing on emissions.

**Table 2-31 Estimated Reductions in Diesel and CNG Engine Energy Consumption Rates due to the HD GHG Phase 2 Program[61]**

| Vehicle Source Type (Source Type ID) | Fuel | Model years | Reduction from MY 2020 Energy Rates |
|---|---|---|---|
| Long-haul Combination Truck (62) | Diesel & CNG | 2021-2023 | 6.9% |
| | | 2024-2026 | 11.4% |
| | | 2027+ | 15.3% |
| Short-haul Combination Truck (61) | Diesel & CNG | 2021-2023 | 6.8% |
| | | 2024-2026 | 11.3% |
| | | 2027+ | 14.4% |
| Other Bus, School Bus, Refuse Truck, Single-Unit Short-Haul, Single-Unit Long-Haul, Motorhomes (41, 43, 51, 52, 53, 54) | Diesel & CNG | 2021-2023 | 7.8% |
| | | 2024-2026 | 12.3% |
| | | 2027+ | 16.0% |
| Transit Bus (42) | Diesel & CNG | 2021-2023 | 7.0% |
| | | 2024-2026 | 11.8% |
| | | 2027+ | 14.4% |

Thus, for LHD45, MHD, HHD and Urban Bus, the running energy rates for MY 2021 and later are estimated with a chain of calculations starting with the HDIUT-based estimates by operating mode and regulatory class, then reduced by applying the HD GHG Phase 1 reduction in Table 2-30 and further reduced by applying the HDGHG Phase 2 reductions listed in Table 2-31. The reductions shown in Table 2-31 reflect a combination of improvements to the engine and other systems, but exclude improvements to aerodynamics and tire rolling resistances. The projected improvements due to aerodynamics and tire rolling resistance are reflected in new road load coefficients, as described in the Population and Activity Report.[6] The relative reductions in energy use from both the Phase 1 and Phase 2 HD rulemakings as applied to the MY 2014-2016 energy rates developed using HDIUT data are displayed in Figure 2-51.

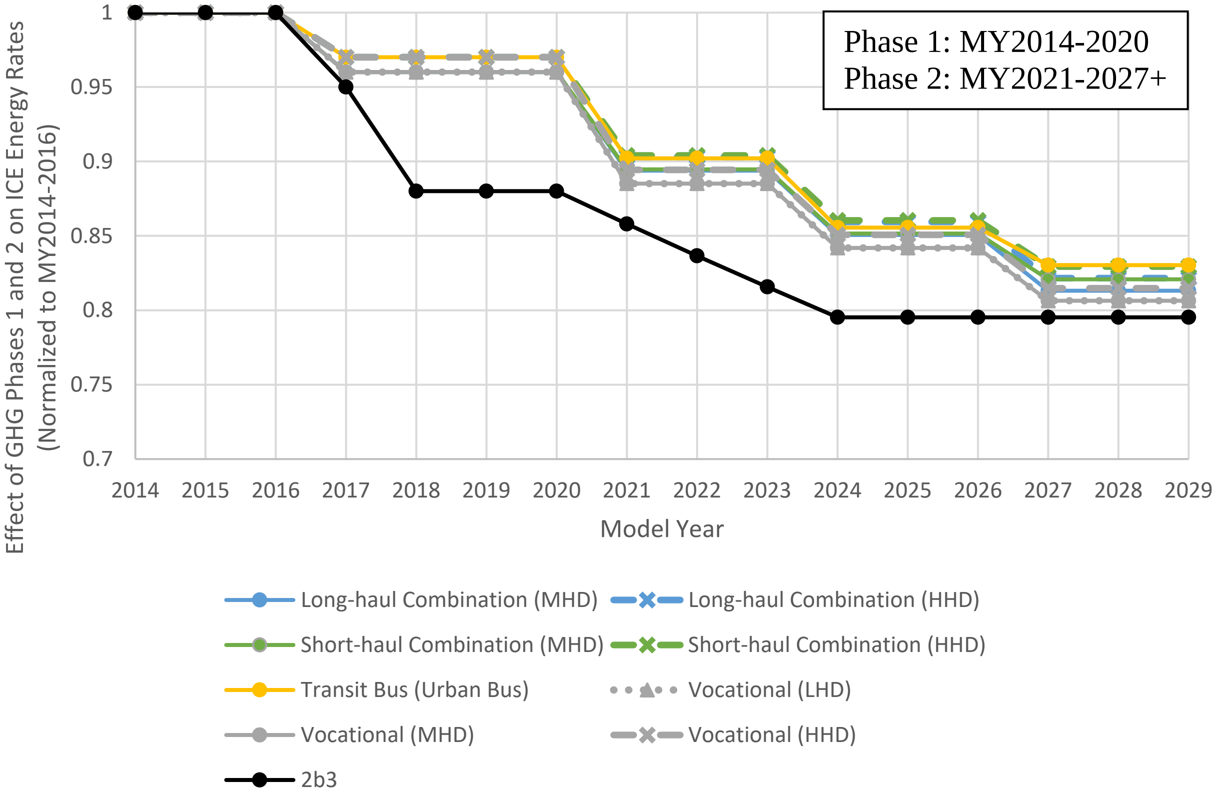

**Figure 2-51 HD GHG Phase 1 and Phase 2 rule reductions in relative running energy consumption rates for LHD2b3, LHD45, MHD, HHD, and Urban Bus diesel vehicles from the MY 2014-2016 baseline**

### *2.1.4.3.2 LHD2b3*

LHD2b3 energy reductions are modelled slightly differently than the other heavy-duty vehicles. Unlike the HD standards for tractors and vocational vehicles, the HD pickup truck/van standards are evaluated in terms of grams of $CO_2$ per mile or gallons of fuel per 100 miles. For simplicity, we apply the diesel chassis-certified reductions to all LHD2b3 vehicles since most of the diesel LHD2b3 vehicles are chassis-certified.[o] The LHD engine-certified vehicles are subject to the light-heavy duty reductions discussed in the previous section that are applied to LHD45 vehicles. In addition, the fuel economy of medium-duty passenger vehicles (MDPVs) are covered by the Light-duty GHG rule.[62]

Because MOVES includes energy rate measurements from LHD vehicles for model years 2014-2016, we renormalized the Phase 1 reductions starting in MY 2017 so they could be applied to the MY 2014-2016 rates using Equation 2-33. Example calculations for LHD2b3 diesel in MY 2018-2020 are provided in Equation 2-35.

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[o] As discussed in Section 1.4, engine-certified LHD2b3 vehicles are re-classified in MOVES as LHD45 vehicles for model year 2017 and later.

$$Renormalized\ Phase\ 1\ reductions\ for\ LHD2b3\ in\ 2018\ thru\ 2020 = \\ = 1 - \frac{1-15\%}{1-\left(\frac{2.3\%+3\%+6\%}{3}\right)} = 1 - \frac{1-15\%}{1-3.8\%} = 1 - \frac{85\%}{96.2\%} = 1 - 88\% = 12\% \qquad \textbf{Equation 2-35}$$

Table 2-32 describes the expected changes in $CO_2$ emissions for diesel chassis-certified LHD2b3 vehicles due to improved engine and vehicle technologies due to the HD GHG Phase 1 program. Note that the impacts of the HD GHG Phase 1 program on gasoline LHD2b3 energy rates are discussed in Section 3.1.3.2.1. Since nearly all HD pickup trucks and vans will be certified on a chassis dynamometer, the $CO_2$ reductions for these vehicles are not treated as separate engine and road-load reduction components, but represented as total vehicle $CO_2$ reductions and applied to all LHD2b3 vehicles in MOVES. MOVES models the HD pickup truck/van standards by lowering the energy rates stored in the emissionRate table. No change is made to the road-load coefficients or weights of passenger or light-duty truck source types. Instead, the energy consumption rates for LHD2b3 were lowered by the percentages shown in Table 2-32 for the corresponding model years.

**Table 2-32 Estimated Total Vehicle Reductions in Energy Consumption Rates for LHD2b3 Diesel Vehicles due to the HD GHG Phase 1 Program**

| Regulatory Class | Fuel | Model years | Reduction from MY 2013 Energy Rates | Renormalized Reductions Applied to MY 2014-2016 Energy Rates (running process) |
|---|---|---|---|---|
| LHD2b3 | Diesel | 2014 | 2.3% | - |
| | | 2015 | 3% | - |
| | | 2016 | 6% | - |
| | | 2017 | 9% | 5% |
| | | 2018-2020 | 15% | 12% |

Table 2-33 shows the projected improvements in $CO_2$ emissions due to the HD GHG Phase 2 program for chassis-certified diesel and gasoline LHD2b3 vehicles. These reductions were applied using the emissionRateAdjustment table for energy and the running process.

Note that we expect the Phase 2 requirements for LHD2b3 to be met via electrification starting in MY2025. Therefore, we only model reductions in diesel energy rates through MY2024; diesel rates for MY2025 and beyond are modeled the same as MY2024. Projected electrification rates are described in the Population and Activity Report.[6]

**Table 2-33 Estimated Total Vehicle Reductions in Energy Consumption Rates for LHD2b3 Diesel and Gasoline due to the HD GHG Phase 2 Program**

| Regulatory Class | Fuel | Model years | Reduction from MY 2020 Emission Rates |
|---|---|---|---|
| LHD2b3 | Gasoline and Diesel | 2021 | 2.50% |
| | | 2022 | 4.94% |
| | | 2023 | 7.31% |
| | | 2024+ | 9.63% |

### *2.1.4.4 Model Year Trends*

Figure 2-52 and Figure 2-53 display the $CO_2$ (g/mile) emission rates and fuel economy values calculated in MOVES from the energy rates using the carbon content and energy density conversion factors for conventional diesel fuel as documented in the MOVES4 Greenhouse Gas and Energy Report.[3] The $CO_2$ (g/mile) emission rates and fuel economy values are estimated using nationally representative operating mode distribution and average speed values. The figures show that, since model year 2010, there are decreasing trends in $CO_2$ (g/mile) with corresponding increases in fuel economy, due to the lower MOVES energy consumption rates as well as the lower source mass values and improved road load coefficients estimated vehicles meeting both Phase 1 and Phase 2 Heavy-Duty Greenhouse Gas Standards. The energy rates by operating mode are constant for model year 2027-2060. However, some of the small differences in $CO_2$ (g/mile) and fuel economy values observed within model year groups and regulatory classes are due to differences in the nationally representative operating modes across model years due changing fractions of regulatory classes among different source types.

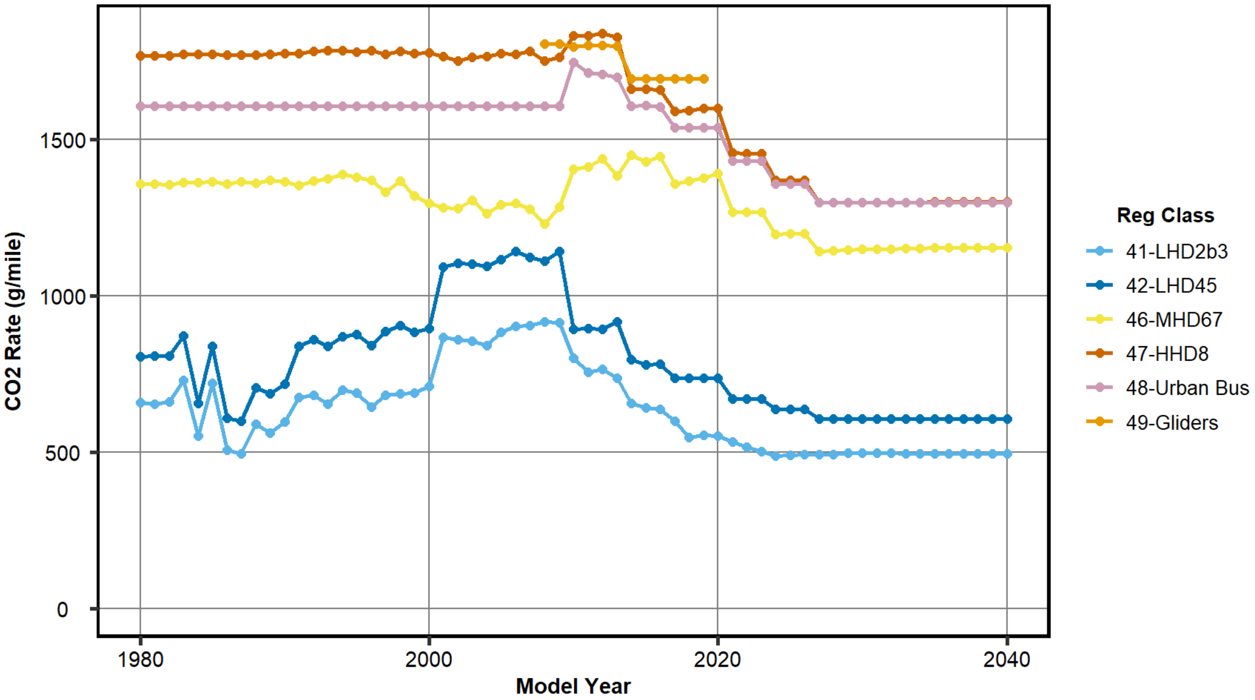

**Figure 2-52. Base running emission rates for $CO_2$ from age 0-3 diesel heavy-duty vehicles averaged over a nationally representative operating mode distribution.**

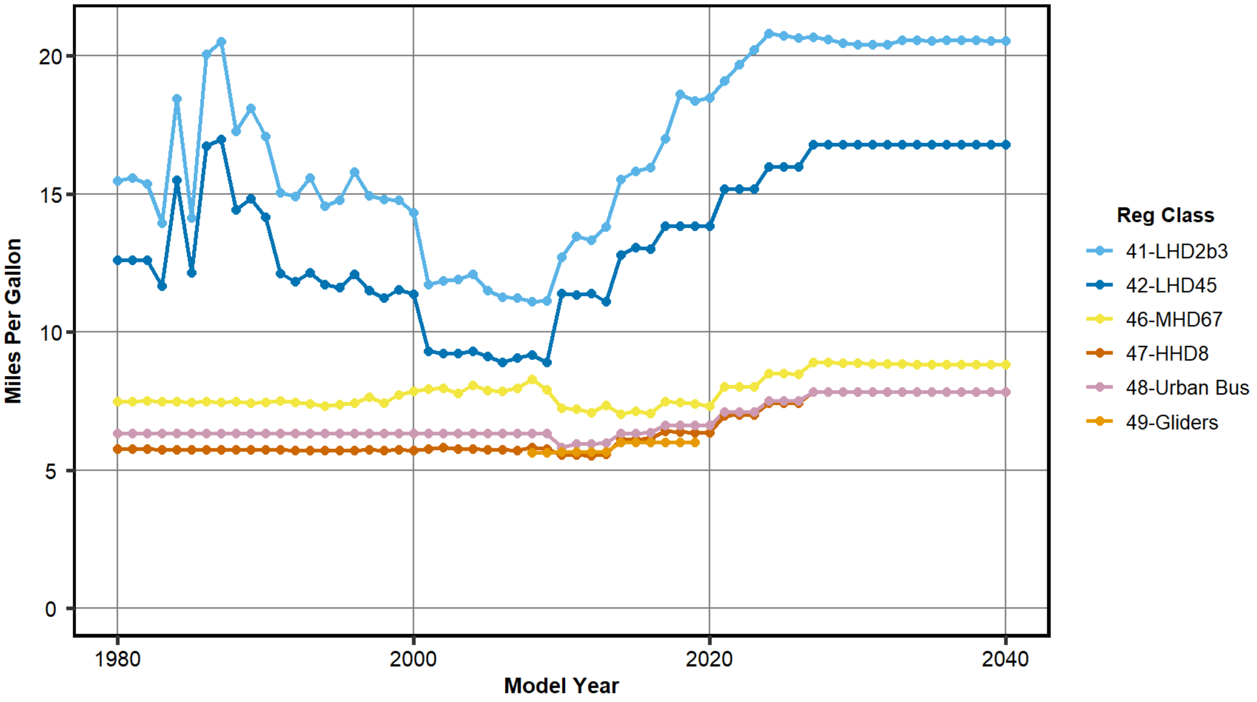

**Figure 2-53. Fuel economy for age 0-3 diesel heavy-duty vehicles averaged over a nationally representative operating mode distribution**

### *2.1.5 Evaluation of Fleet-average Running Rates with Real-World Measurements*

As one evaluation of the MOVES diesel exhaust running rates, Table 2-34 compares preliminary MOVES3 emission rates estimated in fuel-specific units (g/kg-fuel) to fuel-specific emission rates estimated from a remote sensing and tunnel measurements. Haugen et al. (2018) conducted exhaust plume measurements from 1,844 in-use heavy-duty diesel trucks at the Peralta weigh station near Anaheim, CA in 2017, of which over 63% of the fleet were model year 2011 or later. Wang et al. (2019), conduced sampling of the Ft. McHenry Tunnel in Baltimore, MD during winter and summer of 2015. The model year distribution of the Ft. McHenry diesel fleet was not measured. Wang et al. (2018) estimated the heavy-duty emission factors separately from the light-duty vehicles using a linear regression which accounted for the fraction of the fleet is composed of heavy-duty vehicles. The emission rates from both studies are compared to MOVES emission rates estimated from a national scale run with a preliminary version of MOVES3 conducted for calendar year 2016 for all on-road heavy-duty diesel vehicles. No effort was made to match the vehicle operation of the studies or to match the fleet and fuel characteristics (model year distribution, regulatory class distribution). As such, the comparison is only intended to be a rough comparison, to assure that MOVES provide estimates that are in the range of feasible values measured from in-use fleets.

Table 2-34 shows that CO emission factors compare quite well between the different studies. The $NO_x$ values are comparable to the Peralta CA location, but significantly lower than the Ft. McHenry location. THC are also below the Peralta, CA measurements. $PM_{2.5}$ is lower than the Ft.

McHenry estimates, but within the standard error of the winter measurements, and close to the 95% confidence range of the summer measurements (approximately two times the standard error). Given the expected differences in vehicle operation and fleet composition, the comparisons increased our confidence that MOVES is estimating representative in-use running emission factors for heavy-duty diesel vehicles.

**Table 2-34. Comparison of MOVES Emissions with Remote Sensing and Tunnel Measurements (g/kg-fuel)**

| | Peralta CA 2017 HDV (Haugen et al. 2018) | Winter Ft. McHenry MD 2015 (Wang et al. 2019) | Summer Ft. McHenry MD 2015 (Wang et al. 2019) | MOVES3 National Heavy-duty Fleet 2016 |
|---|---|---|---|---|
| THC | 2.2 ± 0.4 | NA | NA | 0.68 |
| CO | 5.9 ± 0.9 | 4.6 ± 2.0 | 7.5 ± 2.6 | 5.2 |
| $NO_x$ | 12.4 ± 0.6 | 29.6 ±4.7 | 17.9 ± 1.4 | 12.2 |
| $PM_{2.5}$ | NA | 0.81 ± 0.89 | 0.61 ± 0.11 | 0.36 |

Note: The error terms are the standard error of the mean based on individual vehicle measurements for the Peralta location and sampling periods for the Ft. McHenry Tunnel.

## 2.2 Start Exhaust Emissions

The start process occurs when the vehicle is started and the engine is not fully warmed up. For modeling purposes, we define start emissions as the increase in emissions due to an engine start. Operationally, we estimate difference in emissions between a test cycle with a cold start and the same cycle with a hot start.[p]

As explained in Section 1.2.2, we define eight stages which are differentiated by soak time length (time duration between engine key off and engine key on) between a cold start (> 720 minutes of soak time) and a hot start FTP (< 6 minutes of soak time). More details on how start emission rates are calculated as a function of soak time, can be found later in this section and in the MOVES light-duty exhaust emission rate report.[9] The impact of ambient temperature on cold starts is discussed in the Emission Adjustments MOVES report.[63]

The next subsections discuss the derivation of heavy-duty diesel start emissions by pollutant and model year group. Start emissions are currently a small contributor to total exhaust emissions from heavy-duty diesel vehicles. No T&M or other age effects are currently applied to the diesel start emissions.

### 2.2.1 THC, CO, and $NO_x$

The pre-2010 model year emissions are discussed in Section 2.2.1.1 and 2010+ model year emission rates are discussed in Sections 2.2.1.2.

#### 2.2.1.1 1960-2009 Model Years

For light-duty diesel vehicles, start emissions are estimated by subtracting FTP bag 3 emissions from FTP bag 1 emissions. Bag 3 and Bag 1 are collected on the same dynamometer cycle, except that Bag 1 starts with a cold start, and Bag 3 begins with a hot start.[p] A similar approach was applied for LHD vehicles tested on the FTP and ST01 cycles, which also have separate bags measuring cold and hot start emissions over identical drive cycles. Data from 21 LHD diesel vehicles, ranging from model years 1988 to 2000, were analyzed. No classifications were made for model year or age due to the limited number of vehicles. The results of this analysis for THC, CO, and $NO_x$ are shown in Table 2-35.

**Table 2-35 Average Start Emissions Increases (g/start) for pre-2010 Model Year Light Heavy-Duty Diesel Vehicles for Regulatory Class LHD2b3 and LHD45 (regClassID 41 and 42)**

| THC | CO | $NO_x$ |
|---|---|---|
| 0.13 | 1.38 | 1.68 |

For pre-2010 model year HHD and MHD trucks, analogous data were unavailable. To provide at least a minimal amount of information, we measured emissions from a 2007 Cummins ISB which is used in both LHD and MHD vehicles on an engine dynamometer at the EPA National Vehicle and Fuel Emissions Laboratory in Ann Arbor, Michigan. Among other idle tests, we performed a cold start idle test at 1,100 RPM lasting four hours, long enough for the engine to warm up. Essentially, the “drive cycle” we used to compare cold start and warm emissions was the idle cycle, analogous to the FTP and ST01 cycles used for LHD vehicles. Emissions and temperature stabilized about 25 minutes into the test. The emission rates through time are shown in Figure 2-54. The biggest drop in emission rate over the test was with CO, whereas there was a slight increase in $NO_x$ (implying that cold start $NO_x$ is lower than running $NO_x$), and an insignificant change in THC.

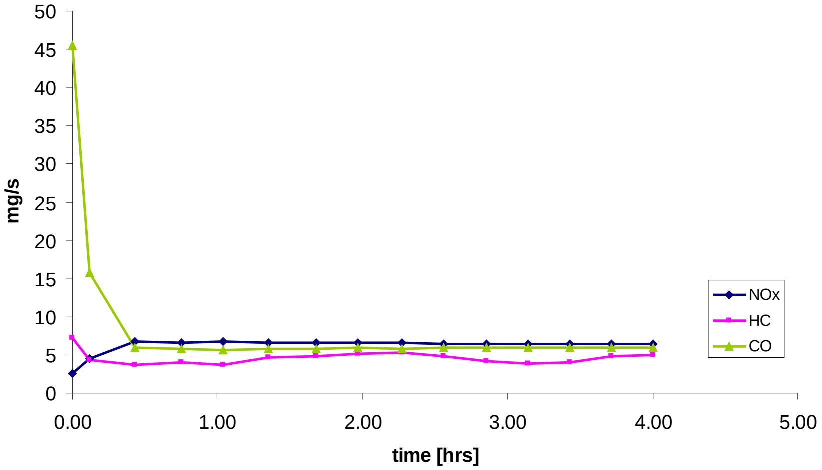

**Figure 2-54 Trends in the Stabilization of Idle Emissions from a Diesel Engine Following a Cold Start (from a 2007 Cummins ISB Measured on an Engine Dynamometer)**

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[p] As discussed in Section 1.2.2, ideally, bag 3 would not include a start, but only include running emissions. Operationally, we use bag 3 with a hot-start because that is the available data, and we assume that the hot-start emissions are small in comparison to the cold-start emissions, and thus have minimal impact on the cold-start estimate. Our estimates of emissions by soak time in Sections 2.2.3.1 and 2.2.3.2 support this assumption; for pre-2010, hot-start THC and CO emissions are less than 10% of the cold-start emissions, and $NO_x$ hot-start emissions are less than 20% of cold-start emissions. For 2010+ emissions the hot-start emissions for THC, CO, and $NO_x$ are less than 1% of the cold-start emissions.

We calculated the area under each curve for the first 25 minutes and divided by 25 minutes to get the average emission rate during the cold start idle portion. Then, we averaged the data for the warm idle portion using the remaining portion of the test (215 minutes). We then calculated the the difference between cold start and warm idle over a 25-minute period of the elevated cold starts as shown in Equation 2-36.

$$\begin{aligned}&\text{Grams per Start} = \\ &= \text{stabilization time} \times (\text{cold start average rate} - \text{hot running average rate}) \\ &= 25 \text{ minutes} \times \left(\sum_{t=0}^{25} \frac{\text{emissions}}{25} - \sum_{t=25}^{240} \frac{\text{emissions}}{215}\right)\end{aligned}$$

**Equation 2-36**

The results are shown in Table 2-36. The measured THC increment is zero. The $NO_x$ increment is negative since cold start emissions were lower than warm idle emissions.

**Table 2-36. Cold-start Emissions Increases (g/start) in Grams on the 2007 Cummins ISB**

| THC | CO | $NO_x$ |
|---|---|---|
| 0.0 | 16.0 | -2.3 |

We also considered $NO_x$ data from University of Tennessee,[64] which tested 24 trucks with PEMS at different load levels during idling. Each truck was tested with a cold start going into low-RPM idle with air-conditioning on. We again used Equation 2-36 to integrated the emissions over the warm-up period to get the total cold start idling emissions. We calculated the warm idling emissions by multiplying the reported warm idling rate by the stabilization time. We used the stabilization period from our engine dynamometer tests (25 minutes). Then, we subtracted the cold start-idle emissions from the warm idle emissions to estimate the cold start increment. We found that several trucks produced lower $NO_x$ emissions during cold start (similar to our own work described above), and several trucks produced higher $NO_x$ emissions during cold start. Due to these conflicting results, and the recognition that many factors affect $NO_x$ emission during start (e.g., air-fuel ratio, injection timing, etc.), we set the default $NO_x$ cold-start increment to zero. Table 2-37 shows our final MOVES inputs for HHD and MHD diesel start emissions increases from our 2007 MY in-house testing. Due to the limited data, the emission rate is constant for all pre-2010 model years and ages.

**Table 2-37. MOVES Inputs for Pre-2010 HHD and MHD Diesel Start Emissions (grams/start) for Regulatory Class 46, 47, and 48. No Differentiation by Model Year or Age.**

| THC | CO | $NO_x$ |
|---|---|---|
| 0.0 | 16.0 | 0.0 |

As discussed in the Emission Adjustments Report[63], MOVES applies an additive adjustment to diesel THC cold-start emissions for ambient temperatures below 72 F. Thus, despite a pre-2010 baseline THC start emission rate of zero, MOVES estimates positive THC start emissions from heavy-duty diesel vehicles at ambient temperatures below 72 F. No temperature adjustments are applied to CO, $PM_{2.5}$ , or $NO_x$ diesel start emissions because no clear trend was found with the data.

#### 2.2.1.2 2010-2026 Model Years

The cold start emissions for 2010 model year and later LHD, MHD, and HHD diesel engines have been updated for MOVES3 based on new data. However, because of the small sample size and lack of real-world data, notable uncertainty about real world heavy-duty diesel start emissions remains.

Similar to the approach taken for light-duty vehicles, the cold start emissions are defined as the difference in emissions between a test cycle with a cold start and the same test cycle with a hot start. Heavy-duty diesel engines are certified using the Heavy-Duty Diesel Engine Federal Test Procedure (FTP) cycle[65]. The test procedure for certification requires that manufacturers run the engine over the FTP cycle with a cold start and then repeat the cycle with a warm start. Starting in model year 2016, EPA began collecting certification data that contained separate cold and hot results for each engine certified. The data that was analyzed for MOVES3 includes the following engine families from 2016 and 2017 model years shown in Table 2-38.

**Table 2-38 Engine Data Analyzed to Estimate the Cold Start Emission Rates for HD Diesel Engines**

| Category | Number of Engines | Manufacturers |
|---|---|---|
| LHD | 5 | Ford, Isuzu, Hino, FPT |
| MHD | 6 | Ford, Hino, Cummins, Detroit Diesel |
| HHD | 11 | Cummins, PACCAR, Detroit Diesel, Volvo, Hino |

The certification data was used to determine the grams emitted per cold start using Equation 2-37.

$$\begin{aligned}Grams\ per\ Start &= [Cold\ FTP\ Emission\ Results\ (g/(hp-hr)) \\ &- Hot\ FTP\ Emission\ Results(g/(hp-hr))] \\ &* FTP\ Cycle\ Work\ (hp-hr)\end{aligned}$$

**Equation 2-37**

The amount of work (hp-hr) performed over the FTP cycle is required to convert the FTP emission results in grams per horsepower-hour into grams, but it is not provided as part of the certification data submitted by the manufacturers to EPA. Furthermore, the FTP cycle work is unique to each engine and is generally calculated based on the engine's maximum speed, curb idle speed, and the maximum torque curve. Therefore, we needed to develop a surrogate from the information that is provided by manufacturers for certification for each engine. We determined that the rated power of an engine correlates well to the FTP cycle work. This analysis was based on FTP cycle work and rated power data from ten HD engines. As shown in Figure 2-55, the FTP cycle work is approximately a linear function of the engine's rated power. For the calculation of cold start emissions for each engine analyzed, the FTP cycle work (hp-hr) was estimated for the engine based on its rated power using the equation in Figure 2-55 – 0.0599 (hr) times the rated power (hp) plus 4.4297 (hp-hr).

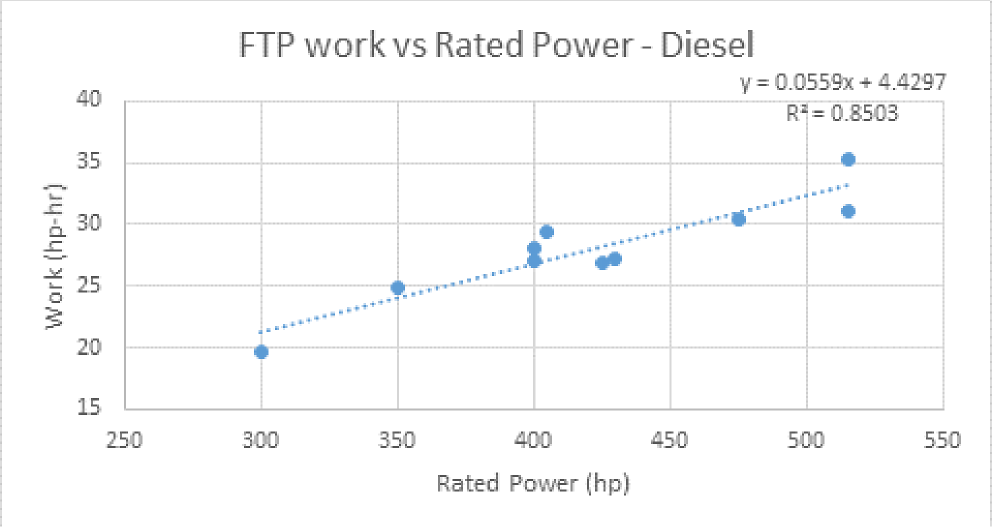

**Figure 2-55: Relationship between HD Diesel Engine Rated Power and FTP Cycle Work**

### *2.2.1.2.1 Heavy-heavy duty*

Analysis of cold and hot start FTP certification data from eleven HHD diesel engines determined the grams per start for THC, CO, $NO_x$, and $PM_{2.5}$. The average and standard deviation of the THC, CO, and $NO_x$ emission levels of the eleven engines are shown in Table 2-39. The $PM_{2.5}$ emissions are summarized in Table 2-45. The sample included both MY2016 and MY2017 engines, ranging in displacement between 7.7 and 14.9 liters, and in rated power between 260 and 605 HP. The default cold start emissions values in MOVES are the mean values shown in the table.

**Table 2-39: Cold Start Emissions for MY2010 and Later Heavy Heavy-Duty Diesel Engines**

| Grams per Start | THC | CO | $NO_x$ |
|---|---|---|---|
| Mean | 0.08 | 6.6 | 8.4 |
| Standard Deviation of Data | 0.1 | 5.6 | 1.7 |

### *2.2.1.2.2 Medium-heavy duty*

The certification data from six MHD diesel engines were used to develop the THC, CO, and $NO_x$ grams emitted per start. The average and standard deviation of the emissions from the six engines are shown in Table 2-40. The sample included MY2016 and MY2017 engines, ranging in displacement between 5.1 and 8.9 liters, and in rated power between 230 and 380 HP. The default values in MOVES are the mean values shown in the table.

**Table 2-40 Cold Start Emissions for MY2010 and Later Medium Heavy-Duty Diesel Engines**

| Grams per Start | THC | CO | $NO_x$ |
|---|---|---|---|
| Mean | 0.20 | 2.5 | 6.4 |
| Standard Deviation of Data | 0.2 | 2.7 | 1.8 |

### *2.2.1.2.3 Light-heavy duty*

Analysis of five LHD diesel engines from the certification data determined the grams per start for THC, CO, and $NO_x$ shown in Table 2-41. The sample included MY2016 and MY2017 engines, ranging in displacement between 3.0 and 6.7 liters, and in rated power between 161 and 330 HP. The default values in MOVES are the mean values.

**Table 2-41 Cold Start Emissions for MY2010 and Later Light Heavy-Duty Diesel Engines (LHD45 and LHD2b3)**

| Grams per Start | THC | CO | $NO_x$ |
|---|---|---|---|
| Mean | 0.005 | 2.47 | 6.77 |
| Standard Deviation of Data | 0.11 | 2.61 | 2.24 |

We are applying the new cold start THC, CO, and $NO_x$ emission rates from the 2016 MY and 2017 MY engines to all 2010 MY and newer engines. The latest tier of HD diesel emission standards completed phase-in in 2010 MY and the aftertreatment systems on these engines are similar and generally include both a diesel particulate filter and selective catalytic reduction system.

##### *2.2.1.2.4 Incorporation of Tier 3 Standards for Light Heavy-Duty Diesel*

The Tier 3 exhaust emission standards affect light heavy-duty diesel vehicles in the LHD2b3 regulatory class (regClassID 41). Reductions are applied to start rates for $NO_x$ only, phasing in from MY2018 to MY2021 as previously described for running emissions in Section 2.1.1.5.5.  No reductions applies to THC and CO rates.

#### *2.2.1.3 2027-2060 Model Years*

As noted in Section 2.1.1.6, the HD2027 standards include duty-cycle standards, off-cycle standards and changes to warranty and useful life requirements. To account for the HD2027 standards, we updated $NO_x$ start emission rates to reflect the changes in the duty-cycle standards using the method described in this section.

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 MOVES4 are not based on in-use data but are based on emissions data from the FTP duty-cycle. Additionally, because the heavy-duty diesel start emission rates in MOVES4 do not vary with age due to insufficient data, we did not estimate changes due to the changes in warranty and useful life.

Because engines meeting the HD2027 standard are not yet in production, to update the $NO_x$ start emission rates for MY2027+, we estimated the $NO_x$ cold start emission rate (g/start) from a CARB Stage 1 HDD engine[66] tested on the FTP duty-cycle cycle after different periods of use (aging).

Table 2-42 contains the $NO_x$ Cold and Hot FTP measurements in Columns (B) and (C) for different aging periods. Column (E), “Cold – Hot,” is calculated as the difference between Columns (B) and (C). The cold start, Column (F), is then calculated by multiplying the difference in Column (E) by the work performed on the FTP cycle, Column (D), as shown in Equation 2-38.

$$\mathrm{NO_X\ Cold\ Start}\ \left(\frac{\mathrm{g}}{\mathrm{start}}\right) = \left[\mathrm{Cold}\ \left(\frac{\mathrm{g}}{\mathrm{hp\cdot hr}}\right) - \mathrm{Hot}\left(\frac{\mathrm{g}}{\mathrm{hp\cdot hr}}\right)\right] \times \mathrm{FTP\ work\ (hp\cdot hr)}$$

**Equation 2-38**

**Table 2-42 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 was 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 2-42 demonstrates that the larger cold start measured with increased aged hours, and after the DPF 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 2-42) to represent the 12-hour cold-start (operating mode 108) emission rate.

To estimate the 12-hour cold-start $NO_x$ emission rate for HHD diesel vehicles subject to the HD2027 standards, we interpolated the HHD 12-hour cold-start between the Stage 1 cold start (3.14 g/start) and the MOVES baseline (MY2010-2026) 12-hour cold-start (8.4 g/start), and their respective FTP duty-cycle standards using Equation 2-39 as shown in Figure 2-56 and Table 2-43. 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.

$$\text{Start ER}_{\text{FTPx,HHD,12 hour}} = \left(\frac{\text{MOVES start}_{\text{HHD,12 hour}} - \text{Stage1 start}}{\text{Baseline FTP} - \text{Stage1 FTP}}\right) \times (\text{FTP}_{\text{x}} - \text{Baseline FTP}) + \text{MOVES start}_{\text{HHD,12 hour}} \qquad \textbf{Equation 2-39}$$

Where:

$\text{Start ER}_{\text{FTPx,HHD,12 hour}}$ = 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).

$\text{Stage1 start}$ = 1000 Post Ash Clean start emission rate from the CARB Stage 1 HHD diesel engine = 3.14 g/start (Table 2-42)

$\text{Stage1 FTP}$ = Composite FTP level of the CARB Stage 1 engine = 0.02 g/hp-hr

$\text{MOVES start}_{\text{HHD,12 hour}}$ = MOVES3 baseline start emission rate (= 8.4 g/start) for MY 2027 heavy heavy-duty diesel engine for a 12-hour soak (operating mode 108)

$\text{Baseline FTP}$ = baseline FTP composite $NO_x$ standard = 0.2 g/hp-hr

$\text{FTP}_{\text{x}}$ = composite FTP standard in the HD2027 standards

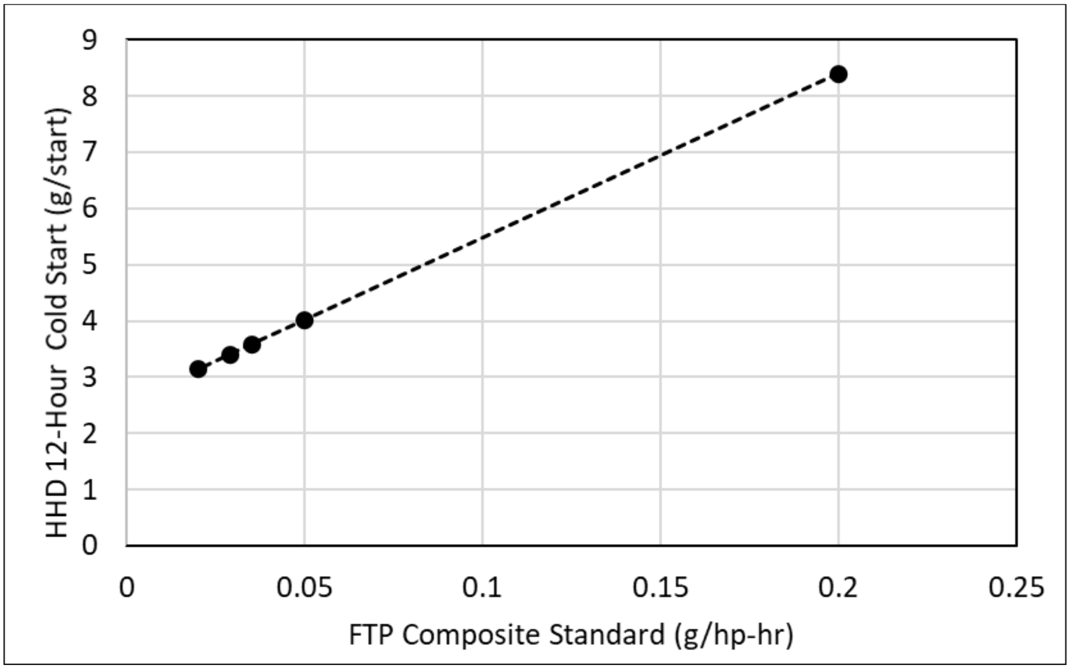

**Figure 2-56 Calculated relationship between the HHD $NO_x$ 12-hour cold-start and the composite FTP $NO_x$ standards**

**Table 2-43 HHD Cold Start Emissions for Baseline and HD2027 Standards**

| **Scenario** | **Applicable Model Years** | **Weighted Average FTP standard (g/hp-hr)** | **Cold Start emissions (g/start)** |
|---|---|---|---|
| Baseline | Model Year 2010-2026 | 0.2 | 8.40 |
| HD2027 Standards | Model Year 2027+ | 0.05 | 4.02 |

We assumed that the relative difference in cold start emission rates by regulatory class is the same in the baseline and HD2027 standards. This calculation was combined with the estimate of emissions by start operating mode and is described in Equation 2-40 in Section 2.2.3.

#### *2.2.1.4 Model Year Summary*

Figure 2-57 through Figure 2-59 display the cold start (operating mode 108) emission rates across model years for heavy-duty diesel vehicles. The figures show the large difference in start emission rates before and after model year 2010. Model year 2010 corresponds to the implementation of (SCR) aftertreatment, as well as the different datasets and methodologies. The rates for LHD2b3 are lower starting in MY2018 due to the phase-in of Tier 3 standards. The HD $NO_x$ emission rates change in MY2027 due to the HD2027 rule.

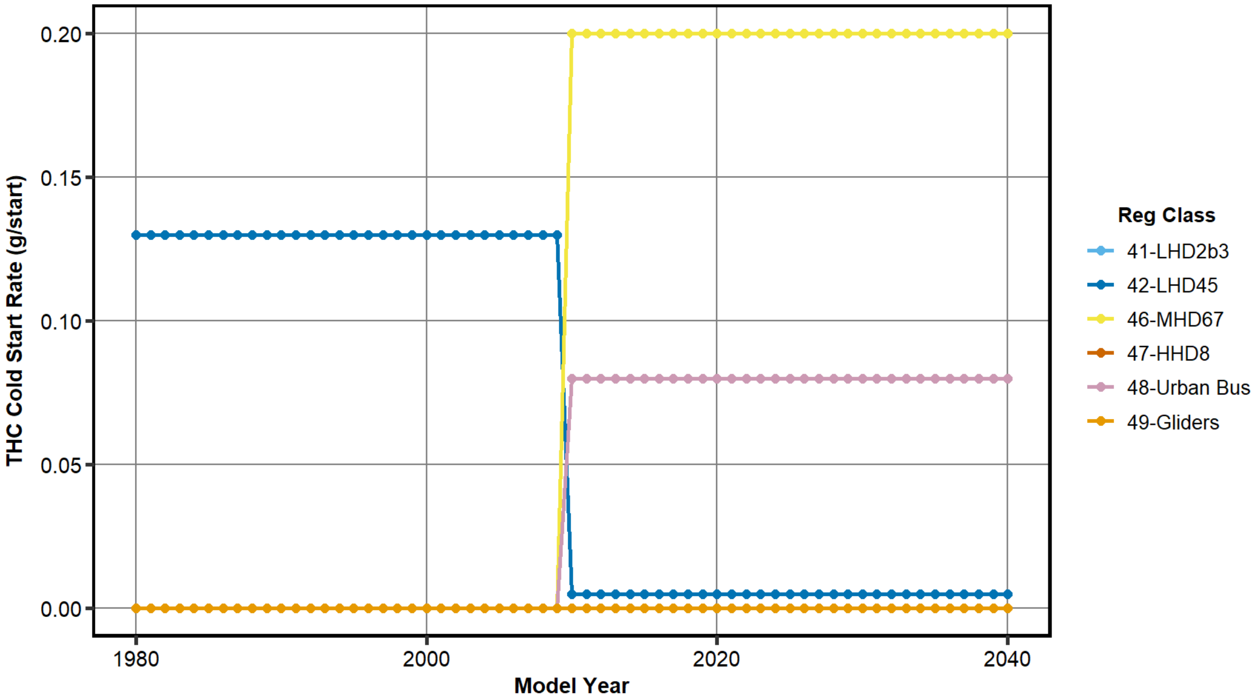

**Figure 2-57 Heavy-duty Diesel THC Cold-Start Emission Rates (g/start) for Age Group 0-3 By Regulatory Class and Model Year**

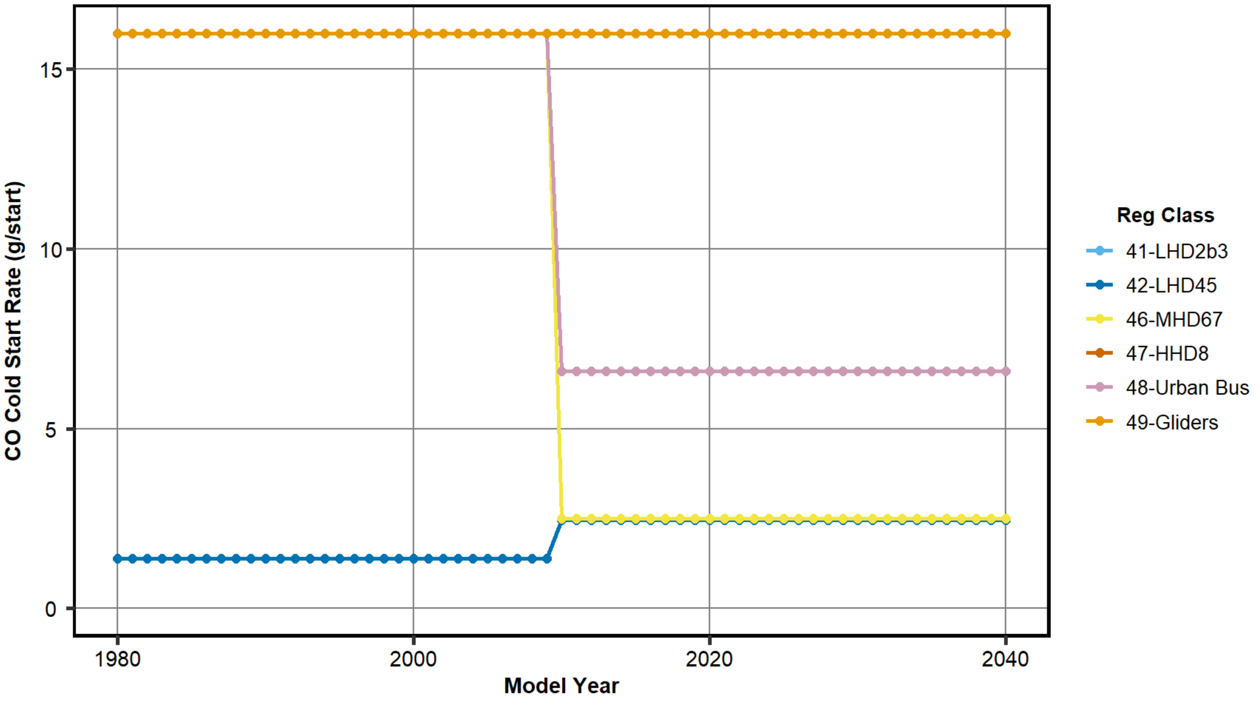

Figure 2-58 Heavy-duty Diesel CO Cold-Start Emission Rates (g/start) for Age Group 0-3 By Regulatory Class and Model Year

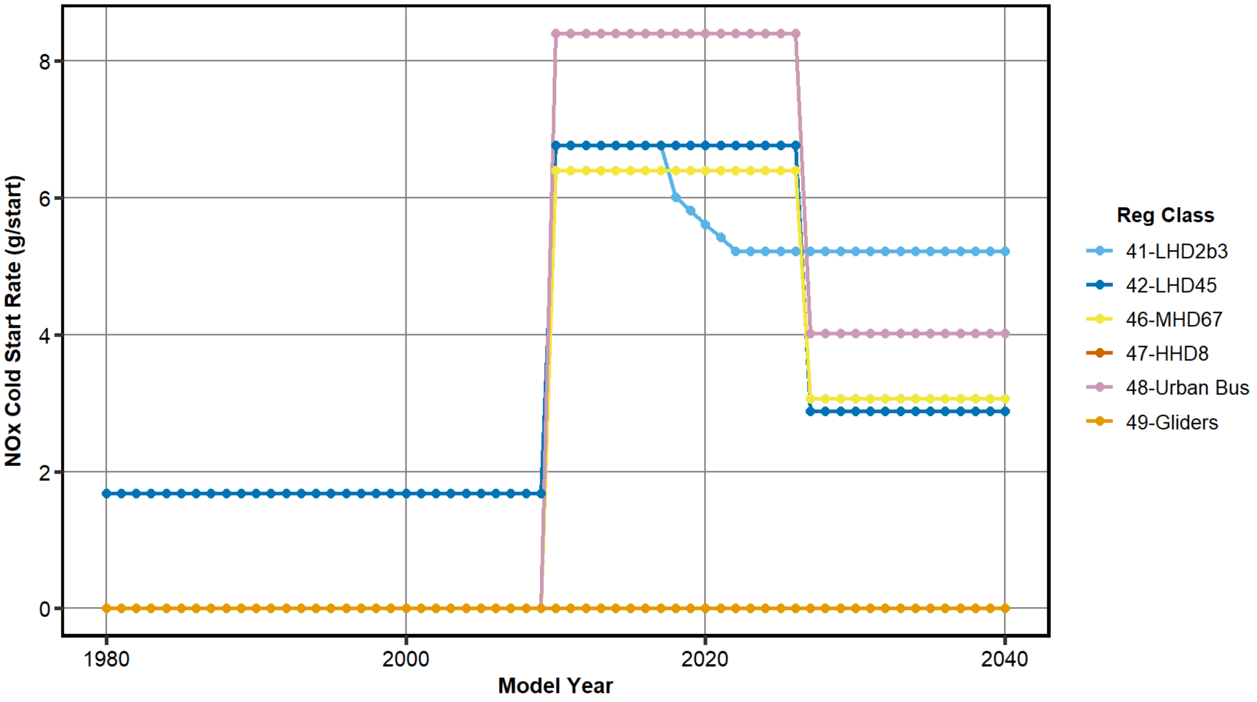

Figure 2-59 Heavy-duty Diesel $NO_x$ Cold-Start Emission Rates (g/start) for Age Group 0-3 By Regulatory Class and Model Year

### *2.2.2 Particulate Matter (PM$_{2.5}$)*

#### *2.2.2.1 1960-2010 Model Years*

Data for particulate matter start emissions from heavy-duty vehicles are limited. Typically, heavy-duty vehicle emission measurements are performed on fully warmed up vehicles. These procedures bypass the engine crank and early operating periods when the vehicle is not fully warmed up.

Data for model year 2009-and-earlier vehicles was only available from engine dynamometer testing performed on one heavy heavy-duty diesel engine, using the FTP cycle with particulate mass collected on filters. The engine was manufactured in MY 2004. The cycle was repeated six times, under both hot and cold start conditions (two tests for cold start and four replicate tests for hot start). The average difference in PM$_{2.5}$ emissions (filter measurement - FTP cycle) was 0.11 grams. The data are shown in Table 2-44.

**Table 2-44 Average PM$_{2.5}$ emissions (grams) from MY 2004 HHD diesel engine tested on the FTP Cycle**

| | PM$_{2.5}$ emissions (grams) |
|---|---|
| Cold start FTP average | 1.93 |
| Warm start FTP average | 1.82 |
| Cold start – warm start | 0.11 |

We use the difference between the cold start and warm start bags to represent the cold start (g/start_ in MOVES.[p] We applied this value to 1960 through 2006 model year vehicles. For 2007 through 2009 model years, we applied a 90 percent reduction to account for the expected use of DPFs, leading to a corresponding value of 0.011 g/start. The value is the same for all heavy-duty diesel regulatory classes.

As introduced in Section 2.1.2.1.8, in MOVES, the PM$_{2.5}$ emission rates are estimated as the elemental carbon (EC) and non-elemental carbon PM (nonEC). We estimated the EC and nonEC from the total PM$_{2.5}$ starts rates by applying the EC/PM fraction of 46.4 percent from the PM$_{2.5}$ speciation profile developed from the idle mode of the UDDS tests from the E55/59 program for pre-2007 trucks.[1] For all 2007+ trucks, we apply the EC/PM fraction of 9.98 percent from the PM$_{2.5}$ speciation profile developed from trucks equipped with diesel particulate filters.[1]

#### *2.2.2.2 2010-2060 Model Years*

The cold start emissions for 2010 model year and later LHD, MHD, and HHD diesel engines were updated in MOVES3 based on new data. We updated the cold start particulate matter emission rates based on the certification data and data analysis methods discussed in Section 2.2.1.2. The resulting cold start emission rates for each HD diesel engine regulatory group are shown in Table 2-45. For LHD diesel vehicles, the certification data yielded zero PM$_{2.5}$ start emissions. We attribute the zero start to the uncertainty of the data (note the standard deviation shown in Table 2-45 is of similar magnitude to that of HHD and MHD). Instead of using the certification test data, we used the data from MHD diesel to represent the LHD diesel PM$_{2.5}$ emission rate in MOVES, because of the overlap in engines and aftertreatment systems between the two categories.

**Table 2-45: Cold Start $PM_{2.5}$ Emission Rates for Heavy-Duty Diesel Emissions for 2010+ MY**

| Grams per Start | HHD | MHD | LHD Test Data | LHD for MOVES[a] |
|---|---|---|---|---|
| Mean of Data | 0.013 | 0.008 | 0.000 | 0.008 |
| Standard Deviation of Data | 0.029 | 0.017 | 0.010 | |

Note:

[a] Instead of using the test data, we used the data from MHD diesel to represent the LHD diesel $PM_{2.5}$ emission rate in MOVES as noted above.

We are applying the new cold start $PM_{2.5}$ emission rates from the model year 2016 and 2017 engines to MY 2010 and newer engines because the PM standards are the same and all the MY 2010 and later engines generally include both a diesel particulate filter (DPF) and selective catalytic reduction (SCR) system.

#### 2.2.2.3 *Model Year Summary*

Figure 2-59 and Figure 2-60 display the cold start (operating mode 108) emission rates across model years for heavy-duty diesel vehicles. As expected, large reductions are shown in model year 2007 with the implementation of diesel particulate filters. Further changes are due to the incorporation of the 2010 and later certification data.

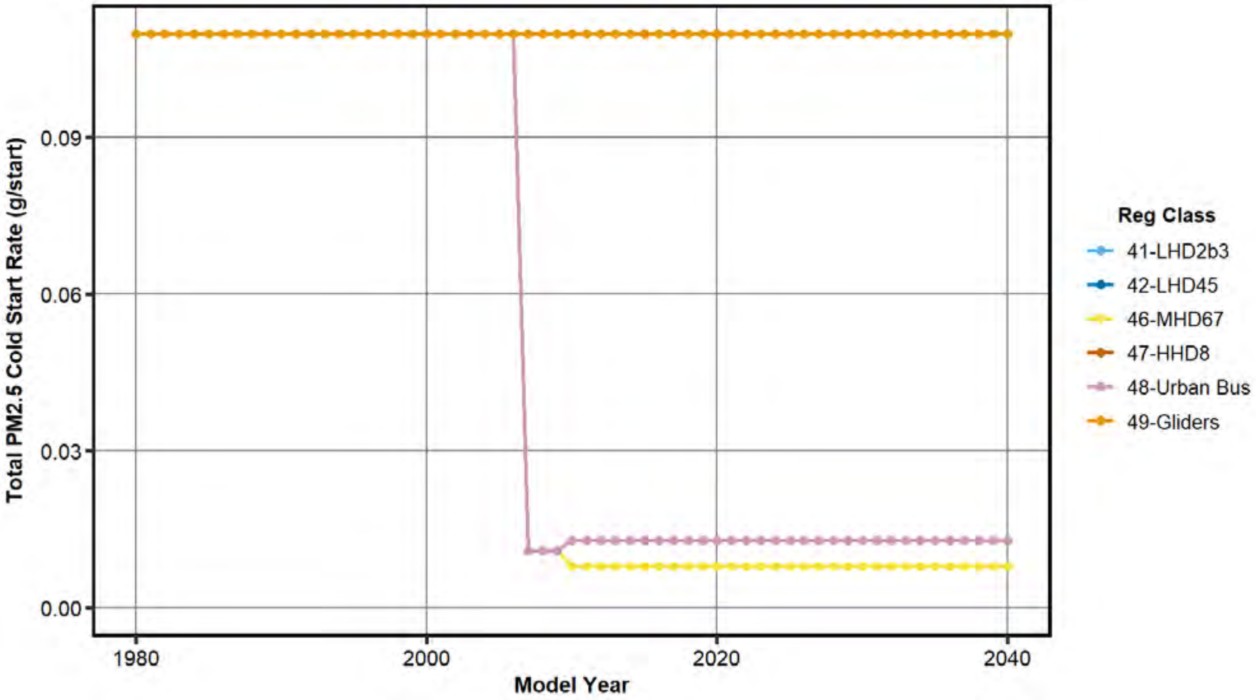

**Figure 2-60 Heavy-duty Diesel $PM_{2.5}$ Cold-Start Emission Rates (g/start) for Age Group 0-3 By Regulatory Class and Model Year. Urban Bus and HHD are equivalent. MHD, LHD45, LHD2b3 are equivalent.**

### 2.2.3 *Adjusting Start Rates for Soak Time*

The discussion to this point has concerned the development of rates for cold start emissions from heavy-duty diesel vehicles. In addition, it was necessary to derive rates for additional operating modes that account for shorter soak times. As with light-duty vehicles, we accomplished this step by applying soak fractions.

In the MOVES input database, operating modes for start emissions are defined in terms of soak time preceding an engine start. The "cold-start" is defined as a start following a soak period of at least 720 minutes (12 hours) and is represented as opModeID=108. An additional seven modes are defined in terms of soak times ranging from 3 min up to 540 min (opModeID = 101-107). Table 1-5 describes the different start-related operating modes in MOVES as a function of soak time. The distribution of vehicle start activity among the start operating modes is described in the MOVES Vehicle Population and Activity report.[6]

#### *2.2.3.1 Adjusting Start Rates for Soak Time – MY 2009 and Earlier*

The soak adjustment ratios we used for THC, CO, and $NO_x$ for MY 2009 and older HD diesel vehicles are illustrated in Figure 2-61 below. Due to limited data, we applied the same soak ratios that we applied to 1996+ MY light-duty gasoline vehicle as documented in the light-duty emission rate report.[9] The soak adjustments are taken from the non-catalyst soak adjustments derived in a CARB report[67] and reproduced in a MOBILE6 report.[68]

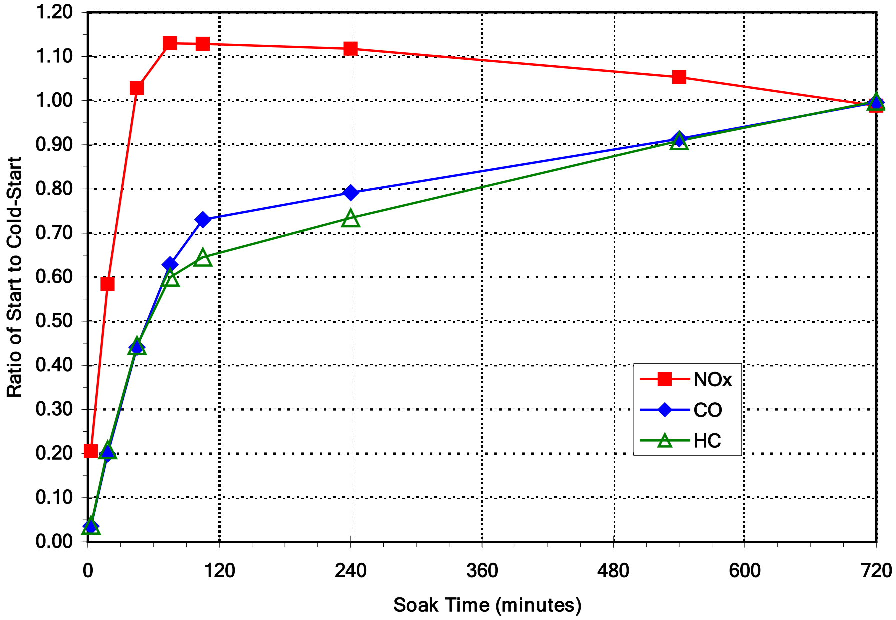

**Figure 2-61. Soak Adjustment Ratios Applied to Cold-Start Emissions (opModeID = 108) to Estimate Emissions for shorter Soak Periods (operating modes 101-107). This figure is reproduced from the Light-Duty Emissions Report[9]**

For light heavy-duty vehicles (regulatory classes LHD2b3 and LHD45), the soak ratios apply to the cold starts for THC, CO and $NO_x$. For medium and heavy heavy-duty vehicles (regulatory classes MHD, HHD, and Urban Bus), only the CO soak ratios are applied to the cold-start emissions, because the base cold start THC and $NO_x$ emission rates for medium and heavy heavy-duty emission rates are zero (see Section 2.2.1.1). The start emission rates entered into MOVES for 2009 and older model year heavy-duty vehicles, derived from applying the soak ratios are displayed in Table 2-46 for THC, CO, and $NO_x$.

**Table 2-46. Heavy-Duty diesel THC, CO, and $NO_x$ Start Emissions (g/start) by Operating Mode for 2009 and Earlier Model Year Vehicles**

| | THC | | CO | | $NO_x$ | |
|---|---|---|---|---|---|---|
| opModeID | LHD[1] | Other HD[2] | LHD | Other HD | LHD | Other HD |
| 101 | 0.0052 | 0 | 0.055 | 0.64 | 0.275 | 0 |
| 102 | 0.0273 | 0 | 0.276 | 3.2 | 0.760 | 0 |
| 103 | 0.0572 | 0 | 0.607 | 7.04 | 1.350 | 0 |
| 104 | 0.0780 | 0 | 0.869 | 10.08 | 1.481 | 0 |
| 105 | 0.0832 | 0 | 1.007 | 11.68 | 1.481 | 0 |
| 106 | 0.0949 | 0 | 1.090 | 12.64 | 1.468 | 0 |
| 107 | 0.1183 | 0 | 1.256 | 14.56 | 1.376 | 0 |
| 108 | 0.1300 | 0 | 1.380 | 16 | 1.298 | 0 |

Notes:

[1] LHD refers to LHD2b3 and LHD45

[2] Other HD refers to the medium heavy-duty, heavy heavy-duty, and urban bus regulatory classes

The $PM_{2.5}$ start rates by operating mode are given in Table 2-47 below. They are estimated by assuming a linear decrease in emissions with time between a full cold start (>720 minutes) and zero emissions at a short soak time (< 6 minutes).

**Table 2-47. Particulate Matter Start Emission Rates (g/start) by Operating Mode (soak fraction) for all HD Diesel vehicles through MY 2009**

| Operating Mode | 1960-2006 MY | 2007-2009 MY |
|---|---|---|
| 101 | 0.0000 | 0.00000 |
| 102 | 0.0009 | 0.00009 |
| 103 | 0.0046 | 0.00046 |
| 104 | 0.0092 | 0.00092 |
| 105 | 0.0138 | 0.00138 |
| 106 | 0.0183 | 0.00183 |
| 107 | 0.0549 | 0.00549 |
| 108 | 0.1099 | 0.01099 |

#### *2.2.3.2 Adjusting Start Rates for Soak Time – MY 2010 and Later*

As described in the preceding section, the start rates are based on data collected from light-duty vehicles in the 1990's. The question arose as to whether they could be considered applicable to heavy-duty diesel vehicles with aftertreatment systems designed to meet the 2007/2010 exhaust emissions standards. To address this question, we initiated a research program in 2016, with the goal of examining the relationships between soak time and start emissions for a set of heavy-duty vehicles. Two test programs were conducted to revise the 2010 MY and later soak curves for heavy-duty diesel vehicles in MOVES3 and later versions. The testing consisted of both chassis and onroad testing of MY 2015 and MY 2016 vehicles.

The first test program included a MY 2015 day-cab tractor with a MY 2015 HHD diesel engine tested on a heavy-duty chassis.[69] The vehicle was relatively new and had 10,000 miles on the odometer. The testing consisted of running two repeats of a transient drive cycle developed by the National Renewable Energy Laboratory (NREL). The vehicle speed trace is shown below in Figure 2-62. Prior to each soak test, the vehicle was first run through two of the NREL cycles. Then the engine was shut off for a specified amount of time to reflect the soak periods shown in Figure 2-62. At least two repeats were conducted for each soak period. The emission measurements included dilute gaseous measurements and triplicate particulate matter filters.

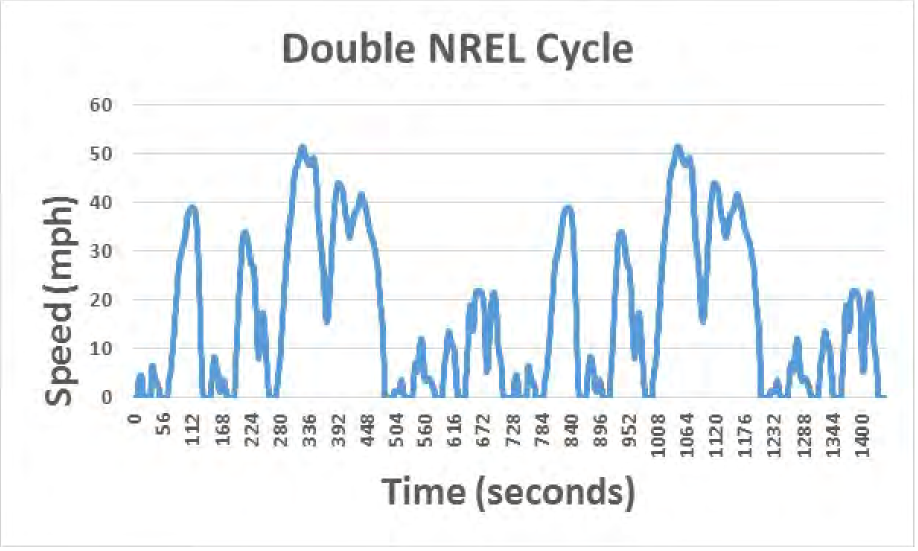

**Figure 2-62 National Renewable Energy Laboratory's Heavy-Duty Vocational Transient Cycle**

The $NO_x$, CO, THC, and $PM_{2.5}$ emission results in terms of grams or mg per mile from the tests over a range of soak periods are shown in Figure 2-63 through Figure 2-66.

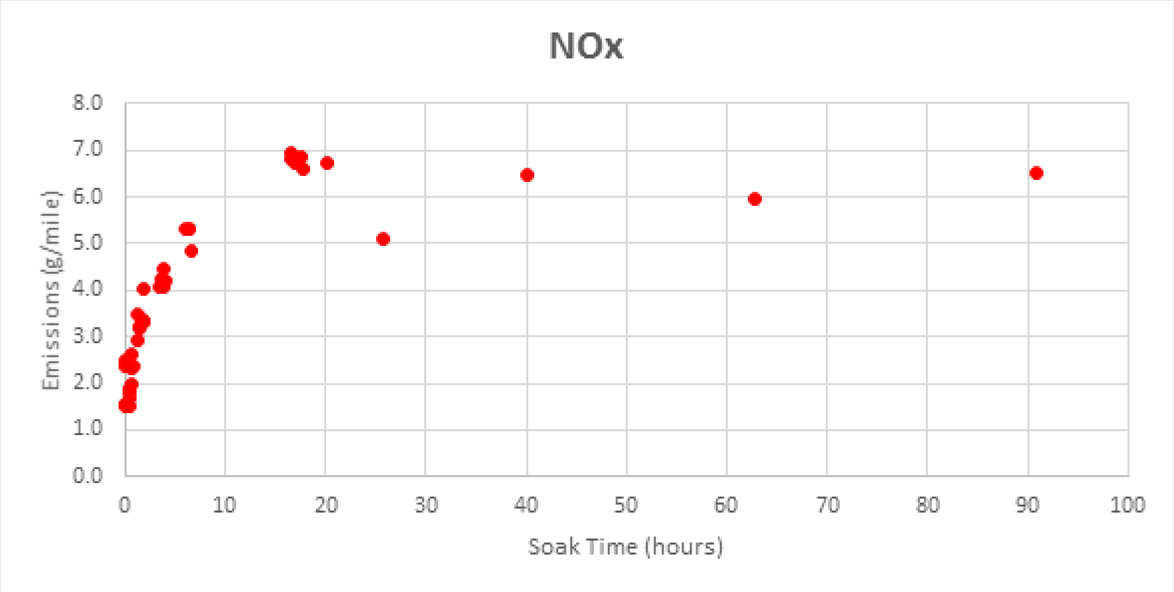

**Figure 2-63 MY 2015 Heavy-Duty Vehicle NO$_x$ Emissions by Soak Time**

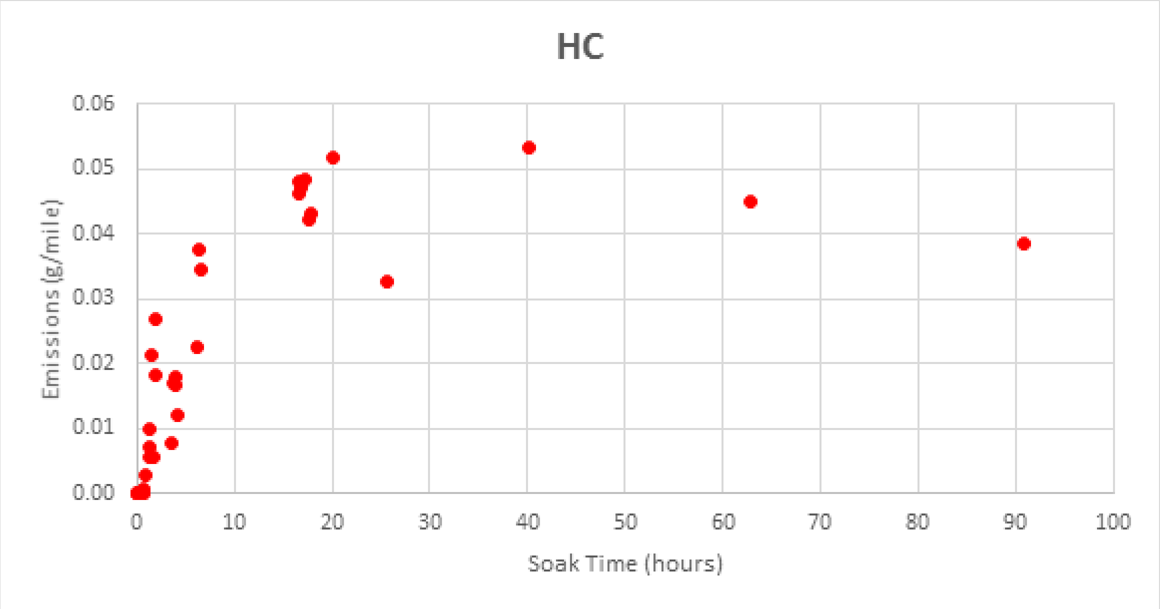

**Figure 2-64 MY 2015 Heavy-Duty Vehicle THC Emissions by Soak Time**

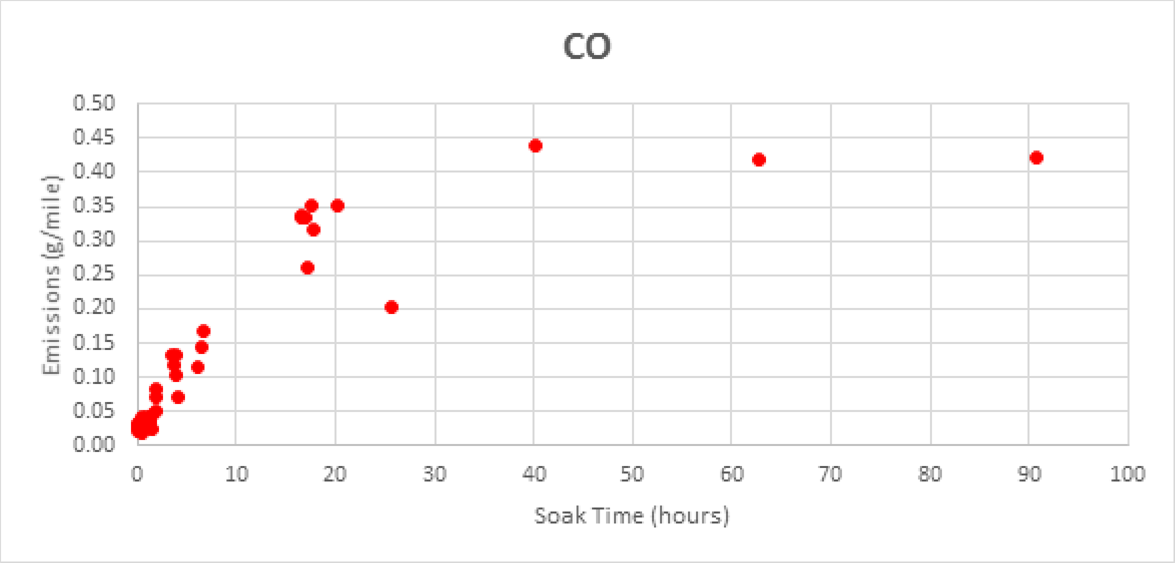

**Figure 2-65 MY 2015 Heavy-Duty Vehicle CO Emissions by Soak Time**

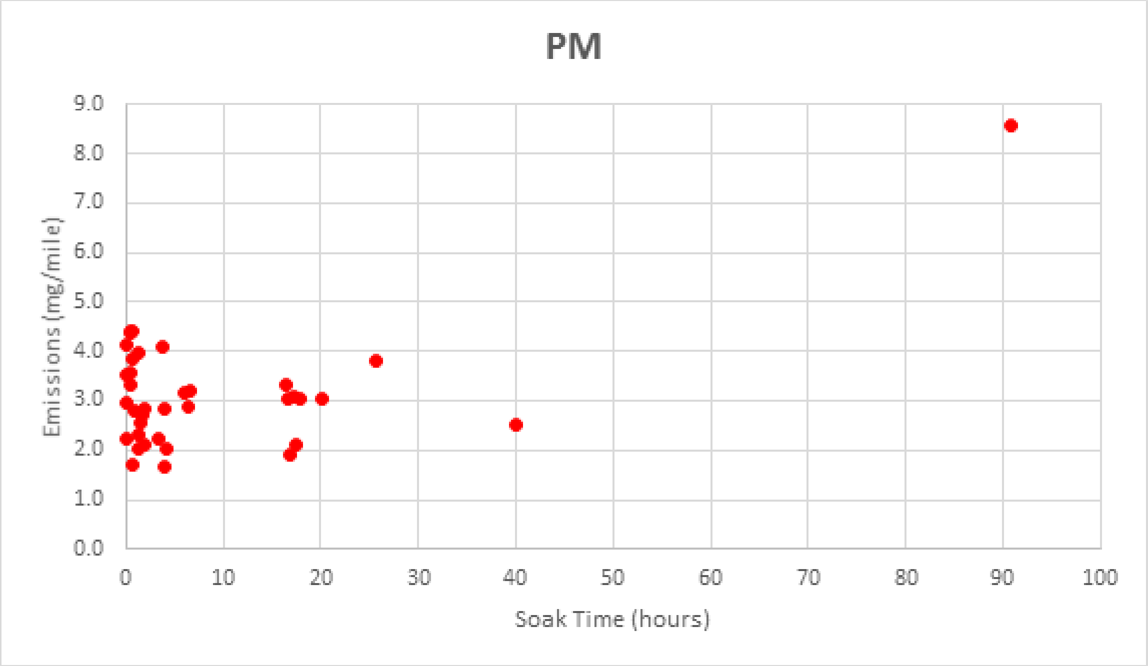

**Figure 2-66 MY 2015 Heavy-Duty Vehicle $PM_{2.5}$ Emissions by Soak Time**

In addition to the chassis testing, onroad testing was conducted using a portable emissions measurement system (PEMS).[70] The emissions data gathered by the PEMS in this test program only included the gaseous emissions, not PM data. A MY 2016 work van with a diesel engine was tested on the road. The vehicle was soaked and started within a laboratory under controlled temperatures. All onroad testing occurred with ambient temperatures over 50 degrees F. Each test began with 10 seconds of idle followed by driving a defined "soak route." A typical vehicle speed profile from the route is shown in Figure 2-67. The route consisted of approximately 700 seconds of driving in a neighborhood/urban environment over approximately 2.7 miles.

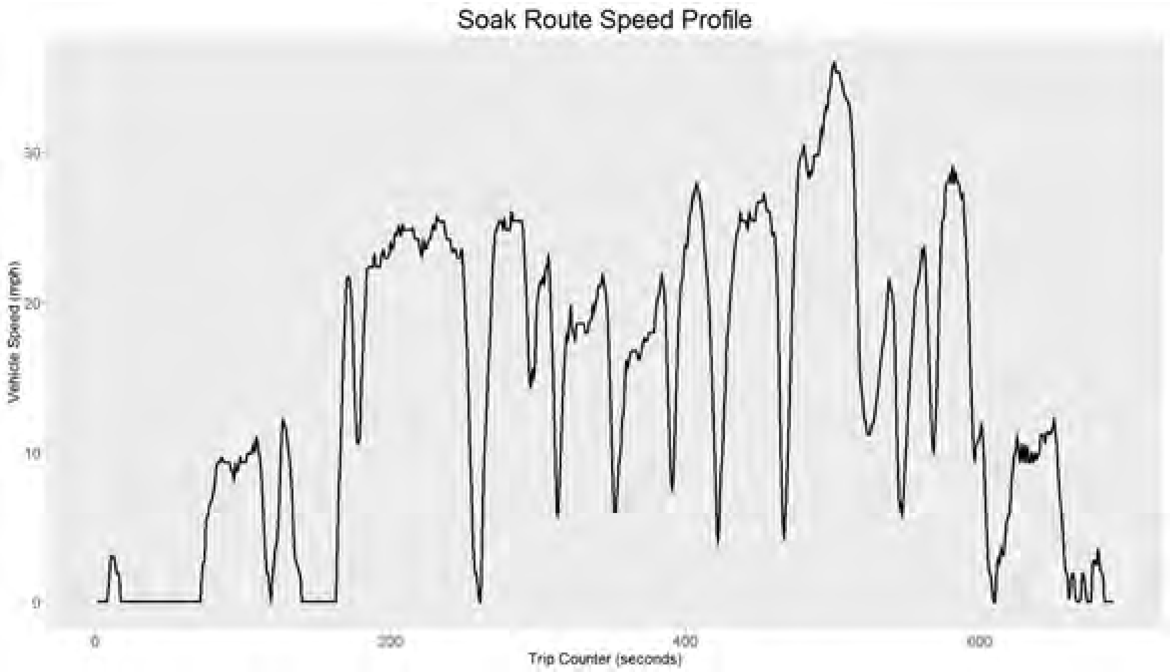

**Figure 2-67 Onroad Soak Drive Route**

The emission results, in terms of total emissions over the route, from the onroad tests are shown in Figure 2-68 through Figure 2-70.

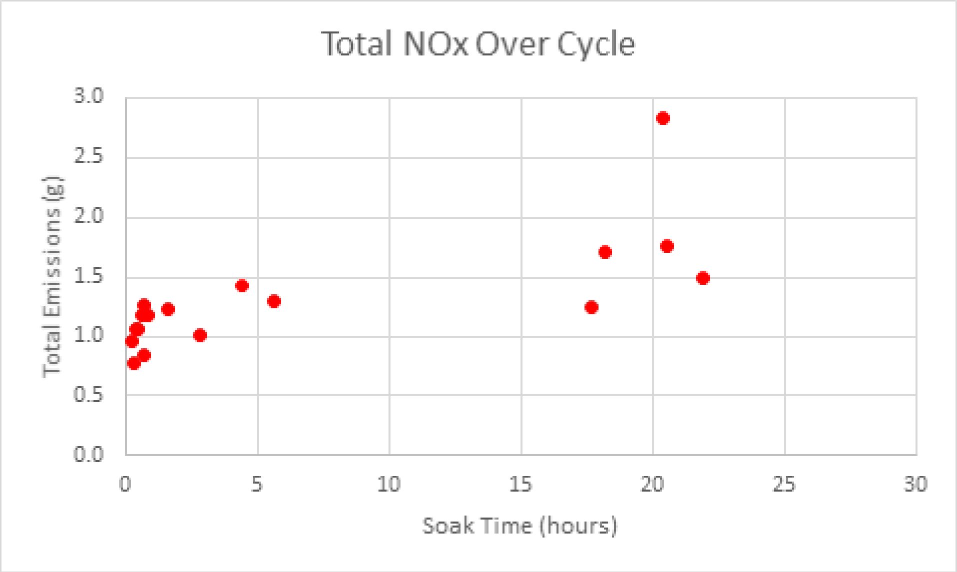

**Figure 2-68 MY 2016 Heavy-Duty Vehicle NO$_x$ Emissions by Soak Time**

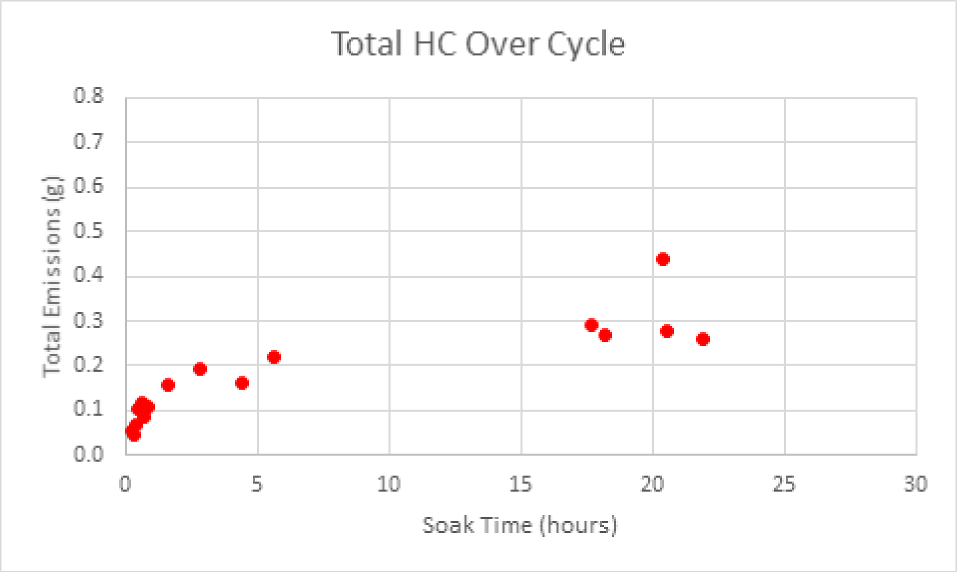

**Figure 2-69 MY 2016 Heavy-Duty Vehicle THC Emissions by Soak Time**

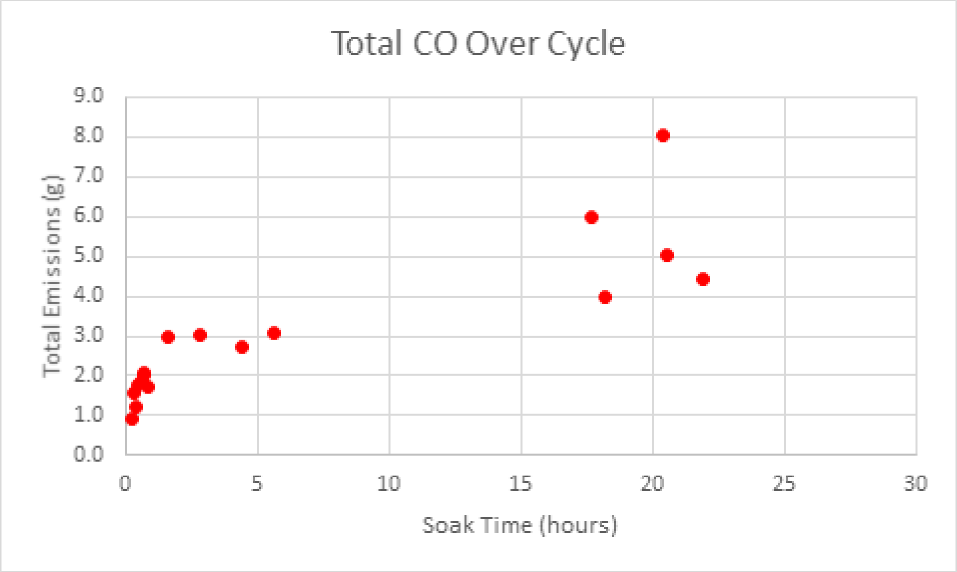

**Figure 2-70 MY 2016 Heavy-Duty Vehicle CO Emissions by Soak Time**

The soak emission adjustment ratios were calculated using a multi-step process based on the chassis test and onroad test results. First, the total emissions over the route or drive cycle were averaged for each soak period for each pollutant ($NO_x$, THC, CO) for each vehicle. Then the start emissions for each soak period were determined by subtracting the average total emissions from the tests with the 3 minute soak time from the emissions from the specific soak period. The ratios for soak period operating modes 102 through 108 were calculated based on the average start emissions of the soak period divided by the average start emissions of the cold start (>12 hours) soak period. The soak fractions for the operating mode 101 were determined by extrapolating the value from the operating mode 102 result using the proportional difference in time between the midpoints of each operating mode 101 and 102 soak times. In other words, soak fraction for operating mode 102 was multiplied by the ratio of 3 minutes divided by 18 minutes (the midpoint times of operating mode 101 and 102). The $NO_x$, CO, and THC soak period ratio results for each vehicle are shown below in Figure 2-71.

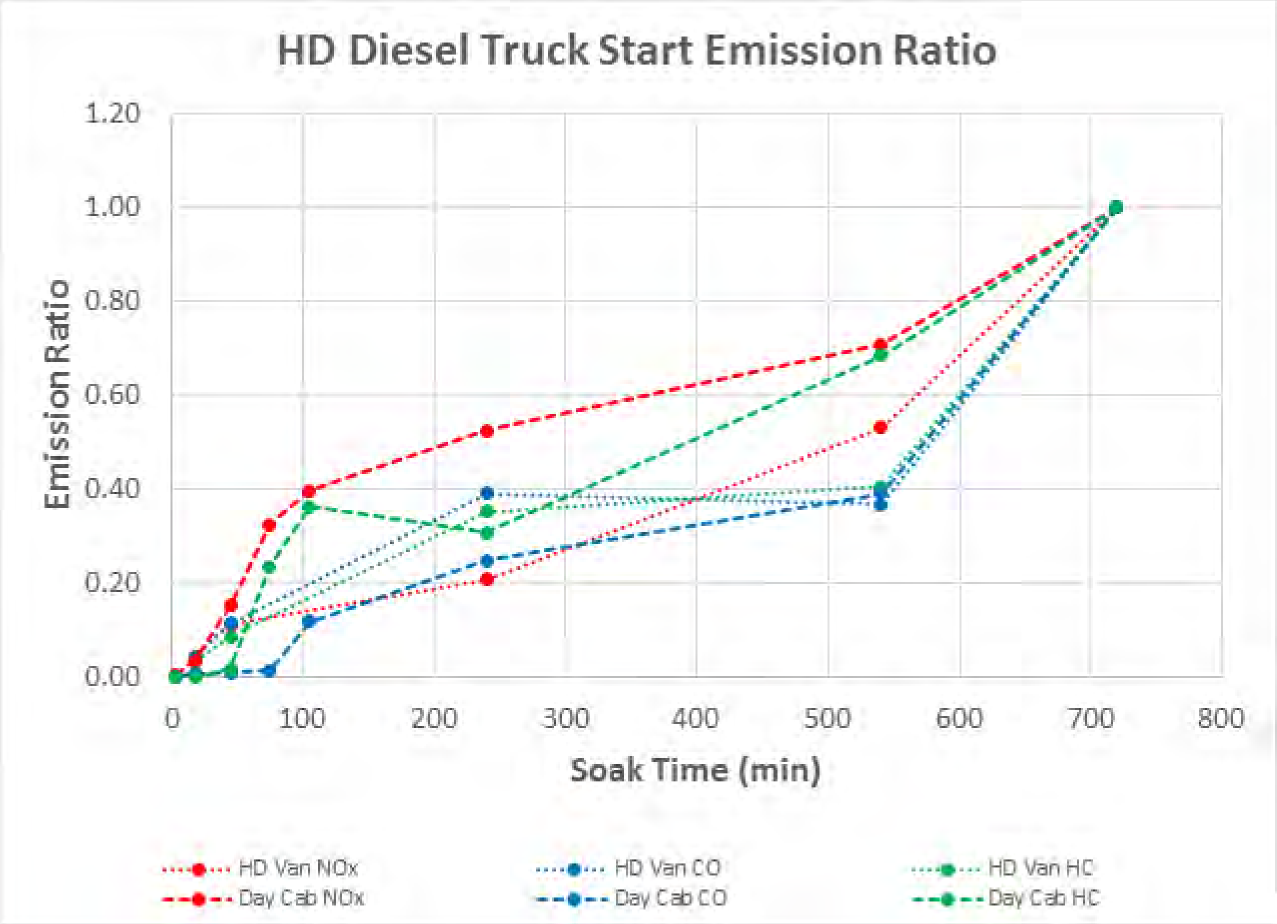

Figure 2-71 Soak Emission Ratios from a MY 2015 HD Day-Cab and a MY 2016 HD Van

The 2010 MY and later heavy-duty diesel soak ratios for MOVES were determined by averaging the results from the two trucks. The resulting soak adjustment ratios are shown in Table 2-48. The soak adjustment ratios are applied to all heavy-duty diesel regulatory classes because the two trucks tested cover the range of HD diesel regulatory classes.

**Table 2-48 HD Diesel Engine Soak Ratios for MY 2010 and Newer**

| Operating Mode | Description | $NO_x$ | CO | THC |
|---|---|---|---|---|
| 101 | Soak Time < 6 minutes | 0.01 | 0.00 | 0.00 |
| 102 | 6 minutes ≤ Soak Time < 30 minutes | 0.04 | 0.03 | 0.02 |
| 103 | 30 minutes ≤ Soak Time < 60 minutes | 0.13 | 0.06 | 0.05 |
| 104 | 60 minutes ≤ Soak Time < 90 minutes | 0.33 | 0.02 | 0.24 |
| 105 | 90 minutes ≤ Soak Time < 120 minutes | 0.40 | 0.12 | 0.36 |
| 106 | 120 minutes ≤ Soak Time < 360 minutes | 0.37 | 0.32 | 0.33 |
| 107 | 360 minutes ≤ Soak Time < 720 minutes | 0.62 | 0.38 | 0.55 |
| 108 | 720 minutes ≤ Soak Time | 1.00 | 1.00 | 1.00 |

For MY2027+ vehicles subject to HD2027 standards, we used Table 2-40 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. We assumed that the relative difference in emission rates by regulatory class and by operating mode is the same for MY2010-2026 and MY2027 and later meeting the HD2027 standards.

$$\begin{aligned}\text{Start ER}_{\text{FTP=x ,reg class=y,soak=z}} &= \text{Start ER}_{\text{Duty cycle standard x,HHD,12}} \\ &\times \left(\frac{\text{MOVES start}_{\text{reg class=y,soak=z}}}{\text{MOVES start}_{\text{HHD,12-hour}}}\right)\end{aligned} \qquad \textbf{Equation 2-40}$$

Where:

$\text{Start ER}_{\text{FTP}}$= the start $NO_x$ emission rates for the HD2027 standards with FTP x (0.035 or 0.05) for regulatory class y (LHD45, MHD, and HHD), and soak length z

$\text{Start ER}_{\text{Duty cycle standard x,HHD,12-hour}}$ = 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)

$\text{MOVES start}_{\text{reg class=y,soak=z}}$ = MOVES3 baseline start emission rate for MY 2027 for regulatory class y (LHD45, MHD, and HHD), and soak length z

$\text{MOVES start}_{\text{HHD,12-hour}}$= MOVES3 baseline start emission rate for MY 2027 HHD diesel engine for a 12-hour soak (operating mode 108)

For example, Figure 2-72 compares the estimated MOVES $NO_x$ start emission rates for HHD diesel vehicles for MY2010-2026 and MY2027 and later.

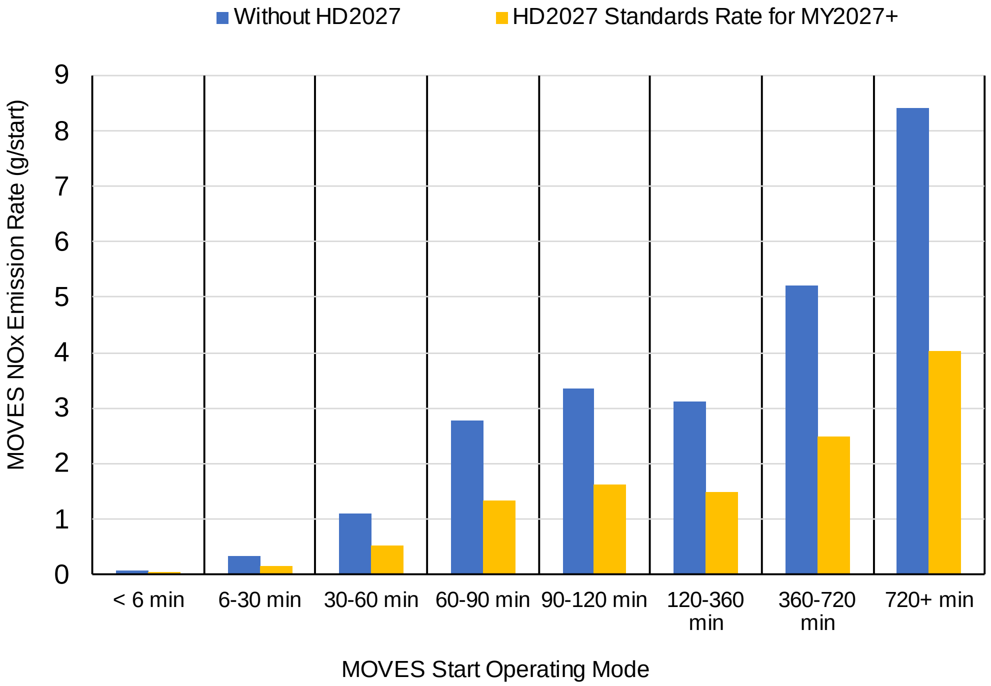

**Figure 2-72 Duty-cycle-based $NO_x$ start emissions for HHD Diesel comparing MY2010-2026 and MY2027+ rates.**

The $PM_{2.5}$ start rates by operating mode for MY 2010 and newer vehicles are presented in Table 2-49 below. They were updated in MOVES3 using a linear interpolation based on the new cold start data (certification data discussed in Section 2.2.2.2) for Operating Mode 108. They are estimated by assuming a linear decrease in emissions with time between a full cold start (>720 minutes) and zero emissions at a short soak time (< 6 minutes). This approach is consistent with the approach taken for MY 2009 and older vehicles, as described in Section 2.2.3.1. We did not revise the approach because we obtained $PM_{2.5}$ data for only one of the trucks and it showed mixed soak effect results.

**Table 2-49 $PM_{2.5}$ Start Emission Rates (g/start) by Regulatory Class and Operating Mode (soak fraction) for all MY 2010 and newer HD Diesel Vehicles**

| Operating Mode | HHD and Urban Bus | MHD | LHD2b3 and LHD45 |
|---|---|---|---|
| 101 | 0.00000 | 0.00000 | 0.00000 |
| 102 | 0.00163 | 0.00100 | 0.00100 |
| 103 | 0.00325 | 0.00200 | 0.00200 |
| 104 | 0.00488 | 0.00300 | 0.00300 |
| 105 | 0.00650 | 0.00400 | 0.00400 |
| 106 | 0.00813 | 0.00500 | 0.00500 |
| 107 | 0.00975 | 0.00600 | 0.00600 |
| 108 | 0.01300 | 0.00800 | 0.00800 |

#### *2.2.3.3 Adjusting Start Rates for Ambient Temperature*

The ambient temperature effects in MOVES are used to estimate the impact ambient temperature has on cooling the engine and aftertreatment system on vehicle emissions. The temperature effect is the greatest for a vehicle that has been soaking for a long period of time, such that the vehicle is at ambient temperature. Accordingly, the impact of ambient temperature should be less for vehicles that are still warm from driving. The emission adjustments report discusses the impact of ambient temperature on cold start emission rates (operating mode 108).[63] The ambient temperature effects for starts with warm and hot soaks (operating mode 101-107) are documented below and recorded in the MOVES startTempAdjustment table.

Because the THC temperature effects in MOVES are modeled as additive adjustments, the adjustment calculated for cold starts needs to be reduced for warm and hot starts. Due to lack of data, we multiply the soak fractions described earlier in Figure 2-61 for pre-2007 trucks by the additive cold temperature effect for the 12-hour cold start (operating mode 108) to obtain cold start temperature adjustments for the warm and hot soaks starts (operating mode 101 through 107) for all model years.[q] The additive cold start adjustment for THC emission factors are displayed in Table 2-50, along with the soak fractions applied. These additive THC starts are applied to all diesel sources in MOVES, including light-duty diesel (regulatory class LDV and LDT). There are currently no diesel temperature effects in MOVES for $PM_{2.5}$, CO, and $NO_x$.

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[q] The temperature effects from pre-2010 technology engines are applied to all model years. We plan to update the temperature effects by operating mode for 2010 and later model year vehicles in future version of MOVES using the data from 2010 and later engines.

**Table 2-50 THC Diesel Start Ambient Temperature Adjustment by Operating Mode**

| Operating mode ID | Start Temp Adjustment | Soak fraction |
|---|---|---|
| 101 | -0.0153×(Temp – 75) | 0.38 |
| 102 | -0.0152×(Temp – 75) | 0.37 |
| 103 | -0.0180×(Temp – 75) | 0.44 |
| 104 | -0.0201×(Temp – 75) | 0.5 |
| 105 | -0.0211×(Temp – 75) | 0.52 |
| 106 | -0.0254×(Temp – 75) | 0.62 |
| 107 | -0.0349×(Temp – 75) | 0.86 |
| 108 | -0.0406×(Temp – 75) | 1 |

### *2.2.4 Start Energy Rates*

The start energy rates (in units of kJ) were developed for MOVES2004[71], and updated in MOVES2010 as documented in the MOVES2010a energy updates report.[57] Figure 2-73 displays the cold starts in grams of $CO_2$ emissions calculated from the energy rates using the carbon content for conventional diesel fuel as documented in the MOVES3 Greenhouse Gas and Energy Report.[3]

As shown, there is more detail in the pre-2000 energy rates. The spike in $CO_2$ g/start for model years 1984-1985 reflects variability in the data used to derive starts, which was consistent with the more detailed approach used to derive the pre-2000 energy rates in MOVES2004. The only updates to the start energy rates post-2000 is the impact of the Phase 1 Heavy-Duty GHG standards, which began phase-in in 2014 and have the same reductions as the running energy rates as presented in Table 2-30 and Table 2-32. It is worth noting that unlike the Phase 1 HD GHG standards, the technologies projected for meeting the Phase 2 HD GHG standards are not expected to have an impact on start energy rates.  Therefore, the start energy rates are constant after MY 2018 (the first year of full phase-in of the HD Phase 1 rule).

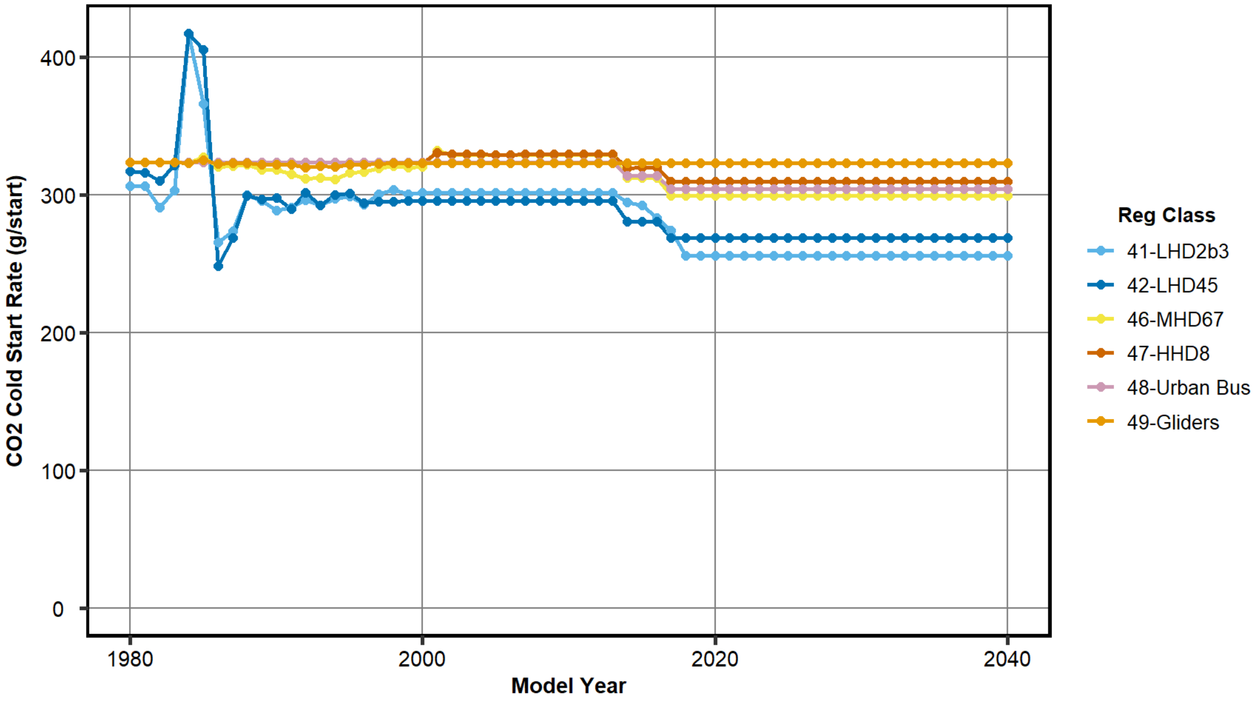

**Figure 2-73 Heavy-Duty Diesel Cold Start CO$_2$ Rates (Operating Mode 108) by Model Year and Regulatory Class**

The start energy rates are adjusted in MOVES to account for increased fuel consumption required to start a vehicle at cold ambient temperatures. The temperature effects are documented in the MOVES2004 Energy Report.[71] Additionally, the energy consumption is reduced for starts that occur when the vehicles have soaked for a short period of time. The soak fractions used to reduce the cold start energy consumption emission rates are provided in Table 2-51. These fractions are used for all model years and regulatory classes of diesel vehicles.

**Table 2-51 Fraction of Energy Consumed at Start of intermediate Soak Lengths compared to the Energy Consumed at a Full Cold Start (operating mode 108)**

| Operating Mode | Description | Fraction of energy consumption compared to full cold start |
|---|---|---|
| 101 | Soak Time < 6 minutes | 0.013 |
| 102 | 6 minutes ≤ Soak Time < 30 minutes | 0.0773 |
| 103 | 30 minutes ≤ Soak Time < 60 minutes | 0.1903 |
| 104 | 60 minutes ≤ Soak Time < 90 minutes | 0.3118 |
| 105 | 90 minutes ≤ Soak Time < 120 minutes | 0.4078 |
| 106 | 120 minutes ≤ Soak Time < 360 minutes | 0.5786 |
| 107 | 360 minutes ≤ Soak Time < 720 minutes | 0.8751 |
| 108 | 720 minutes ≤ Soak Time | 1 |

The energy rates for heavy-duty starts have not been updated due to relatively small contribution the starts have to the energy inventory. Table 2-52 displays the relative contribution of total energy consumption estimated from a national run of MOVES for calendar year 2016, using a draft version of MOVES3 developed for the proposed Clean Trucks Rule.[72] As shown, the estimated energy consumed due to starts is very small in comparison to the energy use of running activity.

**Table 2-52. Relative contribution of total energy consumption from each pollutant process by regulatory class for heavy-duty diesel vehicles in calendar year 2016**

| processID | processName | LHD≤14K | LHD45 | MHD | HHD | Urban Bus | Gliders |
|---|---|---|---|---|---|---|---|
| 1 | Running Exhaust | 98.5% | 99.3% | 99.42% | 98.85% | 99.7% | 98.63% |
| 2 | Start Exhaust | 1.5% | 0.7% | 0.55% | 0.10% | 0.3% | 0.05% |
| 90 | Extended Idle Exhaust | | | 0.03% | 1.03% | | 1.27% |
| 91 | Auxiliary Power Exhaust | | | 0.00% | 0.03% | | 0.05% |

## *2.3 Extended Idling Exhaust Emissions*

In the MOVES model, extended idling is idle operation characterized by long duration idle periods (e.g., > 1 hour[r]) , typically overnight, including higher engine speed settings and extensive use of accessories by the vehicle operator. Extended idling most often occurs during rest periods by long-haul trucking operators where the truck is used as a residence (sometimes referred to as "hotelling"). Operators idle to power accessories such as air conditioning systems or heating systems. Heavy-duty engine and truck manufacturers recommend trucks not idle at low engine speeds for extended periods, because it can "create engine wear and carbon soot buildup in the engine and components."[73] Additionally, idling for extended periods allows the vehicle's exhaust to cool below the effective temperature required for emission aftertreatment systems in modern trucks such as selective reduction catalysts and diesel oxidation catalysts. As a result, extended idle is treated as a separate emission process in MOVES which uses a different emission rate than the idling that occurs during the running emission process.

Extended idling does not include vehicle idle operation that occurs during normal road operation, such as idling at a traffic signal or the "off-network" idle that might occur during a delivery. Although frequent stops and idling can contribute to overall emissions, these modes are included in the normal vehicle hours of operation. Extended idling is characterized by idling periods that last hours rather than minutes.

In the MOVES model, long-haul combination trucks (sourceTypeID 62) is the only source type assumed to have extended idling activity. These trucks are only associated with MHD, HHD and Glider[s] regulatory classes. As an alternative to extended idling, long-haul truck operators can also use auxiliary power units (APUs) or plug into facility's power (shore power) to power their cabin and accessories during hotelling. The emission rates for auxiliary power units (APUs) are discussed in Section 2.4, and the energy consumption rates for shore power are discussed in the Greenhouse Gas and Energy Consumption technical report.[3]

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[r] The default hotelling activity in MOVES3 is estimated from telematics data in which all idle events with duration greater than one hr from long-haul combination trucks are assigned to extended idling.**Error! Bookmark not defined.**

[s] Glider extended idle emission rates are documented in Section 2.5

Extended idle emission rates for THC, CO, $NO_x$ and $PM_{2.5}$ were updated in MOVES3 for all model years. Energy rates were updated for 2007 and later model years. Separate analyses were conducted using different data sets to derive extended idle emission rates for pre-2007 (Section 2.3.1) and 2007 and later long-haul combination trucks (Section 2.3.2). For each range of model years, MOVES applies different data and assumptions regarding the impact of accessory use, frequency of high idle engine speed, and impacts of tampering and mal-maintenance to calculate extended idle emission rates.

### *2.3.1 1960-2006 Model Years*

The MOVES extended idling emission rates for pre-2007 model years were derived from data collected in several distinct test programs under different types of idle conditions. For MOVES3 and later versions, weightings were adjusted from those in previous versions of MOVES to better account for new information on typical extended idling engine idling speeds and loads. These adjustments are described below in Section 2.3.1.2. Appendix D summarizes the data and calculations for the pre-2007 model years.

#### *2.3.1.1 Data Sources*

The references included in this section provide more detailed descriptions of the data and how the data were obtained:

- Testing was conducted on 12 heavy-duty diesel trucks and 12 transit buses in Colorado by McCormick et al.[74] Ten of the trucks were Class 8 heavy-duty semi-tractors, one was a Class 7 truck, and one of the vehicles was a school bus. The school bus data was not used to calculate extended idle rates. The model years ranged from 1990 through 1998. Typical Denver area wintertime diesel fuel was used in all tests. Idle measurements were collected during a 20-minute time period. All testing was done at 1,609 meters above sea level (high altitude).
- Testing was conducted by EPA on five trucks in May 2002 (Lim et al.).[75] The model years ranged from 1985 through 2001. The vehicles were put through a battery of tests including a variety of idling conditions.
- A total of 63 trucks (nine in Tennessee, 12 in New York and 42 in California) were tested over a battery of idle test conditions including with and without air conditioning (Irick et al.).[76] Not all trucks were tested under all conditions. Only results from the testing in Tennessee and New York are described in the IdleAire report (Irick et al.).[76]
- The California test data was collected on 42 diesel trucks in parallel with roadside smoke opacity testing (Lambert)[77]. All tests conducted by the California Air Resources Board (CARB) at a rest area near Tulare, California in April 2002 are described in the Lambert[77] Clean Air Study. All analytical equipment for all testing at all locations was operated by Clean Air Technologies.
- Fourteen trucks were tested as part of the E-55/59 Coordinating Research Council (CRC) study of heavy-duty diesel trucks with idling times either 900 or 1,800 seconds long.[78]

- The National Cooperative Highway Research Program (NCHRP)[79] obtained the idling portion of continuous sampling during transient testing to determine idling emission rates on two trucks.
- A total of 33 heavy-duty diesel trucks were tested in an internal study by the City of New York (Tang et al.)[80]. The model years ranged from 1984 through 1999. One hundred seconds of idling were added at the end of the WVU five-mile transient test driving cycle.
- A Class 8 Freightliner Century with a 1999 engine was tested using EPA's onroad emissions testing trailer based in Research Triangle Park, North Carolina (Brodrick).[81] Both short (10 minute) and longer (five hour) measurements were made during idling. Some testing was also done on three older trucks.
- Five heavy-duty trucks were tested for particulate and $NO_x$ emissions under a variety of conditions at Oak Ridge Laboratories (Storey et al.).[82] These are the same trucks used in the EPA study (Lim et al.).
- The University of Tennessee (Calcagno et al.) tested 24 1992 through 2006 model year heavy-duty diesel trucks using a variety of idling conditions including variations of engine idle speed and load (air conditioning).[64]

#### *2.3.1.2 Analysis*

We used the data sources referenced above to estimate the emission rates for particulate matter ($PM_{2.5}$ ), oxides of nitrogen ($NO_x$), hydrocarbons (THC), carbon monoxide (CO) and carbon dioxide ($CO_2$). The data were grouped by truck and bus and by idle speed and accessory usage to develop emission rates representative of extended idle emissions.

The important conclusion from the analysis was that truck operator behavior plays an important role when assigning emission rates to periods of extended idling. Factors such as accessory use and engine idle speed, which are controlled by operators, affect engine load and emission rates during extended idling. The impacts of other factors, such as engine size, altitude, model year within MOVES groups, and test cycle are negligible.

We first evaluated the studies on engine idle speed. NREL's review of owner's manuals found that several heavy-duty engine manufacturers recommend use of fast idle (> 1000 rpm) if the engine needs to idle for extended periods.[83] In a 2004 UC-Davis survey (Lutsey et al. 2004), respondents' average engine idle speed was 866 rpm, with small peaks around 650 and 1000 rpm.[84] About one-third of the respondents indicated they changed their idle speed from its usual setting, which is consistent with the distribution of the responses where about one-third of the idle engine speeds reported were 1000 rpm or faster. A 2015 study by Hoekzema (2015)[85] suggested that even fewer trucks operated in a high idle condition. Drivers surveyed for this study reported high idle operation (> 1000 rpm) just 18 percent of the time during idling periods of an hour or more. Additionally, Hoekzema (2015) cited similar studies representing 764 trucks that averaged engine speeds of 886 rpm during extended idle. Therefore, in MOVES3 and later versions, we reduced the amount of high idle from 100 percent assumed in MOVES2014 to 33 percent, to better match the references noted above.

The use of accessories (e.g., air conditioners, heaters, televisions, etc.) provides recreation and comfort to the operator and increases load on the engine. There is also a tendency to increase idle speed during long idle periods for engine durability. The emission rates estimated for the extended idle in MOVES assume both accessory use and engine idle speeds set higher than used for "curb" (non-discretionary) idling. We classify the extended idling that does not employ high speed idle without additional auxiliary loads as "curb idle."

Emissions data from the references in the data sources section (2.3.1.1) was classified into one of three idle conditions. The first condition, which has a low engine speed (<1,000 rpm) and no air conditioning is representative of curb idle. The second condition is representative of extended idle with higher engine speed (>1,000 rpm) and no air conditioning. The third represents an extended idle condition with higher engine speed (>1,000 rpm) and air conditioning. For the purpose of this analysis, the load placed on the engine due to air conditioning is assumed to represent all forms of accessory load that may be used during hotelling.

Note that some of the idle tests are of short duration. We believe it is reasonable to classify the short-duration tests as curb idle in our calculations of extended idle emissions. We are using the short-duration idle tests from the pre-2007 MY vehicles because idle emissions stabilize more quickly than later model years because the pre-2007 vehicles lack the emission aftertreatment technologies that can lose effectiveness as exhaust cools during longer idle periods.

For 1990 and earlier, we developed curb idle emission rates based on the analysis of the 18 heavy-duty diesel trucks from 1975-1990 model years used in the CRC E-55/59 study and one MY 1985 truck from the Lim study. The curb idle rates were then adjusted using ratios from 1991-2006 trucks to estimate the elevated $NO_x$ emission rates characteristic of higher engine speed and accessory loading of extended idle.

In particular, as summarized in the tables in Appendix D, data from 188 vehicles were used to estimate curb idle $NO_x$ emission rates for 1991-2006 model year heavy-duty diesel trucks. The curb idle $NO_x$ emission rate of 91 g/hr was calculated by weighting the average $NO_x$ emission rate from each test by the number of vehicles tested. Four studies and results from 31 vehicles included higher idle engine speed and air conditioner use, which resulted in a weighted idle $NO_x$ emission rate of 227 g/hr. The ratio of the 1991-2006 MY $NO_x$ emission rate from curb idle to idle with high engine speed and A/C was applied to the 1990 and earlier model year curb idle rate to get the calculated 1990 and earlier $NO_x$ emission rate with high engine speed and A/C. A similar strategy was applied to the THC, CO, and $CO_2$ emission rates for 1990 and earlier model years.

For both the MY 1960-1990 and 1991-2006 vehicles, using the data summarized in Appendix E, adjusted emission rates were calculated for each pollutant by weighting the overall "high speed idle, A/C on" results by 0.33 and the "low speed idle, A/C off" (i.e., curb idle) results by 0.67 to account for the fraction of idling at high and low engine speeds.

The $NO_x$, THC, CO, and $PM_{2.5}$ emission rates from this data analysis are primarily from diesel HHD trucks. In MOVES2014, we calculated the MHD extended idle emission rates as half of the corresponding HHD emission rates. However, a study by Khan et al. (2009)[86] found that MHD and HHD trucks had similar emission rates during extended idle. Consequently, MOVES applies the same extended idle emissions rates to MHD and HHD, as shown in Table 2-53.

MOVES stores $PM_{2.5}$ emission rates according to elemental carbon (EC) and non-elemental carbon (NonECPM), but the data sources used to calculate the extended idle emission rates reported only total $PM_{2.5}$. As mentioned in Section 2.1.2.1.8, an EC/PM fraction of 46.4 percent is applied for the running exhaust idle operating mode (opModeID 1), and we also apply it to extended idle. The resulting EC and NonECPM rates are also shown in Table 2-53.

No adjustment to the rates are made to account for tampering and mal-maintenance (T&M) because the pre-2007 trucks do not have the exhaust aftertreatment technologies that are anticipated to see large emission increases when they are tampered or mal-maintained. While the 188 trucks used for these estimates may not fully represent real-world emission deterioration, they do include real-world vehicles at a variety of ages and conditions and thus it would be "double-counting" to apply the exhaust running T&M effects to these rates.

**Table 2-53. Pre-2007 Extended idle emission rates (g/hour) in MOVES by pollutant for MHD and HHD**

| Model Year Groups | $NO_x$ | THC | CO | $PM_{2.5}$ | EC | Non-ECPM |
|---|---|---|---|---|---|---|
| Pre-1991 | 69.3 | 49.8 | 50.8 | 5.39 | 2.50 | 2.89 |
| 1991-2006 | 136 | 25.6 | 55.0 | 2.48 | 1.15 | 1.33 |

### 2.3.2 2007-2026 Model Years

The extended idle emission rates for model years 2007 to 2026 are based on the following data sources and analysis.

#### 2.3.2.1 Data Sources

The extended idle emission rates for model year 2007 and later heavy-duty diesel combination long-haul trucks (sourceTypeID 62) diesel emission rates in MOVES are based on two test programs measuring extended idle emissions from HHD diesel trucks. The Texas Transportation Institute (TTI) tested extended idle emission from 15 heavy-duty diesel tractors ranging from model year 2005[t] to 2012.[87] Another study conducted by California Air Resources Board (ARB)[88] tested five tractors (engine model years 2007 and 2010). As discussed in the analysis section (Section 2.3.2.2), the four MY 2005 and 2006 engines included in the TTI study are included in the development of the 2007 and later model year emission rates for THC, CO, $NO_x$, and energy because there is no noticeable differences in the emission rate for these model years from comparable MY 2007 and later engines. For $PM_{2.5}$, these engines are only used for comparison and to develop T&M adjustment factors.

The study (TTI or ARB), engine model year, engine manufacturer, odometer, the $NO_x$ certification level, California Clean Idle certification, and engine aftertreatment are listed for each of the trucks in Table 2-54. The last three columns in Table 2-54 are taken from the California Executive Order

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[t] Although 2005-2006 model year engine data was available at the time of the MOVES3 MY 2007+ analysis, we lacked the time and resources to incorporate them into the pre-2007 emission rates.

certification database.[89] $NO_x$ certification level (g/bhp-hr) is the standard to which the engine was certified. Some 2010 and later engines were certified above the 0.2 g/bhp-hr $NO_x$ 2010 federal standard due to the emissions averaging, banking and trading (ABT) program, and EPA allowance of nonconformance penalty (NCP) engines in 2012.[90] In these cases, the family emission limit for which the vehicle was certified is reported in Table 2-54. California Clean Idle Certification was implemented in 2008 and allows engines that are certified to a 30 g/hr idle $NO_x$ standard to idle beyond the 5-minute idle limit initiated in 2008 in California. The aftertreatment column in Table 2-54 indicates whether the engine was certified with an oxidation catalyst (OC), diesel particulate filter or periodic trap oxidizer (DPF), and/or selective catalytic reduction (SCR) system.

**Table 2-54. HHD Diesel Tractors Used to Update the MY 2007 and Later Extended Idle Emission Rates**

| Study | Engine MY | Engine | Odometer | $NO_x$ cert (g/bhp-hr) | Clean Idle Certified? | Aftertreatment |
|---|---|---|---|---|---|---|
| TTI | 2005 | Caterpillar | 484,550 | 2.4 | No | OC |
| TTI | 2006 | Cummins | 505,964 | 2.4 | No | |
| TTI | 2006 | Volvo | 640,341 | 2.4 | No | |
| TTI | 2007 | Cummins | 406,740 | 1.2 | No | OC, DPF |
| ARB | 2007 | Cummins | 390,000 | 2.2 | No | OC, DPF |
| ARB | 2007 | DDC | 10,700 | 1.2 | No | OC, DPF |
| TTI | 2008 | Cummins | 353,945 | 2.4 | Yes | OC, DPF |
| TTI | 2008 | Mack | 82,976 | 1.2 | Yes | DPF |
| TTI | 2009 | Mack | 96,409 | 1.2 | Yes | OC, DPF |
| TTI | 2010 | Mack | 89,469 | 0.2 | Yes | OC, DPF, SCR |
| TTI | 2010 | Navistar | 73,030 | 0.5 | Yes | OC, DPF |
| TTI | 2010 | Navistar | 57,814 | 0.5 | Yes | OC, DPF |
| TTI | 2010 | Navistar | 10,724 | 0.5 | Yes | OC, DPF |
| ARB | 2010 | Cummins | 13,500 | 0.35 | Yes | OC, DPF, SCR |
| ARB | 2010 | Navistar | 70,000 | 0.5 | Yes | OC, DPF |
| ARB | 2010 | Volvo | 68,000 | 0.2 | Yes | OC, DPF, SCR |
| TTI | 2011 | Mack | 95,169 | 0.2 | Yes | OC, DPF, SCR |
| TTI | 2012 | Mack | 6,056 | 0.2 | Yes | OC, DPF, SCR |
| TTI | 2012 | Mack | 11,989 | 0.2 | Yes | OC, DPF, SCR |
| TTI | 2012 | Mack | 25,148 | 0.2 | Yes | OC, DPF, SCR |

The 15 trucks from the TTI program were tested in an environmental chamber under hot and cold conditions to represent summer conditions in Houston, TX and winter conditions in the Dallas-Fort Worth area. The test data we used in this analysis were the measurements taken after a twelve-hour soak, where the vehicle had idled for at least one hour, and the vehicle had reached a 'stabilized' idling condition. The vehicles were tested at the engine load required to run the heater or air conditioning under the cold winter or hot summer conditions (see Table 2-55) but were not commanded to be in the high idle state.

While the TTI tests included idling after different soak lengths and 'commanded high idle' for engines capable of idling with an engine speed approximately 400 rpm higher than their standard idle speed, we decided not to use the 'commanded high idle' emission rates for several reasons:

1) Six of the fifteen TTI trucks were not able to be commanded into high idle.

2) The ‘stabilized’ idling emission tests did contain some high idle that appears representative of automatic engine control strategies for 2007 and later trucks. Two of the trucks included high idle during the winter stabilized tests due to automatic engine control strategies. We assume that for 2007 and later technology trucks, operators and manufacturers rely on automatic engine control strategies rather than the vehicle operators to employ high idle conditions[u]. Because most of the engines did not use high engine speeds to power the heater/air conditioner during the winter/summer conditions, we assume this engine operation of MY 2007 and later trucks is also representative of in-use operation.

3) The emissions impact of “commanded” high idle versus stabilized idle was not as pronounced as observed in the pre-2007 trucks. For the TTI study, the high idle $NO_x$ rates were only ~36 percent higher than the stabilized emission rates. By using the stabilized emission rates, we are using emission rates that are not much different than the “commanded” high idle emission rates.

For these reasons, the summer and winter stabilized conditions were deemed to be the best estimate of real-world extended idle emissions. The ‘stabilized’ idle emission rates (g/hr) for the winter and summer conditions, are reported in Figure 2-74 through Figure 2-78.

**Table 2-55. Ambient Test Conditions for the TTI Extended Idle Tests**

| Test ID | Temperature | Relative Humidity | Auxiliary Load |
|---|---|---|---|
| Hot (Summer) | 100℉ (37.8℃) | 70% | Air conditioning |
| Cold (Winter) | 30℉ (-1.1℃) | N/A | Heating System |

ARB tested five trucks on a chassis dynamometer on the ARB HHDDT 4-mode cycle, reporting the g/hr results from the 10-minute ‘Idle’ mode. Before testing the ‘Idle’ mode, the vehicle was first warmed on a pre-conditioning cycle, and then soaked for 10-20 minutes.[91] Additional test conditions were not reported by ARB, but we assumed that the ARB vehicles were tested at moderate temperatures, with no auxiliary loading. Thus, we treated the ARB data as more representative of an extended idling truck that did not require significant A/C or heating system auxiliary loading on the engine, where the extended idling occurred shortly after active driving by the main engine.

#### *2.3.2.2 Analysis*

In developing the extended idle emission rates, we averaged the emission rate from each of the tests, within model year ranges that represent engine and aftertreatment technology groups that have similar impacts on extended idle emissions. Where possible, we used all 35 tests (15 trucks × 2 conditions = 30 TTI tests, and 5 ARB tests). Because there were more TTI tests, the average within each model year group is weighted significantly towards the TTI tests. We chose to weight

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[u] As discussed earlier, our assumptions for pre-2007 trucks are different.

each test equally, because we believe the TTI data are more representative of real-world extended idle conditions, because they were tested with auxiliary loads at non-standard 'lab' temperatures.

The individual test results and the average emission rates by model year group are presented in the following figures (Figure 2-74 to Figure 2-78). Within each figure, the tests are distinguished according to the test condition – 'hot' and 'cold' conditions represent the tests from the TTI test program; 'lab' test condition are the tests from the ARB test program. Additionally, we indicate if the test was from a truck equipped with SCR or not, which we found was the most useful aftertreatment classifier to determine engine model year groups.

For $CO_2$, CO, and $NO_x$, we do not model any increase in emissions to account for deterioration, including tampering, of the engines or emission control systems, because we did not observe strong effects of the emission control on the extended idle emission rates for these pollutants – the aftertreatment technology (oxidation catalyst, selective catalytic reduction systems) may not be fully functional during the extended idle conditions, due to lower exhaust temperature occurring at extended idle. On the other hand, for THC and $PM_{2.5}$ emissions, we adjust the model year group emission rates to account for deterioration of the aftertreatment systems, as discussed in more detail below.

Figure 2-74 displays the $CO_2$ individual test results. No trend with respect to aftertreatment or model year is observed (nor was one expected). The emissions from cold tests tend to be higher than the hot tests, which are both higher than the ARB laboratory tests. Two of the cold tests have extended idle emission rates > 10,000 g/hr which is likely due to higher engine rpm for these engines during the cold tests. TTI observed that some engines have an engine control strategy, termed "cold ambient protection," which increases the idle engine speed at cold temperature to warm the coolant temperature and protect against engine wear. We calculated an average $CO_2$ extended idle emission rate for all 2007 and later trucks by using all the data and treating each test equally across all model years.

The $CO_2$ extended idle emission rate is used to derive the energy and fuel consumption extended idle rate of 97,084 kJ/hr and 0.71 gallons-diesel/hr, respectively. We used the conversion factor of 0.0736 g $CO_2$/kJ and 10,045 g $CO_2$/gallon from B3.4 biodiesel (3.4% percent biodiesel blend) highway diesel reported from the MOVES GHG and Energy Report.[3]

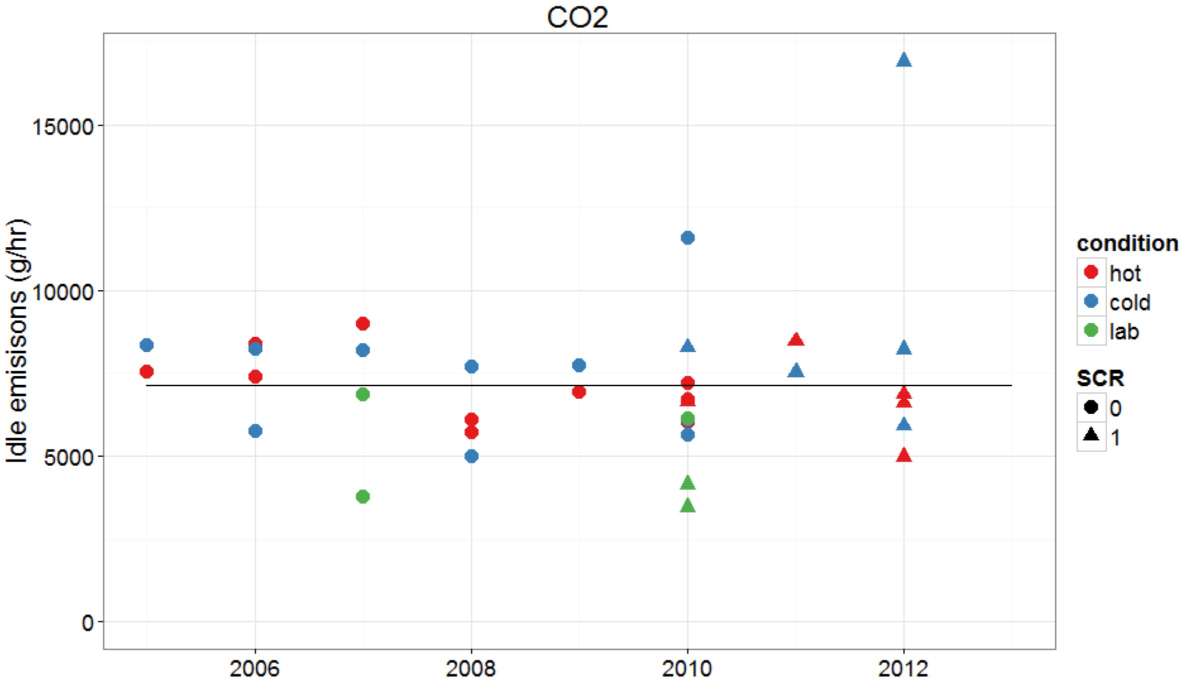

**Figure 2-74. $CO_2$ Emission Rates from the TTI and ARB Programs by Engine Model Year, and Average Emission Rate (line) based on all the data.**

Note:
Within “condition,” “hot” refers to the summer conditions from the TTI tests, “cold” refers to the winter conditions from TTI, and “lab” refers to the laboratory tests conducted by ARB. For SCR, 0 means the truck does not have a selective catalytic reduction system (SCR), and 1 means the truck has SCR.

Figure 2-75 displays the CO individual test results. No trend is observed with respect to model year or use of aftertreatment. The laboratory ARB tests are lower than the TTI tests, which could be due to the lower fuel consumption of the tests. The CO emission rate is slightly lower than the emission rate for 1990-2006 MY of 55 g/hr. Similar to $CO_2$, a single average emission rate is calculated for all the tests results and is applied to all 2007 and later model years.

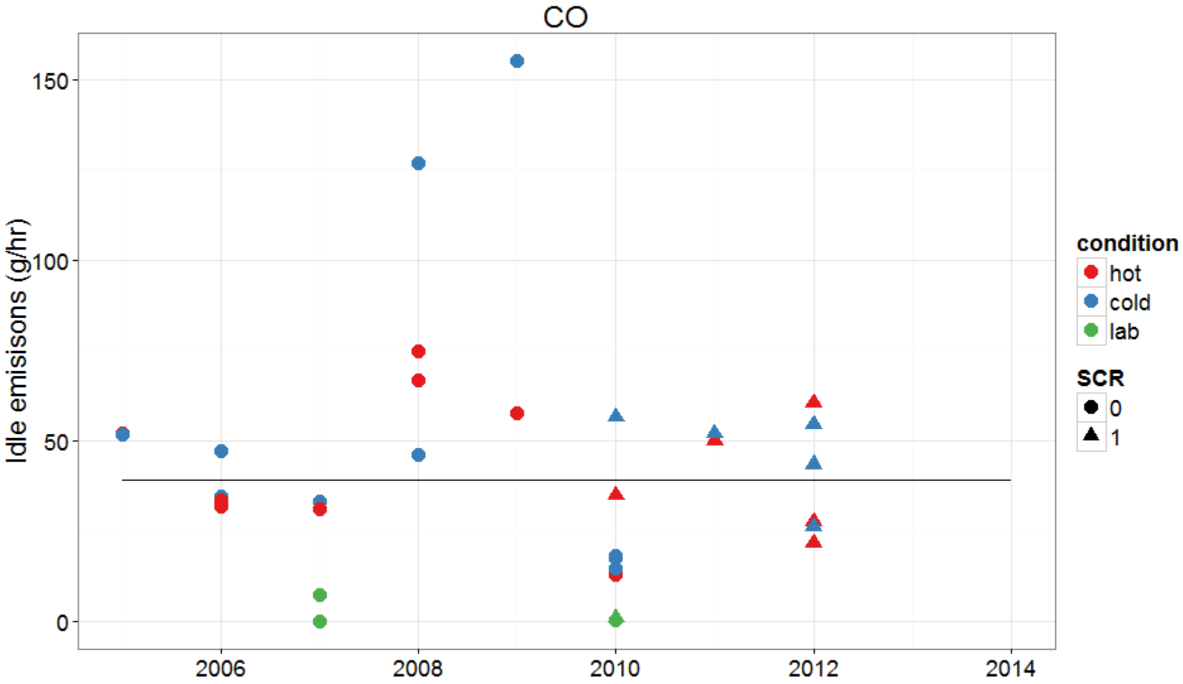

**Figure 2-75. CO Emission Rates from the TTI and ARB Programs by Engine Model Year, and Average Emission Rate (line) Based on All the Data**

Figure 2-76 displays the $NO_x$ individual test results. We initially expected the data to show a decrease in the extended idle emission rates beginning in MY 2008 to account for the California Clean Idle Certification (all MY 2008 and later trucks were clean-idle certified). However, no reduction was observed. We also expected to observe a decrease in 2012, with the full implementation of SCR, but this was also not the case. Therefore, we calculated average $NO_x$ emission rates for two model year groups (2005-2009) and (2010-2026) as represented by a solid line in Figure 2-76. The MY 2005-2009 rates calculated in this analysis are applied to the 2007-2009 model years. Given the variability of the data, the 2007-2009 average rate of 100 g/hr compares well to the MY 1991-2006 rate of 136 g/hr shown in Figure 2-79.

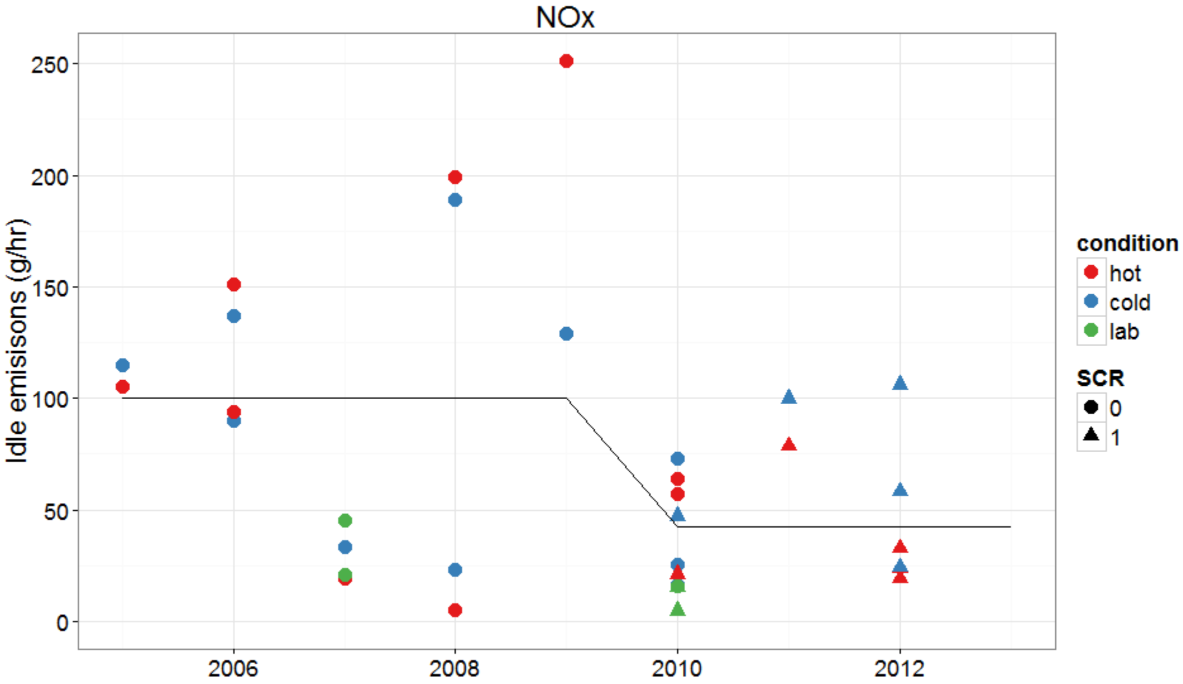

**Figure 2-76. NO$_x$ Emission Rates from the TTI and ARB Programs by Engine Model Year, and Average Emission Rates for 2005-2009 and the 2010-2012 Engine Model Years (lines)**

Figure 2-77 displays the THC individual test results. The results are displayed with the SCR aftertreatment, rather than according to the use of an oxidation catalyst aftertreatment. The use of SCR corresponded better to THC emissions than the reported use of an oxidation catalyst. We believe the SCR aftertreatment classification is a surrogate for the combined engine control and aftertreatment system used with SCR equipped trucks that have a large impact on THC emissions. For example, with the use of SCR, engines can be calibrated to run leaner, which reduces engine-out THC emissions. Additionally, SCR systems rely on oxidation catalysts, or catalyzed DPFs to convert NO to $NO_2$, which also reduces the THC tailpipe emissions.

We calculated average emission rates for three model year groups 2005-2009, 2010-2012 and 2013 and later model years. The 2005-2009 model year vehicles include a combination of DPF and non-DPF equipped trucks[v] and are used to represent the 2007-2009 emission rates in MOVES. The 2010-2012 represents DPF equipped trucks, with some penetration of SCR equipped trucks. The model year group representing 2013 and later model years was developed because starting in 2013, Navistar began certifying a heavy heavy-duty diesel (HHDD) engine equipped with SCR aftertreatment. In 2014 and 2015, Navistar and all other engine manufacturers certified all their HHDD engines equipped with SCR aftertreatment.[92] Therefore, emission rate for the 2013+ model year group was estimated by averaging the rates of all the SCR equipped trucks in the data set, even though the dataset did not include any data on 2013 and later model year engines.

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[v] The 2005-2009 THC rates here are ~3 times smaller than the MOVES3 THC rates for MY 1990-2006 derived in Section 2.3.1.2, which may be due to the small sample size of overlapping model year vehicles (3 MY 2005-2006 trucks) in the TTI study.

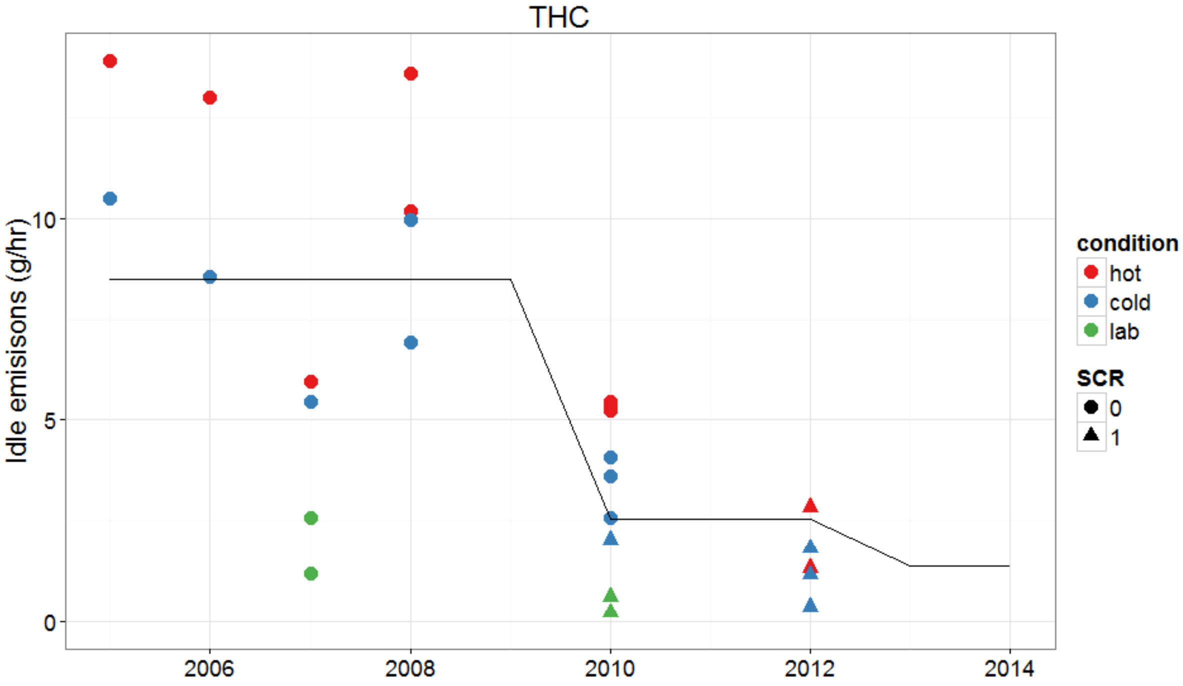

**Figure 2-77. THC Emission Rates from the TTI and ARB Programs by Engine Model Year, and Average Emission Rates for 2005-2009, 2010-2012, and 2013+ (SCR only) Engine Model Years (lines)**

Figure 2-78 displays the $PM_{2.5}$ individual test results. The ARB tests reported zero emission or “Not Reported due to PM collection failure” for the five ARB tests, and thus, only the TTI data was used to develop the $PM_{2.5}$ extended idle emission rates. For the same reasons provided for the THC results, the use of an SCR-equipped engine and aftertreatment systems should also have a significant impact on the $PM_{2.5}$ emissions. Additionally, and as expected, the implementation of diesel particulate filters starting in 2007 model year had a significant impact on the $PM_{2.5}$ emissions.

We grouped the individual emission tests into four model year groups: 2005-2006 (pre-DPF), 2007-2009 (DPF, pre-SCR), 2010-2012 (DPF and phase-in of SCR) and 2013 and later model years (SCR only). Because the MY 2005-2006 $PM_{2.5}$ emission rates are significantly different than the MY 2007-2009 emission rates, they are grouped separately. The 2005-2006 rates from this study are not used to update the pre-2007 $PM_{2.5}$ emission rates.[w] The other model years and aftertreatment groups are used to estimate the MOVES emission rates for MY 2007 and later. As for THC, we used the results from the 2010 and later SCR equipped trucks to calculate $PM_{2.5}$ emission rate for the 2013 and later model year group.

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[w] The MY 2005-2006 $PM_{2.5}$ emission rates measured from the TTI data are only ~3 times higher than the MY 2007-2009 $PM_{2.5}$ rates, and roughly ~10 times smaller than the $PM_{2.5}$ rates for MY 1990-2006 (2.5 g/hr). We would expect a larger decrease in $PM_{2.5}$ emission rates with the use of DPF as discussed in Section 2.3.3. Differences could be due to PM sampling methods, or variation in the truck emissions given the small sample size of 2005-2006 model year trucks in the TTI study. As mentioned above, we did not update the pre-2007 $PM_{2.5}$ emission rates in MOVES with information from the TTI dataset due to limitations on time and resources.

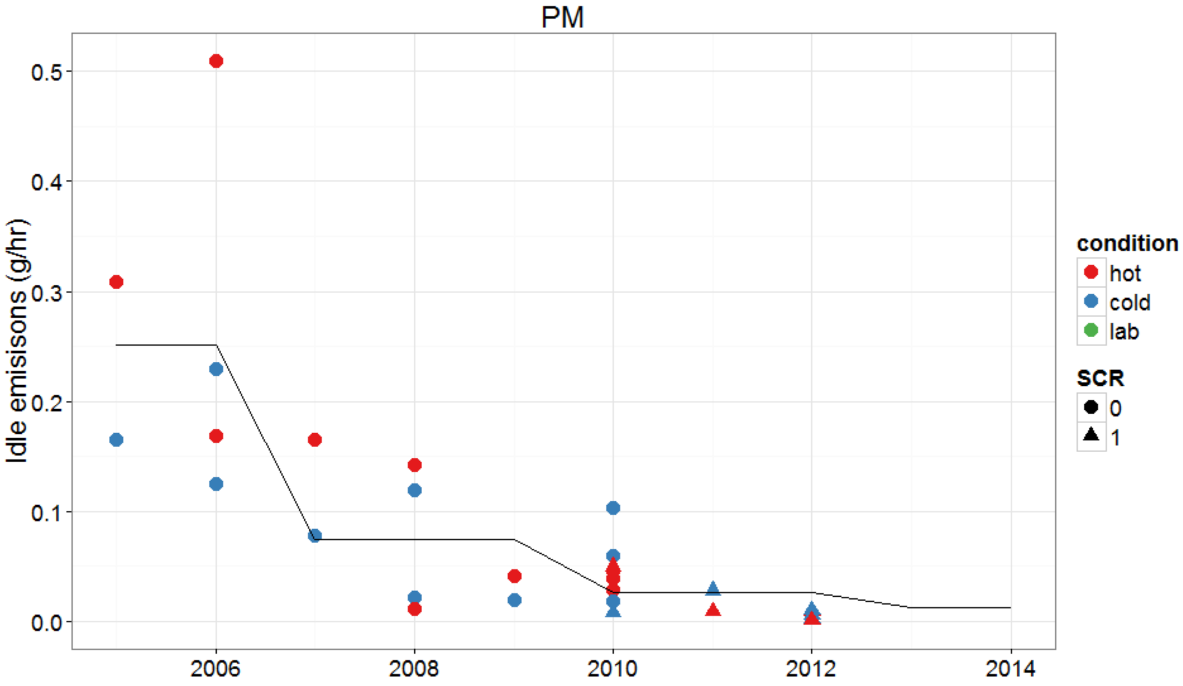

**Figure 2-78. PM2.5 Emission Rates from the TTI Program by Engine Model Year, and average Emission Rates Using for 2005-2006, 2007-2009, 2010-2012, and 2013+ (SCR only) Engine Model Years (lines)**

$PM_{2.5}$ emission rates in MOVES are composed of elemental carbon (EC) and non-elemental carbon PM (nonEC). The TTI study measured total $PM_{2.5}$ emissions, but not EC. We used the EC/PM fractions from the sources listed in Table 2-56 to estimate the EC and $PM_{2.5}$ emission rates.

**Table 2-56. Baseline elemental carbon to $PM_{2.5}$ fraction assumed for extended idling**

| Model Year Group | EC/PM | Source |
|---|---|---|
| Pre-2007 | 0.26 | MOVES2014 Extended Idling[35] [x] |
| 2007-2009 | 0.10 | ACES Phase I[91] |
| 2010+ | 0.16 | ACES Phase II[93] |

### *2.3.2.3 Tampering and Mal-maintenance*

As discussed in Section 2.3.1.2, we did not incorporate tampering and mal-maintenance effects on the pre-2007 extended idle rates. For the 2007 and later extended idle rates, we incorporated the effects of the effect of tampering and mal-maintenance (T&M) for two reasons:

1. The twenty vehicles used to estimate the extended idle emission rates did not appear to include any tampered or mal-maintained vehicles with elevated emission rates. In addition, 14 of the 20 vehicles had odometer readings with less than 100,000 miles (Table 2-54).

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[x] The pre-2007 EC/PM ratio for extended idling has subsequently been updated in MOVES3 to be 46.4% as discussed in Section 2.3.1, but it was not updated for this analysis.

2. The 2007 and later technology includes aftertreatment technology, including diesel oxidation catalysts (DOC) and diesel particulate filters (DPF). We anticipate that the failure of these after-treatment systems would significantly increase extended idle emissions if they were tampered or mal-maintained.

We incorporated the T&M effects for extended idle exhaust using different data and methodology than was used to derive the tailpipe exhaust emission rates for two reasons:

1. Extended idle emissions in MOVES are stored in the EmissionRate table, and are not distinguished by vehicle age, as the running and start exhaust emission factors. To fit the current MOVES structure, we incorporated the effects of T&M into a single emission rate by model year that applies to all vehicle ages.

2. We are less confident in the application of the emission effects of T&M failures estimated for running emissions in Appendix B to extended idling emission. For example, we do not think failure of selective catalytic reduction (SCR) aftertreatments systems should impact extended idling $NO_x$ emission rates as much as running exhaust emissions, because the SCR systems is not fully operational during long idling periods. Instead, we estimated the effects of T&M on 2007 and later extended idle emissions using pre-2007 extended idle emissions as surrogate values for 2007 and later extended idle emission with failed aftertreatment systems.

As shown in the figures above, the THC and $PM_{2.5}$ emissions showed the largest reductions in extended idle emissions with newer model year vehicles. We believe that the reductions are due primarily to the continued effectiveness of the catalyzed diesel particulate filter even during extended idling conditions. For the MOVES extended idle THC and $PM_{2.5}$ emission rates, we included an estimate of the impact of deterioration and failure of the diesel particulate filters in calculating the 2007-2009, 2010-2012, and 2013+ model year group emission rates as discussed in Appendix C, and displayed in Table 2-57. As shown, the MOVES EC/PM emission rates for MY 2007+ trucks are slightly higher than the 'Baseline' EC/PM fractions in Table 8-2, because the fleet emissions are assumed to include some emission contribution from trucks with failed DPFs, which have a higher EC/PM fraction.

**Table 2-57. Extended Idle Emission Rates for 2007 and Later Model Year Heavy-Duty Vehicles**

| Model Year Group | $CO_2$ (g/hr) | CO (g/hr) | $NO_x$ (g/hr) | THC (g/hr) | $PM_{2.5}$ (g/hr) | EC (g/hr) | nonEC (g/hr) | EC/PM |
|---|---|---|---|---|---|---|---|---|
| 2007-2009 | 7151 | 39.3 | 100.5 | 8.5 | 0.087 | 0.012 | 0.076 | 0.13 |
| 2010-2012 | 7151 | 39.3 | 42.6 | 2.7 | 0.034 | 0.006 | 0.028 | 0.18 |
| 2013+ | 7151 | 39.3 | 42.6 | 1.6 | 0.021 | 0.004 | 0.017 | 0.20 |

#### *2.3.2.4 MHD Regulatory Class*

The extended idle emission rates for MHD are assumed to be the same as HHD for the following two reasons. First, MHD trucks are estimated to account for only five percent of long-haul combination trucks in the US and therefore, they are a minor contributor to the emissions from extended idling trucks. Second, Khan *et al.* 2009[94] evaluated extended idle emission rates of pre-2007 MHD engines and did not observe a pronounced difference in extended idle emission rates between MHD and HHD trucks. Taken together, these imply that any difference in emissions modeled with unique MHD extended idling rates would be minimal, so without any extended idling data on 2007 and later model year MHD trucks, we felt it was most defensible to keep the MHD emission rates the same as the HHD emission rates.

### 2.3.3 2027-2060 Model Years

For MY2027 and later vehicles subject to HD2027 standards, we anticipate that reductions in the HHD and MHD $NO_x$ extended idle emissions rates will be driven by the idle standard, rather than the duty-cycle standards in the rule. The duty-cycle standards do not contain high duration extended idling (> 1 hour) that is representative of truck hotelling activity. We did not estimate any change in extended idle emission rates due to the lengthened warranty or useful life periods because MOVES extended idle rates do not vary by age.

First, we estimated extended idle emission rates that would comply with the off-cycle $NO_x/CO_2$ g/kg standard calculated in Table 2-13. We then used Equation 2-25 to calculate the extended idle off-cycle $NO_x$ g/hr emission rate based on the MOVES extended idle $CO_2$ g/hr emission rate, as shown in Table 2-58.

**Table 2-58 Calculation of HHD and MHD Extended Idle $NO_x$ g/hr Emission Rates for MY2027+**

| **Model Year Group** | **MOVES Extended Idle Rates $CO_2$ (kg/hr)** | **Idle Standard (g/hr)** | **Idle Standard $NO_x/CO_2$ (g/kg)** | **Idle-standard compliant $NO_x$ emission rate (g/hr)** |
|---|---|---|---|---|
| 2027-2028 | 7.191 | 9 | 1.17 | 8.42 |
| 2029+ | 7.191 | 8.7 | 1.13 | 8.14 |

### 2.3.4 Model Year Trends

Figure 2-79 through Figure 2-82 illustrate the extended idle emission rates in MOVES4 for regClassIDs 46 and 47.

As shown, the $NO_x$ and the CO extended idle emission rates have a relatively small decrease between the pre-2007 and the 2007+ model years. For THC and $PM_{2.5}$, we observe large decreases starting in MY 2007, which is consistent with our understanding of the effect of diesel particulate filters. We observed a decrease by ~29 times in extended idle $PM_{2.5}$ rates between the pre-2007 and post-2007 extended idle rates corresponding to the implementation of the DPFs, which is consistent with the ~27 times decrease in $PM_{2.5}$ running exhaust emission rates from $PM_{2.5}$ certification data as discussed in Section 2.1.2.1.7. Extended idle rates for $NO_x$ decrease in MY 2027 due to the HD2027 rule, but other pollutant rates remain unchanged.

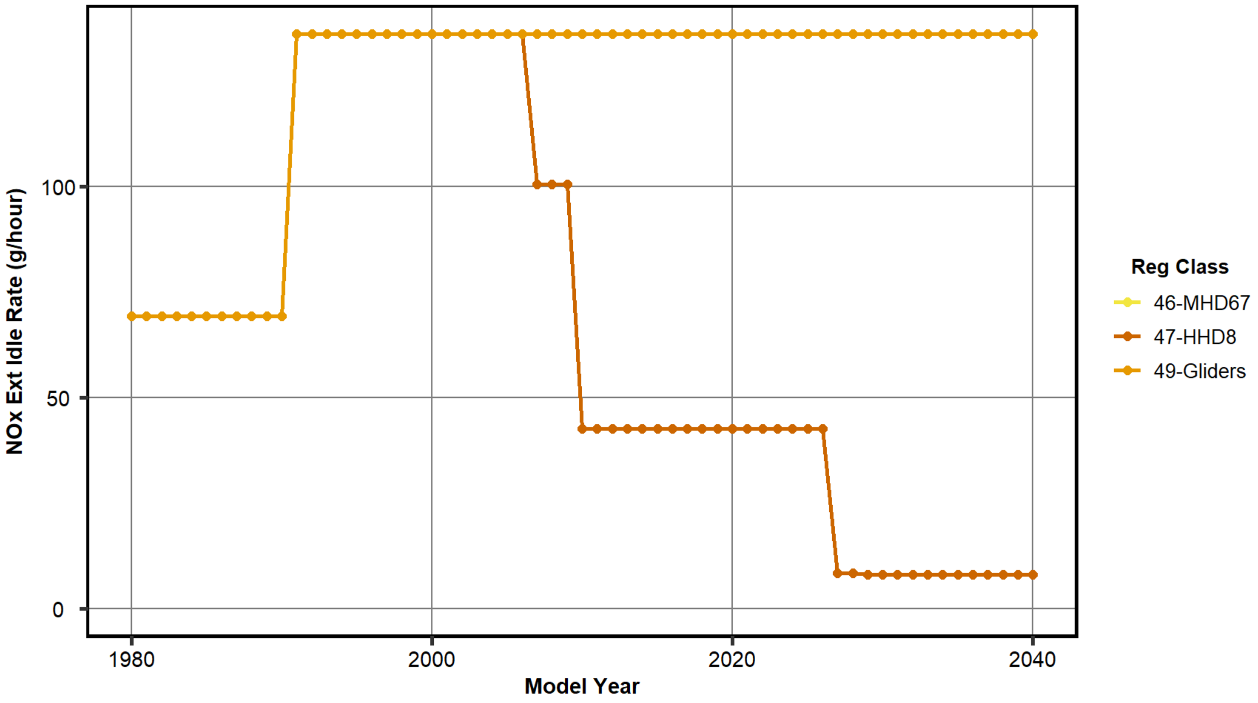

**Figure 2-79. Extended Idle $NO_x$ Emission Rates for HHD and MHD Diesel Vehicles by Model Year**

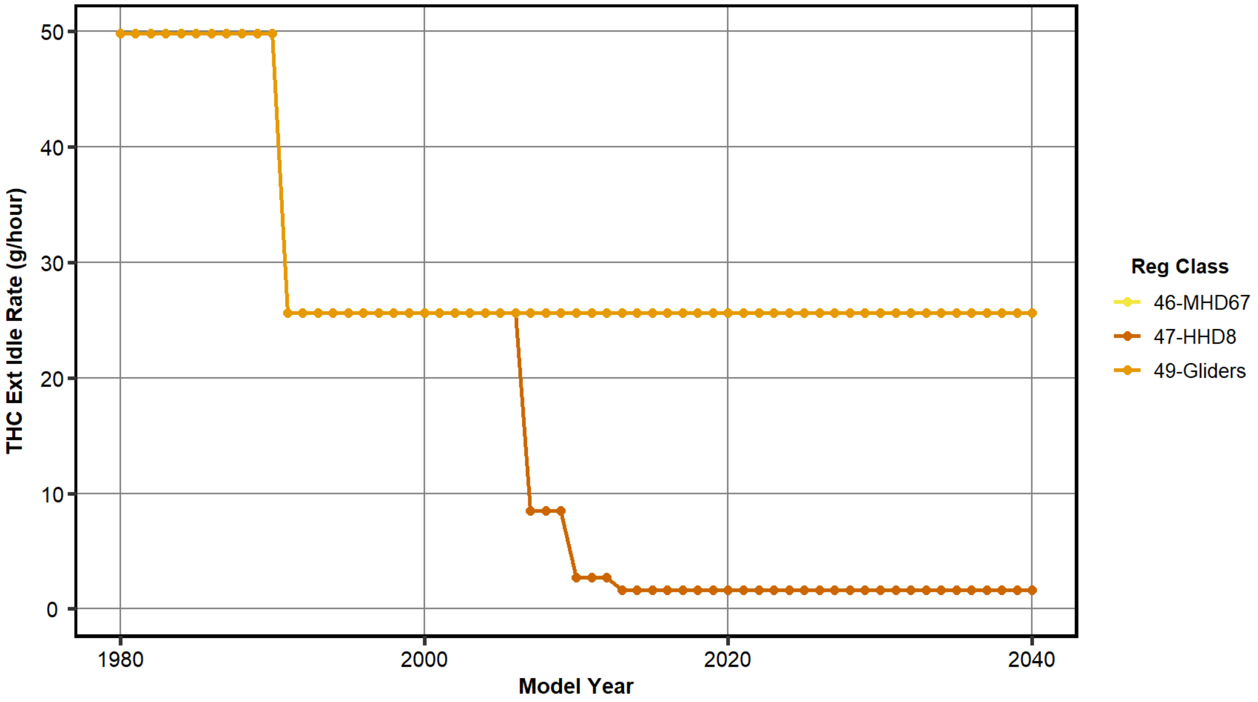

**Figure 2-80. Extended Idle THC Emission Rates for HHD and MHD Diesel Vehicles by Model Year**

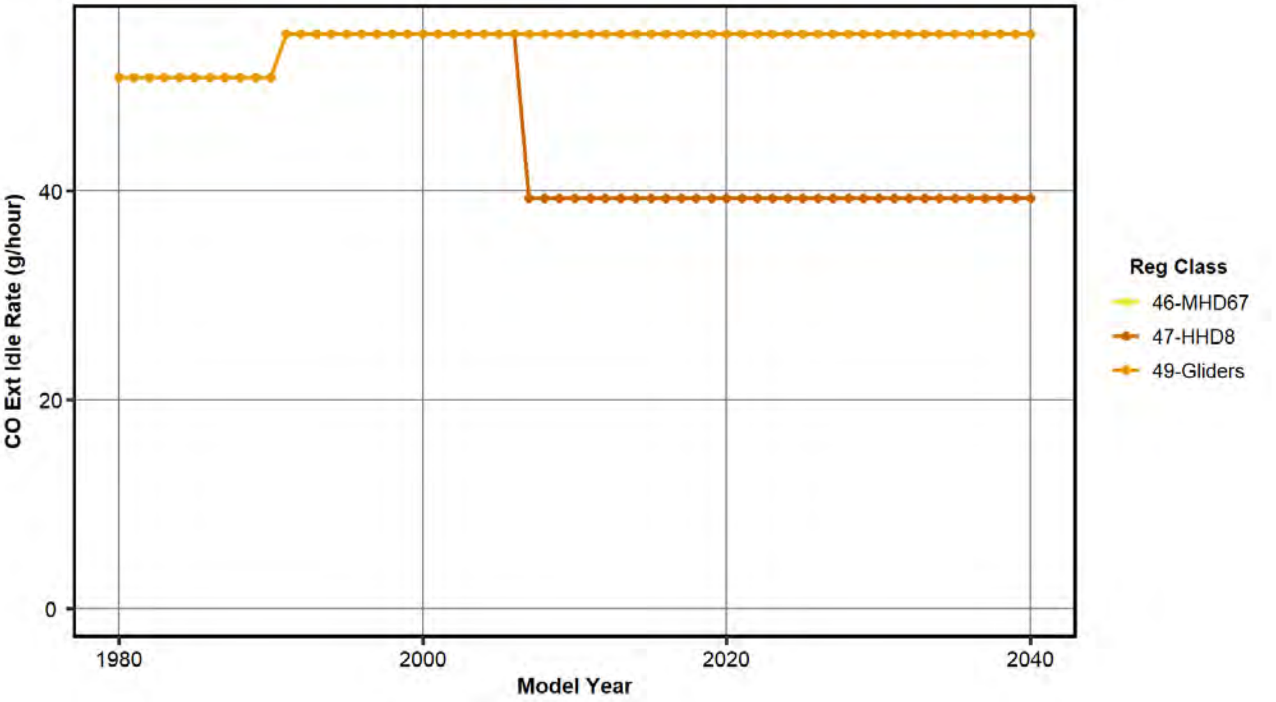

**Figure 2-81 Extended Idle CO Emission Rates for HHD and MHD Diesel Vehicles by Model Year**

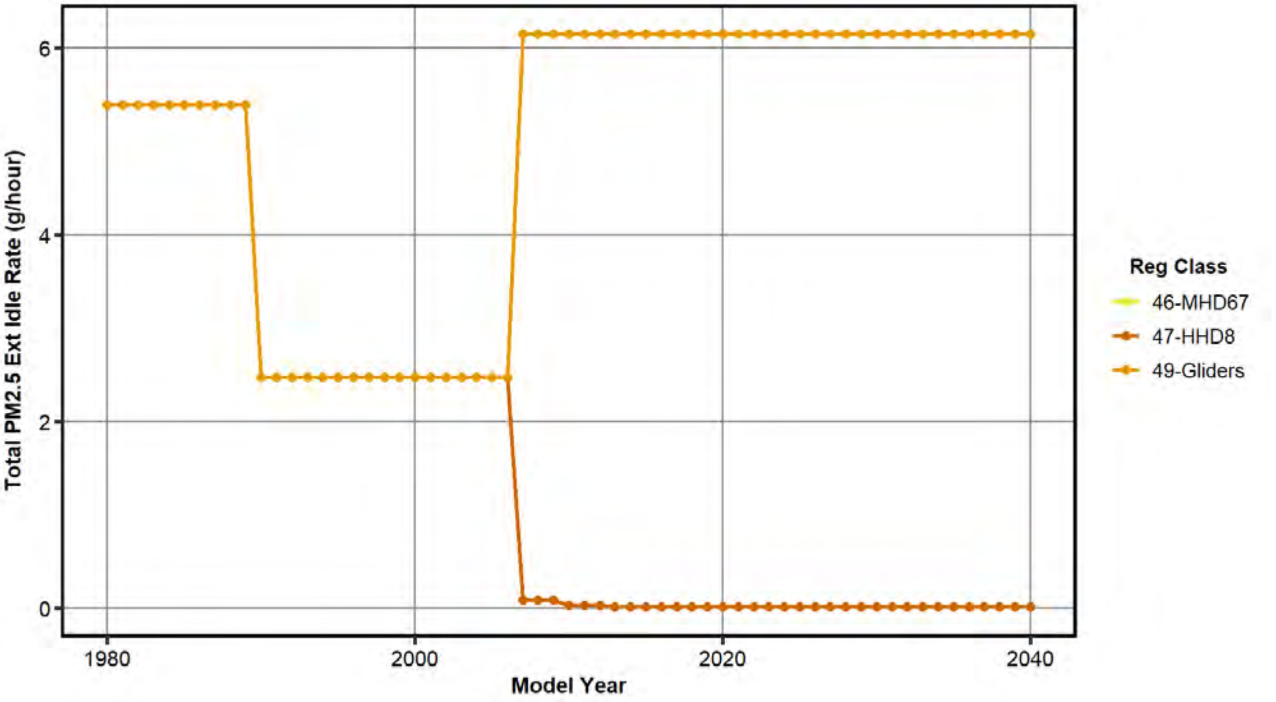

**Figure 2-82. Extended Idle $PM_{2.5}$ Emission Rates HHD and MHD Diesel Vehicles by Model Year**[y]

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[y] Glider emission rates are intended to be the same for all model years from 2000 through 2060. However, for EC and non-EC PM, the pre-MY 2007 values were updated without changing the post-MY 2007 values. We plan to update the MY 2007 and later EC and non-EC PM rates for gliders in future versions of MOVES. Glider emissions prior to model year 2008 are not used in the MOVES model since the gliders do not exist in the fleet.

### 2.3.5 Extended Idle Energy Rates

The pre-2007 extended idle energy emission rates are unchanged from those originally developed for MOVES2004 and are documented in the Energy and Emissions Report[71], and are displayed in Figure 2-83. The extended idle energy consumption rates are the same for regulatory class MHD and HHD diesel vehicles. The extended idle energy rates for 2007+ trucks were updated in MOVES3 and estimated using the $CO_2$ emission rates presented in Table 2-57 and are also plotted in Figure 2-83. The extended idle energy consumption rates are the same for regulatory class MHD and HHD diesel vehicles.

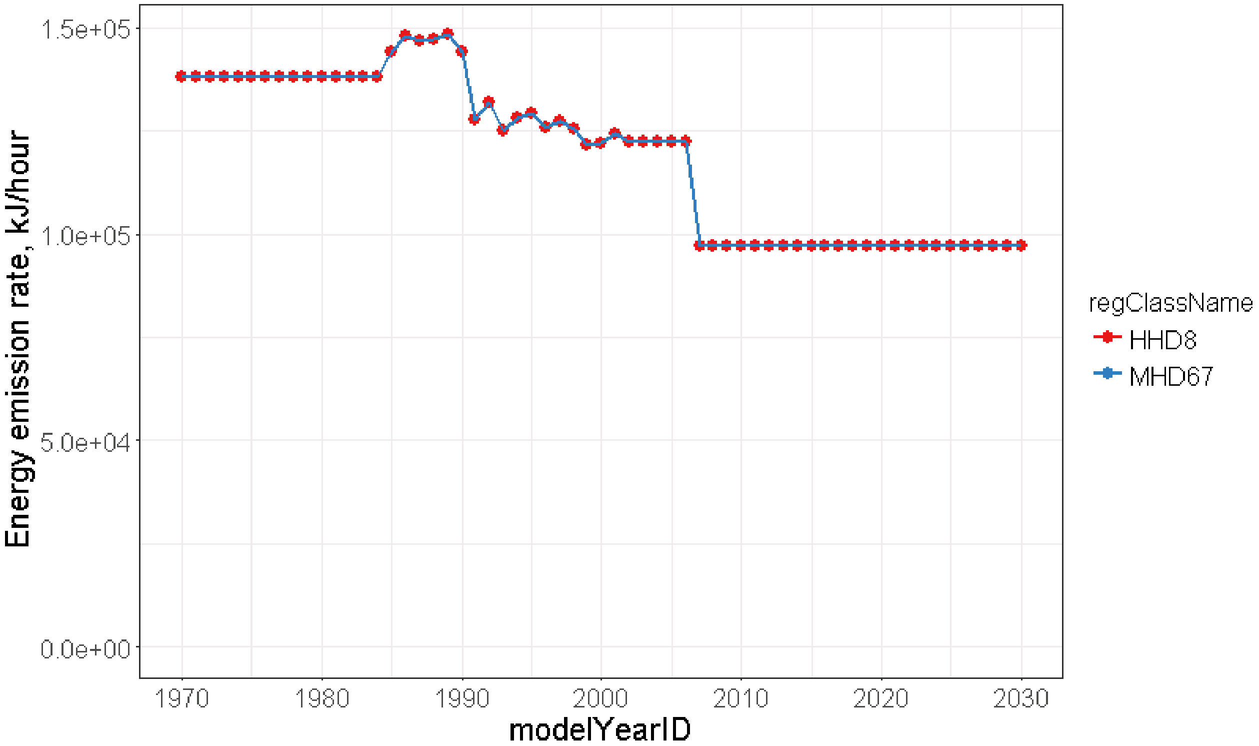

**Figure 2-83. Extended Idle Energy Emission Rates for HHD and MHD Diesel Trucks**

## 2.4 Auxiliary Power Unit Exhaust

Auxiliary power unit (APU) exhaust is a separate emission process in MOVES. APU usage only applies to the vehicles with hotelling activity, which are the heavy-duty regulatory classes (MHD, HHD, and Gliders) within the combination long-haul truck source type (sourceTypeID 62). The APU emission rate for MHD, HHD and glider regulatory classes are the same for each model year. The projected use of APUs during hotelling due to the HD GHG Phase 2 program, shown below in Table 2-59, were used to revise the “hotellingactivitydistribution” table in MOVES[61], as is also discussed in the Population and Activity Report.[6]

**Table 2-59: Projected APU Use during Extended Idling for Combination Long-Haul Tractor-Trailers**

| Vehicle Type | Model years | Diesel APU Penetration | Battery APU Penetration |
|---|---|---|---|
| Combination Long-Haul Trucks | 2010-2020 | 9% | 0% |
| | 2021-2023 | 30% | 10% |
| | 2024-2026 | 40% | 10% |
| | 2027+ | 40% | 15% |

The APU emission rates in MOVES are based on two studies that measured in-use APU emission rates. The Texas Transportation Institute (TTI, 2014)[95] tested two diesel APU systems with and without diesel particulate filters at ambient temperatures of 100˚F and 0˚F. The exhaust emission rates (THC, CO, $CO_2$, and $NO_x$) and the exhaust flow rates were measured using an ECOSTAR gaseous portable emission measurement system. The PM mass was measured using a BG-3 partial flow dilution and filter sampling system. Limitations of the TTI study are discussed in the HD GHG Phase 2 MOVES documentation.[101,z]

The second study used to update APU emission rates was by Frey and Kuo (2009),[96] who tested two APU systems (APU ID 2 and 3), equipped with 2006 Kubota Z482 engines. The APU systems were tested at a range of electric output loads to obtain the fuel consumption relationship with the electric power demands, and the fuel-based emission rates. The study measured the in-use APU electric loads from a fleet of 20 vehicles (10 trucks equipped with each APU system) for over a year. They then used the relationship between electric power demand and the fuel-based emission factors with the average energy use of the APU system to estimate average APU (g/hr) emission rates of $CO_2$, CO, $NO_x$, THC, and PM for both a mild temperature (50-68˚F) scenario and a high temperature (100˚F+) scenario. Frey and Kuo 2009 reported a PM emission rate, but the emission rate is ‘inferred from the literature’ because their PM measurements were semi-qualitative.

An additional two studies were used as a source of data to compare and evaluate the APU emission rates obtained from the studies mentioned above. TTI 2012[97] conducted testing of two APU systems using their environmental chamber at both 100˚F and 0˚F. The APU systems (APU 4 and 5) manufacturer, engine make and model year were maintained confidential in the report. Storey et al. 2003[98] tested a Pony Pack APU System (APU ID 6), equipped with a Kubota Z482 engine, in an environmental chamber at both 90˚F and 0˚F. This is one of the studies used by Frey and Kuo 2009[96] to determine the PM emission factor for the APU’s tested in their study. The engine year, engine displacement, and engine power were not reported in the TTI 2012 and Storey et al. 2003 studies. For this reason, these studies were used only as comparative data sets.

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[z] Problems in testing meant only one of the APU systems could be used. Additionally, PM composition (EC/PM fraction) was measured on tests with errors in the exhaust flow measurement. The PM emission rates determined invalid for these tests were excluded and repeated, but the PM composition measurements from these tests were considered valid and were not repeated.

**Table 2-60. APU Engines and Studies Used in This Analysis**

| APU ID | Engine Model | Engine Year | Displacement (L) | Power (HP/kW) | Tier | Study |
|---|---|---|---|---|---|---|
| 1 | Kubota Z482 | 2011 | 0.48 | 14.2/11 | Tier 4 | TTI 2014[95] |
| 2 | Kubota Z482 | 2006 | 0.48 | 10.9/8.1 | Tier 2 | Frey and Kuo 2009[96] |
| 3 | Kubota Z482 | 2006 | 0.48 | 10.9/8.1 | Tier 2 | Frey and Kuo 2009 |
| 4 | Confidential Information | | | | | TTI 2012[97] |
| 5 | Confidential Information | | | | | TTI 2012 |
| 6 | Kubota Z482 | | | | | Storey *et al.* 2003[98] |

Table 2-61 contains the in-use emission rates measured from reviewed APU systems. As shown, the emission and fuel rates for the APUs measured in the TTI 2014, and Frey and Kuo 2009 (APU ID 1, 2 and 3) compare well with the APU emission rates reported from TTI 2009 Storey *et al.* 2003 (APU ID 4, 5, and 6). The impact of the DPF is clearly shown on the PM emission rates from APU ID 1, as expected. However, there does not appear to be a substantial impact of the DPF on the gaseous emissions ($CO_2$, CO, $NO_x$, and THC). Additionally, no notable emission effects are observed with respect to the nonroad emission standard tier or engine model year.

The impact of ambient temperature can be observed within individual studies. For APU ID 2 and 3, the $CO_2$, and fuel consumption are higher at the hot ambient temperatures compared to the mild conditions, which is expected. However, there is no consistent trend between hot and cold conditions, when the APU is required to either cool or heat the tractor cabin. For APU ID 1 and 4, the cold temperatures had higher $CO_2$ emissions and fuel use. For APU ID 5 and 6, the hotter temperatures had higher $CO_2$ emissions and fuel use.

For CO, $NO_x$, THC, and PM there are conflicting trends with respect to ambient temperature. For APU 2 and 3, $NO_x$ and PM emissions are higher at the hot conditions compared to mild conditions, consistent with the higher fuel use. However, CO shows lower emissions at hot conditions, and THC shows a mixed trend. For the other studies, there is no consistent trend between the hot and cold conditions.

**Table 2-61. In-Use APU Emission Rates**

| APU ID | $CO_2$ (g/hr) | CO (g/hr) | $NO_x$ (g/hr) | THC (g/hr) | PM (g/hr) | Fuel (gal/hr) | Ambient condition | Temperature (°F) | DPF present |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 4340 | 7.3 | 18.6 | 1.35 | 0.96 | 0.43 | Cold | 0 | No |
| 1 | 4270 | 5.1 | 20.0 | 0.73 | 0.02 | 0.43 | Cold | 0 | Yes |
| 1 | 2820 | 6.2 | 23.5 | 1.35 | 0.56 | 0.29 | Hot | 100 | No |
| 1 | 2800 | 5.2 | 23.7 | 1.52 | 0.03 | 0.28 | Hot | 100 | Yes |
| 2 | 3000 | 20.4 | 6.3 | 1.4 | 1 | 0.3 | Mild | 60[a] | No |
| 3 | 2500 | 7.2 | 13.4 | 1.3 | 0.8 | 0.25 | Mild | 60 | No |
| 2 | 3900 | 13.9 | 11.5 | 1.5 | 1.3 | 0.38 | Hot | 100 | No |
| 3 | 3600 | 6.3 | 20.2 | 1 | 1.2 | 0.36 | Hot | 100 | No |
| 4 | 3100 | 5.8 | 19 | 1.3 | 1.23 | 0.3 | Hot | 100 | No |
| 5 | 3600 | 7.3 | 24 | 0.8 | 0.58 | 0.35 | Hot | 100 | No |
| 4 | 4000 | 3.9 | 22 | 1.2 | 0.75 | 0.39 | Cold | 0 | No |
| 5 | 2800 | 24 | 14 | 2.4 | 0.98 | 0.28 | Cold | 0 | No |
| 6 | 2146 | 25 | 8.7 | 7.8 | 0.48 | 0.22 | Cold | 0 | No |
| 6 | 2351 | 10.8 | 11.4 | 4.2 | 1.00 | 0.24 | Hot | 90 | No |

Note:

[a] Frey and Kuo 2009 report the mild condition for auxiliary loads on the trucks is for ambient temperatures ranging from 10-20°C (50-68°F)

Because the only notable trend in the APU emissions data was the large decrease in PM emission rates with the use of a DPF, we developed "no DPF" baseline MOVES emission rates using the "no DPF" results from TTI, 2014 and Frey and Kuo, 2009 (APU ID 1, 2, and 3). We first averaged the emission rates within the cold, hot, and mild conditions as shown in Table 2-62.

**Table 2-62. Average APU Emission Rates from non-DPF APU IDs 1, 2, and 3 according to Cold, Hot, and Mild Ambient Conditions**

| $CO_2$ (g/hr) | CO (g/hr) | $NO_x$ (g/hr) | THC (g/hr) | PM (g/hr) | Fuel (gal/hr) | Ambient condition | Temperature (°F) | DPF present |
|---|---|---|---|---|---|---|---|---|
| 4340 | 7.27 | 18.59 | 1.35 | 0.96 | 0.43 | Cold | 0 | No |
| 3440 | 8.80 | 18.41 | 1.28 | 1.02 | 0.34 | Hot | 100 | No |
| 2750 | 13.80 | 9.85 | 1.35 | 0.90 | 0.28 | Mild | 60 | No |

Next, we calculated a fleet-average APU emission rate. Similar to our treatment of the extended idle emission rates, we equally weighted the different ambient conditions. For APUs, we weighted each ambient condition (Cold, Hot, and Mild) equally in developing the fleet-average emission rate shown in Table 2-64.

We estimated elemental carbon (EC) fraction of PM from composition measurements made on APU ID 1 as reported in Appendix J. For each test, we calculated the elemental carbon/total carbon ratio, and then averaged the ratio across all cold and hot tests, separately for the DPF and the non-DPF tests as shown in Table 2-63. We assumed that total carbon (TC) is a reasonable approximation of the total $PM_{2.5}$ emissions from the APU, and we used the EC/TC ratio from the non-DPF tests as the source of the EC/PM fraction to derive the EC and nonEC emission rates in Table 2-64.

**Table 2-63. Average Elemental Carbon/Total Carbon Ratio for APU ID 1 without and with a Diesel Particulate Filter (DPF)**

| | EC/TC ratio |
|---|---|
| APU 1 non-DPF | 0.138 |
| APU 1 DPF | 0.073 |

**Table 2-64. Fleet-Average Non-DPF Equipped APU Emission Rates in MOVES**

| $CO_2$ (g/hr) | CO (g/hr) | $NO_x$ (g/hr) | THC (g/hr) | $PM_{2.5}$ (g/hr) | EC (g/hr) | NonEC (g/hr) | EC/PM | Fuel (gal/hr) |
|---|---|---|---|---|---|---|---|---|
| 3510 | 10.0 | 15.6 | 1.3 | 0.96 | 0.13 | 0.83 | 0.14 | 0.35 |

The HD GHG Phase 2 rule implements a phase-in standard that requires APUs installed in new tractors to meet lower PM standards from MY 2021 through MY 2024 (beyond the Tier 4 nonroad standards).[99] The APU PM standards along with the current Tier 2 and Tier 4 nonroad standards for nonroad diesel engines 8≤kW<19 (11≤hp<25) are shown in Table 2-65.[100]

**Table 2-65: Nonroad (8≤KW<19) Tier 2 and Tier 4, and HD GHG Phase 2 Emission Standards**

| Emission Standard | CO | NMHC + $NO_x$ | PM |
|---|---|---|---|
| | g/kW-hr (g/hp-hr) | g/kW-hr (g/hp-hr) | g/kW-hr (g/hp-hr) |
| Tier 2 2005-2007 | 6.6 (4.9) | 7.5 (5.6) | 0.8 (0.6) |
| Tier 4 2008-2020 | 6.6 (4.9) | 7.5 (5.6) | 0.40 (0.30) |
| APU 2021-2023 | | | 0.15 (0.11) |
| APU 2024+ | | | 0.02 (0.01) |

We developed the projected APU emission rates due to the new standards by comparing the manufacturer submitted emission levels of two engines commonly used in APU systems based on the engine information and emission levels obtained from the publicly available US EPA nonroad certification database. The development of these rates are described in the HD GHG Phase 2 MOVES documentation and summarized here.[101]

We anticipate that the APU manufacturers will meet the 2021 PM standard by modifying the engine control strategy (such as using leaner air fuel mixture) rather than by using an aftertreatment such as a diesel particulate filter. Such a strategy is likely to lead to increased $NO_x$ emissions – the decrease in PM emissions between the 2012 and 2013 certified APU engines was accompanied by 25 percent increase in $NO_x$ emissions. Thus, we estimated a slight $NO_x$ disbenefit in obtaining a lower PM standard. We estimated the in-use APU $NO_x$ emissions for 2021-2023 by multiplying the baseline emissions by 1.25 (15.6 * 1.25 = 19.5 g/hr). We do not anticipate any increases to occur in $CO_2$, CO, or THC emissions with the 2021 standard, and expect the emissions will not change in 2021 for these pollutants.

To achieve the APU PM standard for MY 2024, we anticipate APU manufacturers will be required to use DPF aftertreatment. The average PM emission rate from the DPF-equipped APU ID 1 tests was 0.025 g/hr (Table 2-61), which is similar to the extended idle PM emission rate for 2013+ trucks (Table 2-57) of 0.021 g/hr. We do not believe the data are sufficient to determine a difference in PM emission rates between APU and main engine extended idling when both engines are equipped with diesel particulate filters. Thus, we used the MY 2013+ extended idle $PM_{2.5}$ emission rate as the APU emission $PM_{2.5}$ emission rate for 2024 and later model years (Table

2-57). We used the EC/PM split measured from the DPF-equipped APU (Table 2-63) to estimate the EC and nonEC emission rates.

From the in-use testing of APU ID 1, we did not observe a meaningful impact on the $CO_2$, CO, $NO_x$, and THC emissions with the use of the DPF. Thus, for the model year 2024 and later APUs, we maintained the same emissions rates as were used in the 2010-2020 model year group. The emission standard adjusted APU emission rates by model year group are shown in Table 2-66.

**Table 2-66 APU Emission Rates in MOVES with APU PM Controls in the HD GHG Phase 2 Program**

| Model Year | CO2 (g/hr) | CO (g/hr) | $NO_x$ (g/hr) | THC (g/hr) | $PM_{2.5}$ (g/hr) | EC (g/hr) | NonEC (g/hr) | EC/PM | Fuel (gal/hr) |
|---|---|---|---|---|---|---|---|---|---|
| 2010-2020[1] | 3510 | 10.0 | 15.6 | 1.3 | 0.96 | 0.13 | 0.83 | 0.14 | 0.35 |
| 2021-2023 | 3510 | 10.0 | 19.5 | 1.3 | 0.32 | 0.044 | 0.28 | 0.14 | 0.35 |
| 2024-2050 | 3510 | 10.0 | 15.6 | 1.3 | 0.021 | 0.0015 | 0.019 | 0.073 | 0.35 |

Note:

[1] The default APU allocation in MOVES assigns APU usage beginning in model year 2010. If MOVES users specify APU usage in years previous to 2010, it will use the 2010-2020 APU emission rate.

## *2.5 Glider Vehicle Emissions*

"Glider vehicles" or "Gliders" refer to vehicles with old powertrain (engine, transmission and/or rear axle) combined with a new chassis and cab assembly. Most gliders are Class 8 heavy heavy-duty vehicles. They typically use model year 2001 or older remanufactured engines that do not have to use emissions controls such as DPF or SCR needed to meet the stringent PM and $NO_x$ standards starting MY 2007+. [102]

Starting with MOVES3, we model the emission impacts of the glider vehicles as a separate regulatory class (regClassID 49) because their population became significant starting with model year 2008 as described in the Population and Activity Report.[6]

For modeling purposes, all glider vehicles are presumed to be combination trucks (sourceTypeID 61 and 62) running on diesel fuel. EPA's in-house glider vehicle emission testing data[103] suggest that glider emissions have similar THC, $NO_x$, $PM_{2.5}$, and $CO_2$ running exhaust emission rates to the MOVES model year 2000 heavy heavy-duty vehicles (regClassID 47), while CO from glider vehicles is higher. Based on this analysis, the MOVES running, start, and extended idling exhaust rates for gliders of all model years[aa] are set equal to those of the model year 2000 heavy heavy-duty vehicles.

For example, Figure 2-84 shows a comparison of the running exhaust emission rates (for age 0-3 group) of regClass 47 (heavy heavy-duty) vs. regClass 49 (glider vehicles) for selected pollutants and model year groups. The rates for the two regulatory classes are identical for model year 2000. For later model years, however, the emissions rates for regular heavy heavy-duty vehicles are significantly lower due to more stringent emission standards, whereas the rates for glider vehicles stay the same at the model year 2000 levels.

The auxiliary power unit (APU) exhaust emission rates of the glider vehicles, on the other hand, are set equal to those of regular (non-glider) heavy heavy-duty vehicle fleet. This is consistent with our assumption that glider vehicles have the same vehicle characteristics as regular heavy heavy-duty vehicles for non-powertrain components, and thus, have the same APU, aerodynamics, rolling resistance, brake and tire wear.

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[aa] Glider emission rates are intended to be the same for all model years from 2000 through 2060. However, for EC and non-EC PM, the pre-MY 2007 values were updated without changing the post-MY 2007 values. As discussed in the activity report, glider activity in MOVES begins in model year 2008.

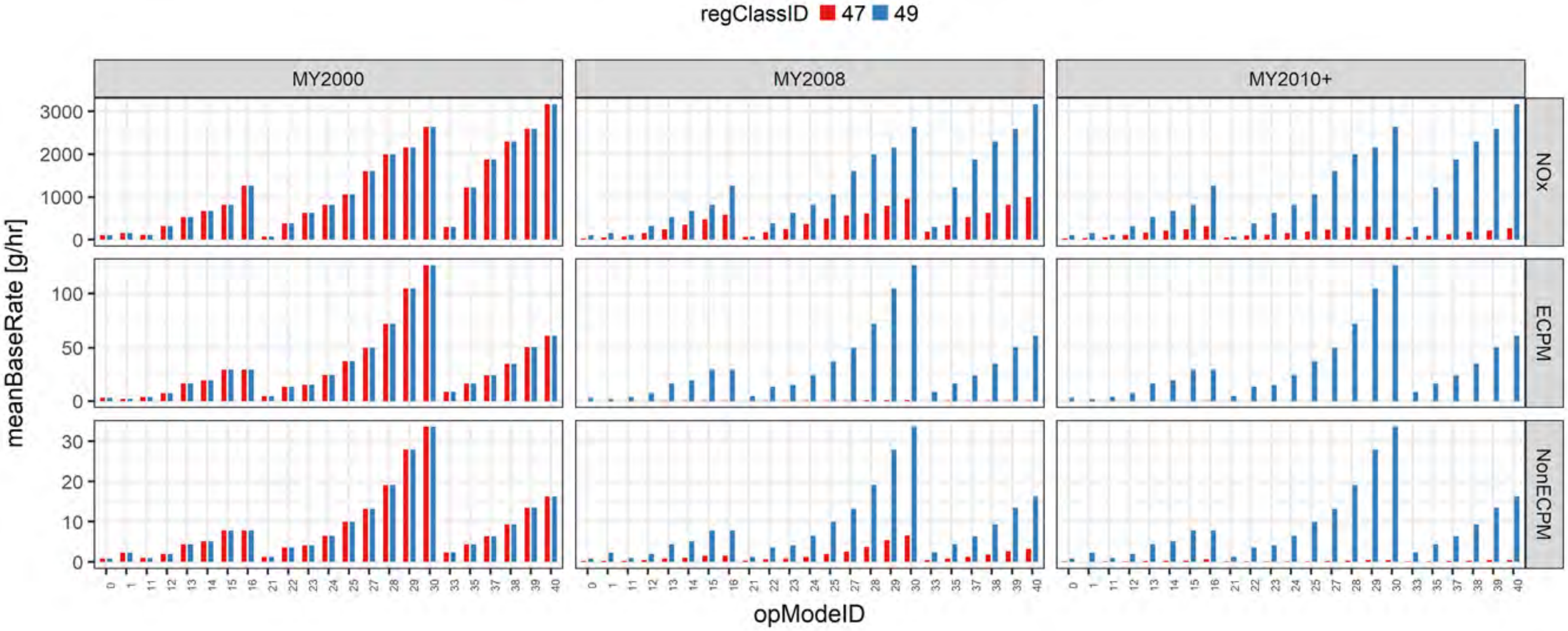

Figure 2-84. Comparison of the running exhaust emission rates (0-3 age group) of HHD (regClassID 47) vs. Gliders (regClassID 49) for selected pollutants ($NO_x$, ECPM, NonECPM) and model year groups

# 3 Heavy-Duty Gasoline Exhaust Emissions

The discussion of heavy-duty gasoline vehicles first covers running exhaust emissions (Section 3.1), followed by start emissions (Section 3.2). Within each emission process, we discuss the derivation of the emission rates by pollutant and model year group. As gasoline-fueled vehicles are a small percentage of the heavy-duty vehicle fleet, the amount of data available on their emissions is more limited.

## *3.1 Running Exhaust Emissions*

### *3.1.1 THC, CO and $NO_x$*

The heavy-duty gasoline running rates were analyzed in three stages. The MY 1960-2007 emission rates were originally developed in MOVES2010. In MOVES2014, we updated the MY 2008-2009 heavy-duty gasoline rates to account for the Tier 2 and 2007 heavy-duty rulemakings. In MOVES3, we updated the MY 2010-2026 emission rates based on the more recent testing data. In MOVES4, we revised the MY2027+ emission rates to account for the impact of HD2027 rule. The analysis of $PM_{2.5}$ running exhaust emission rates are discussed separately in Section 3.1.2 because it used separate data and analyses than for the gaseous pollutants.

#### *3.1.1.1 1960-2007 Model Years*

The heavy-duty gasoline emission rates for model year 2007 and earlier were carried over from previous versions of MOVES. They are based on analysis of four medium heavy-duty gasoline trucks from the CRC E-55 program and historical data from EPA's Mobile Source Observation Database (MSOD)[104], which has results from chassis tests performed by EPA, contractors and outside parties. The heavy-duty gasoline data in the MSOD is mostly from pickup trucks which fall mainly in the LHD2b3 regulatory class. Table 3-1 shows the total number of vehicles in these data sets. In the real world, most heavy-duty gasoline vehicles fall in either the LHD2b3 or LHD45 class, with a smaller percentage in the MHD class. There are very few HHD gasoline trucks now in use.

**Table 3-1 Distribution of Vehicles in the Data Sets by Model Year Group, Regulatory Class and Age Group**

| Model year group | Regulatory class | Age group | |
|---|---|---|---|
| | | 0-5 | 6-9 |
| 1960-1989 | MHD | | 2 |
| | LHD2b3 | | 10 |
| 1990-1997 | MHD | | 1 |
| | LHD2b3 | 33 | 19 |
| 1998-2002 | MHD | 1 | |
| | LHD2b3 | 1 | |

Similar to the HD diesel PM, THC, and CO analysis described above, the chassis vehicle speed and acceleration, coupled with the average weight for each regulatory class, were used to calculate STP

(Equation 1-6). To supplement the available data, we examined engine certification data as a guide to developing model year groups for analysis. Figure 3-1 shows averages of certification results by model year.

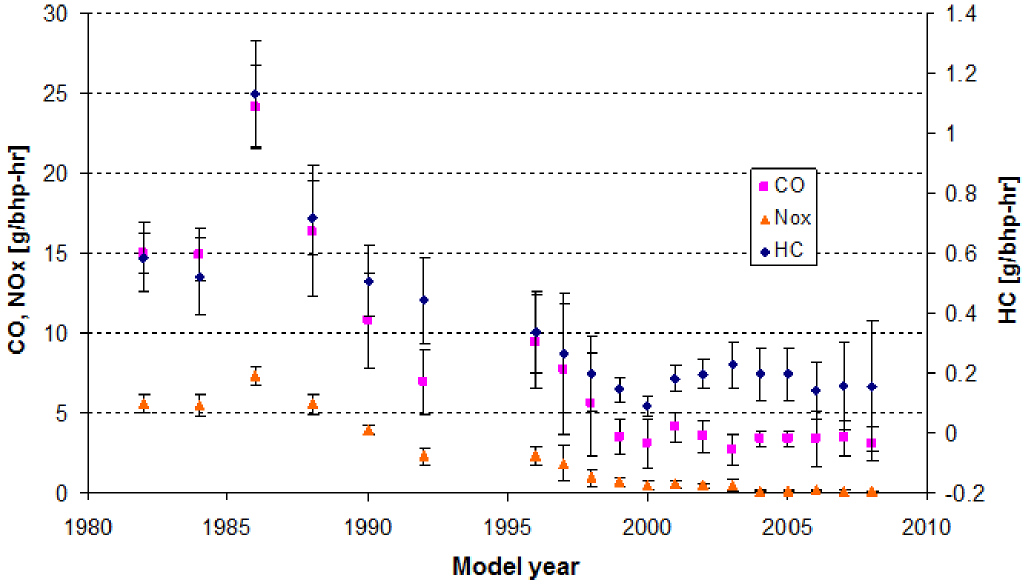

**Figure 3-1 Brake-Specific Certification Emission Rates by Model Year for Heavy-Duty Gasoline Engines**

Based on these certification results, we decided to classify the data into the coarse model year groups listed below.

- 1960-1989
- 1990-1997
- 1998-2007

Unlike the analysis for HD diesel vehicles, we used the age effects present in the data itself. We did not incorporate external tampering and mal-maintenance assumptions into the HD gasoline rates. Due to the sparseness of data, we used only the two age groups listed in Table 3-1, and applied the same age effects to all the heavy duty regulatory classes.

##### *3.1.1.1.1 LHD*

The emission rates for LHD (LHD2b3 and LHD45, regClassID 41 and 42, respectively) were analyzed by binning the emission measurements using the STP with a fixed mass factor of 2.06 (Table 1-3). Figure 3-2 shows all three pollutants vs. operating mode. In general, emissions follow the expected trend with increasing STP, though the trend is most pronounced for $NO_x$. As expected, $NO_x$ emissions for light heavy-duty gasoline vehicles are much lower than for light heavy-duty diesel vehicles.

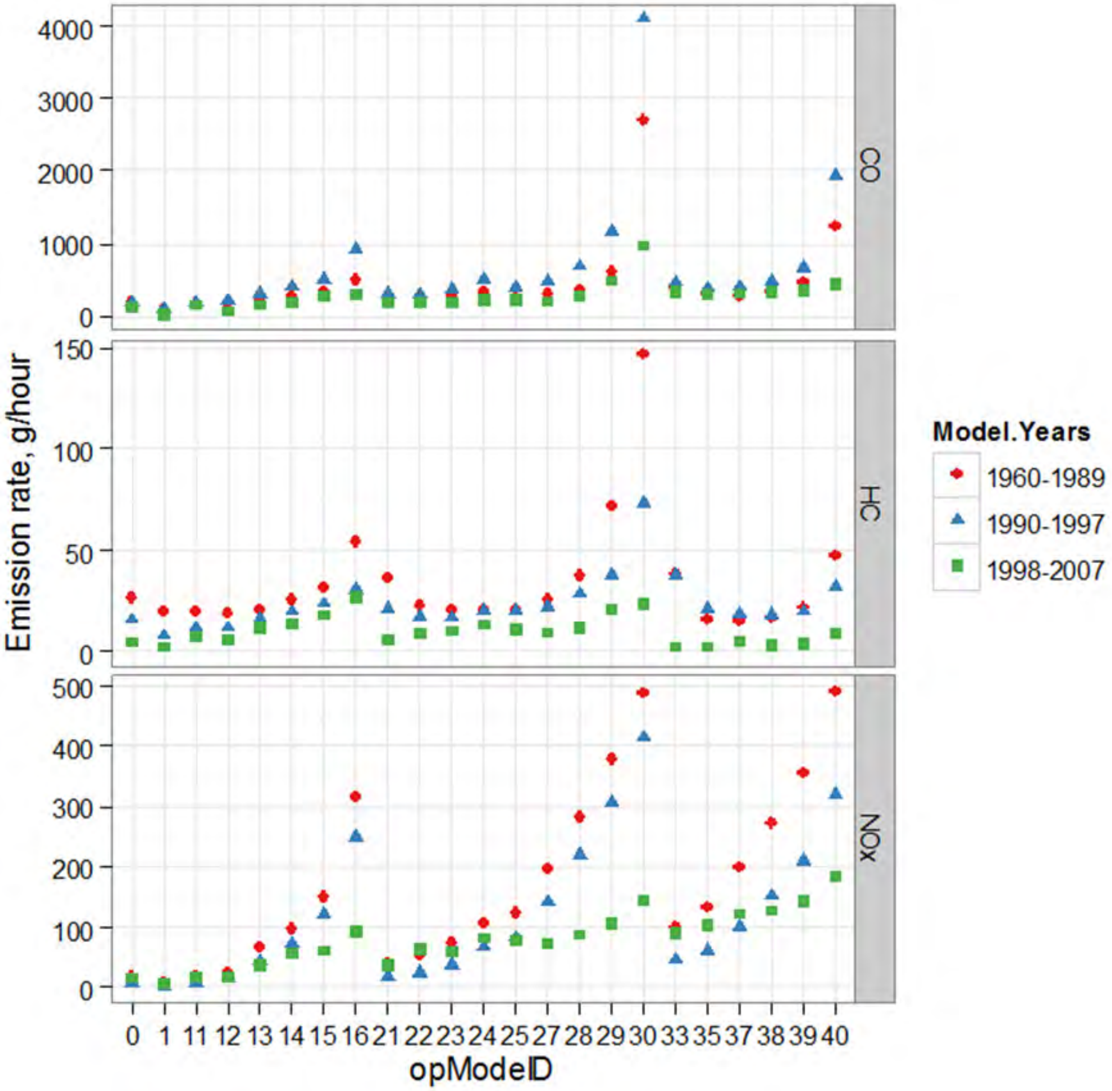

**Figure 3-2. Emission Rates by Operating Mode for MY Groups 1960-1989, 1990-1997, and 1998-2007 at Age 0-3 Years for LHD2b3 and LHD45 Vehicles**

Table 3-2 displays the multiplicative age effects by operating mode for LHD gasoline vehicles. The relative age effects are derived from the sample of vehicle tests summarized in Table 3-1. The multiplicative age effects are used to estimate the aged emission rates (ages 6+) years from the base emission rates (ages 0-5) for THC, CO, and $NO_x$. These multiplicative age effects apply to all model year groups between 1960 and 2007. As discussed earlier, we derived multiplicative age effects from the pooled data across the three model year groups and regulatory classes due to the limited data set.

**Table 3-2 Relative Age Effect on Emission Rates between Age 6+ and Age 0-5 for LHD Gasoline Vehicles in Model Years 1960-2007**

| OpModeID | THC | CO | $NO_x$ |
|---|---|---|---|
| 0 | 2.85 | 1.45 | 1.67 |
| 1 | 2.43 | 1.79 | 1.85 |
| 11 | 3.12 | 1.66 | 1.88 |
| 12 | 2.85 | 2.05 | 1.69 |
| 13 | 3.55 | 2.68 | 1.48 |
| 14 | 3.43 | 2.84 | 1.46 |
| 15 | 3.37 | 3.03 | 1.26 |
| 16 | 3.76 | 3.88 | 1.06 |
| 21 | 2.78 | 1.67 | 1.42 |
| 22 | 2.64 | 1.64 | 1.36 |
| 23 | 2.96 | 1.67 | 1.32 |
| 24 | 2.83 | 1.62 | 1.21 |
| 25 | 3.23 | 2.79 | 1.43 |
| 27 | 3.21 | 3.20 | 1.21 |
| 28 | 3.20 | 4.04 | 1.11 |
| 29 | 3.00 | 3.90 | 1.05 |
| 30 | 2.55 | 2.56 | 1.05 |
| 33 | 1.95 | 2.00 | 1.77 |
| 35 | 2.67 | 2.20 | 1.59 |
| 37 | 2.80 | 2.24 | 1.42 |
| 38 | 2.46 | 2.06 | 1.34 |
| 39 | 2.46 | 2.30 | 1.27 |
| 40 | 2.47 | 2.59 | 1.17 |

Figure 3-2 illustrates the emissions trends by age group for the 1998-2007 model year group. Since we did not use the tampering and mal-maintenance methodology as we did for diesels, the age trends reflect our coarse binning with age. For each pollutant, only two distinct rates exist – one for ages 0-5 and another for age 6 and older.

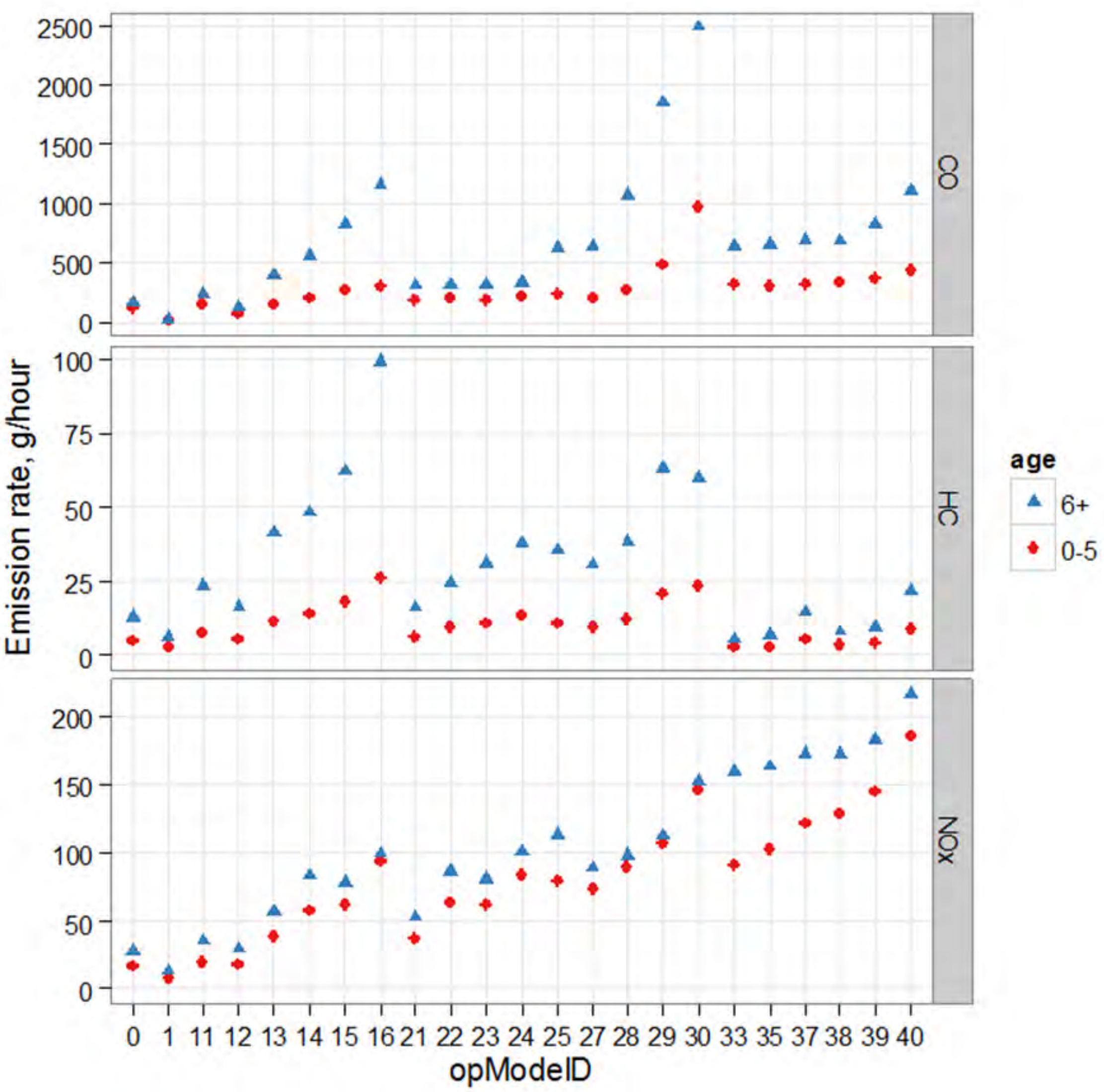

**Figure 3-3. Emission Rates by Operating Mode and Age Group for MY 1998-2007 Vehicles in Regulatory Class LHD2b3 and LHD45**

#### *3.1.1.1.2 MHD and HHD*

Like the LHD rates described above, the 2007 and earlier MHD and HDD gasoline rates are based on emissions data from the mix of LHD2b3 and MHD vehicles outlined in Table 3-1. The same model year groups were used to classify the emission rates: 1960-1989, 1990-1997, and 1998-2007. Also, we used the same relative increase in emission rates for the age effect. The only difference from the analysis of LHD emission rates is that the regulatory class MHD and HHD emission rates were analyzed using STP operating modes with a fixed mass factor of 17.1. The resulting MHD and HHD emission rates for THC, CO, and $NO_x$ for each model year group are presented in Figure 3-4.

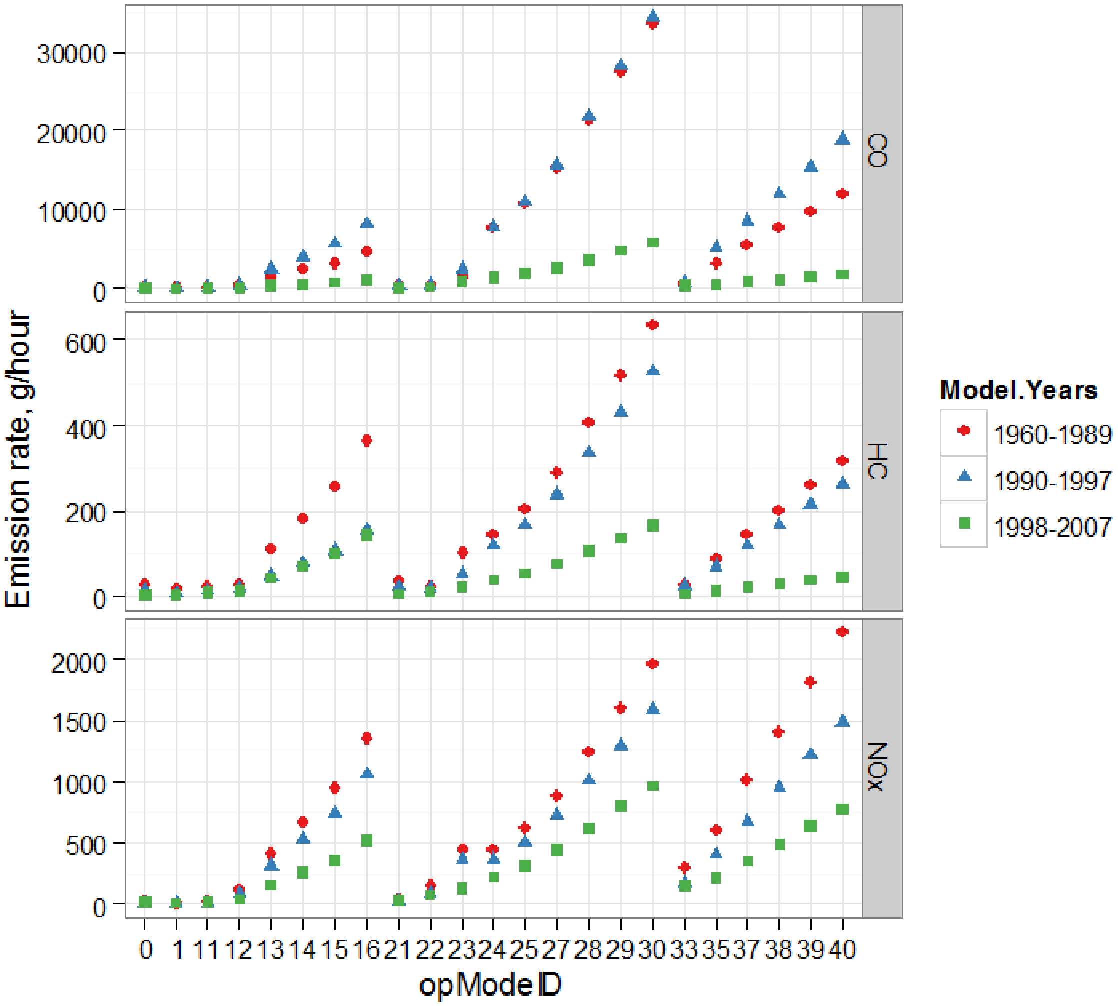

**Figure 3-4. Emission Rates for MY 1990-1997 at age 0-3 years for Regulatory Class MHD and HHD**

Table 3-3 displays the multiplicative age effects by operating mode for MHD, and HHD gasoline vehicles. While these age effects were derived from the same data as those for the LHD vehicles, these heavy-duty age effects are slightly different, because the operating modes are defined with the STP scaling factor of 17.1. For operating modes that do not depend on the scaling factor (opModeID 0, 1, 11, and 21), the age effects are the same as the LHD age effects. Also, because the vehicles tested were LHD2b3 and MHD vehicles, no data were available in the high STP power modes (typically only a HHD truck would reach these). Thus, the higher operating modes (opModeID 13-16, 24-30, and 35-40) use the same values as the closest operating mode bin with data.

**Table 3-3 Relative Age Effect on Emission Rates between Age 6+ and Age 0-5 for MHD and HHD Gasoline Vehicles in All Model Years 1960-2060**

| OpModeID | THC | CO | $NO_x$ |
|---|---|---|---|
| 0 | 2.85 | 1.45 | 1.67 |
| 1 | 2.43 | 1.79 | 1.85 |
| 11 | 3.12 | 1.66 | 1.88 |
| 12 | 3.36 | 3.12 | 1.13 |
| 13 | 3.53 | 3.16 | 1.11 |
| 14 | 3.53 | 3.16 | 1.11 |
| 15 | 3.53 | 3.16 | 1.11 |
| 16 | 3.53 | 3.16 | 1.11 |
| 21 | 2.78 | 1.67 | 1.42 |
| 22 | 3.08 | 2.59 | 1.23 |
| 23 | 2.97 | 3.31 | 1.05 |
| 24 | 1.80 | 1.54 | 1.03 |
| 25 | 1.80 | 1.54 | 1.03 |
| 27 | 1.80 | 1.54 | 1.03 |
| 28 | 1.80 | 1.54 | 1.03 |
| 29 | 1.80 | 1.54 | 1.03 |
| 30 | 1.80 | 1.54 | 1.03 |
| 33 | 2.45 | 2.41 | 1.33 |
| 35 | 2.16 | 2.41 | 1.19 |
| 37 | 2.16 | 2.41 | 1.19 |
| 38 | 2.16 | 2.41 | 1.19 |
| 39 | 2.16 | 2.41 | 1.19 |
| 40 | 2.16 | 2.41 | 1.19 |

Figure 3-5 displays the resulting emission rates by operating mode bin and age group for the LHD45, MHD, and HHD gasoline vehicles, which were calculated by applying the multiplicative age effects in Table 3-3.

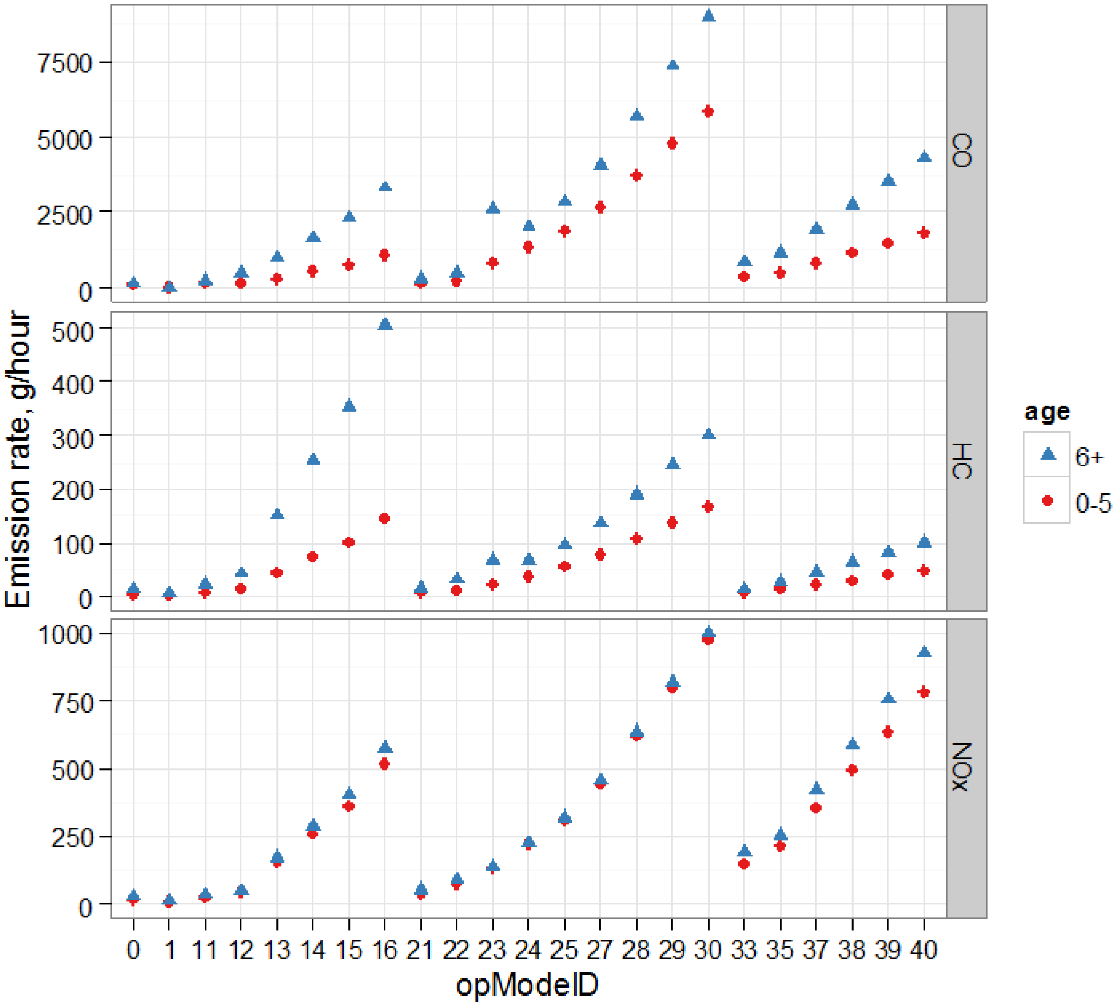

**Figure 3-5. Emission Rates by Operating Mode and Age Group for MY 1998-2007 Vehicles in Regulatory Class MHD and HHD Gasoline Vehicles**

### *3.1.1.2 2008-2009 Model Years*

#### *3.1.1.2.1 LHD*

The MY 2008 and 2009 LHD emission rates are updated from the MY 2007 LHD emission rates to account for the phase-in of the Tier 2 and HD 2007 rulemaking which set emissions standards for medium-duty passenger vehicles (MDPV), Class 2b, and Class 3 chassis-certified vehicles. Medium duty passenger vehicles fall within the LHD2b3 regulatory class in MOVES. The useful life emission standards for these vehicles are shown in Table 3-4.

**Table 3-4 Useful Life FTP Standards from the Tier 2 Rulemaking[105] and the HD 2007 Rule[107]**

| | MDPV (Tier 2 Bin 5) | 8.5k – 10K (Class 2B) | 10K-14K (Class 3) |
|---|---|---|---|
| Units | g/mile | g/mile | g/mile |
| Fully Phased in MY | 2009 | 2009 | 2009 |
| THC | 0.09 NMOG | 0.195 NMHC | 0.230 NMHC |
| CO | 4.2 | 7.3 | 8.1 |
| $NO_x$ | 0.07 | 0.2 | 0.4 |

This section documents the THC, CO and $NO_x$ emission rates for regulatory class LHD2b3 vehicles in model years 2008 and 2009. In conducting this analysis, we lacked any modal data on LHD vehicles and therefore, we ratioed the modal emission rates measured from light-duty vehicles by the difference in standards.[9] By MY 2008, the certification results demonstrated that LHD2b3 were nearing the emission levels of light-duty vehicles certified to the Tier 2 Bin 8 standard.[35] Consequently, we relied on the MOVES2014 analysis of in-use Tier 2 Bin 8 vehicles conducted for the light-duty emission rates.[9] We applied this analysis to derive MY 2009 emission rates, then calculated MY 2008 rates by interpolating between MY 2007 and MY 2009.

Although the light-duty rates are based on VSP, rather than STP, adapting them for the LHD2b3 rates was deemed an acceptable approximation because the gasoline LHD2b3 gasoline vehicles are chassis-certified to distance-based standards (g/mi). Accordingly, the vehicle emissions rates are less dependent on the individual power and weight of the vehicle, and should scale approximately to the g/mile emission standards.[bb]

Based on these assumptions, we scaled modal rates for Tier 2 Bin 8 vehicles by the ratio of FTP standards to the calculated aggregate LHD2b3 standards documented in the MOVES2014 heavy-duty exhaust report.[35,cc] Table 3-5 displays the aggregated LHD2b3 standards, Bin 8 FTP standard and the ratio between the standards by pollutant.

**Table 3-5 Aggregate LHD2b3 Standard Ratios against Bin 8 Modal Rates**

| | Aggregate LHD2b3 FTP standard | Bin 8 FTP standard | Aggregate LHD2b3/Bin 8 |
|---|---|---|---|
| NMOG | 0.18 | 0.1 | 1.8 |
| CO | 7.49 | 3.4 | 2.2 |
| $NO_x$ | 0.22 | 0.14 | 1.6 |

We took an additional step to "split" these ratios into "running" and "start" components, such that the running rates increased twice as much as the start rates, while maintaining the same simulated value for the FTP composite. This split ratio is consistent with typical emission reduction trends, where running emissions are reduced about twice as much as start emissions.[9] The "split" ratios for

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[bb] This approximation needs to be revisited in the future now that we have updated the mass of LHD vehicles in MOVES3 to range from 3.5 to 7.8 metric tons**Error! Bookmark not defined.**, which differs from the $f_{scale}$ value of 2.06 metric tons.

[cc] As documented in MOVES2014 documentation, this analysis assumed that 5% of the gasoline LHD2b3 engines were engine-certified, but, actually, all gasoline fueled LHD2b3 vehicles are chassis-certified. However, the engine-certification standard has a small impact on the calculated aggregated standard conducted for MOVES2014.

running and start, which were applied to the light-duty Tier 2 Bin 8 vehicle emission rates are shown in Table 3-6.

**Table 3-6 Ratio Applied to Light-Duty Tier 2 Bin 8 Emission Rates to Estimate Regulatory Class LHD2b3 Emission Rates for 2008-2009 MY**

| | THC | CO | $NO_x$ |
|---|---|---|---|
| Running | 2.73 | 2.73 | 1.95 |
| Start | 1.37 | 1.37 | 1.00 |

We also adopted the light-duty deterioration effects and applied them to the MY 2009 regulatory class LHD2b3 (regClassID 41) emission rates. The light-duty emission rates have age effects that change with each of the 6 age groups in MOVES, as shown in Table 3-7.

**Table 3-7 Multiplicative Age Effect used for Running Emissions for Regulatory Class LHD2b32009 Model Year**

| ageGroupID | THC | CO | $NO_x$ |
|---|---|---|---|
| 3 | 1 | 1 | 1 |
| 405 | 1.95 | 2.31 | 1.73 |
| 607 | 2.80 | 3.08 | 2.21 |
| 809 | 3.71 | 3.62 | 2.76 |
| 1014 | 4.94 | 4.63 | 3.20 |
| 1519 | 5.97 | 5.62 | 3.63 |
| 2099 | 7.20 | 6.81 | 4.11 |

After applying the steps described above (scaling the emission factors by ratio of FTP standards, and applying light-duty deterioration trends), we restricted the scaled data so that the individual emission rates by operating mode were never higher than MY 1998-2007 regulatory class LHD2b3 rates. This step essentially "capped" the emission rates, such that none of the modal rates for MY 2009 are higher than their counterparts for MY 2007 and earlier. MY 2008 rates are interpolated between MY 2007 and MY 2009 emission rates as discussed later.

This final step "capped" the model year 2009 emission rates in the highest operating modes, as shown in Figure 3-6.. For THC, emission rates in operating modes 28-30 and 38-40 were capped for some or all age groups by the pre-2007 emission rates. For CO, emission rates in 12 of the 23 running operating modes (1, 16, 23-24, 27-30, 35-40) were capped by the pre-2007 rates. None of the $NO_x$ emission rates were impacted by this step. Figure 3-6. shows the regulatory class LHD2b3 model year 2008-2009 emission rates for CO, THC, and $NO_x$. In the figure, rates "capped" by the pre-2007 rates exhibit the uncharacteristic "stairstep" deterioration trends. Even with the "capping" effects, the rates for regulatory class LHD2b3 (regClassID 41) are higher than those for light-duty trucks (regClassID 30), with a few exceptions. The few exceptions are some of the age-dependent THC and or CO emission rates in operating modes 1, 30, 38, 39, and 40. However, the majority of emission rates are considerably higher for the heavy-duty (LHD2b3) than for the light-duty trucks. Similarly, when the FTP is simulated from the resulting rates, estimated composites are substantially higher for LHD2b3 than for light-duty trucks.

The Light-duty Tier 2 standards shown in Table 3-4 phase-in at a rate of 50 percent in MY 2008 and are considered fully phased in by MY 2009.[106] For estimating emission rates in MOVES, we used the same assumptions to estimate the MY 2008 emission rates. The MY 2008 running emission rates are interpolated between the MOVES 2007 and 2009 emission rates by operating mode and age group.

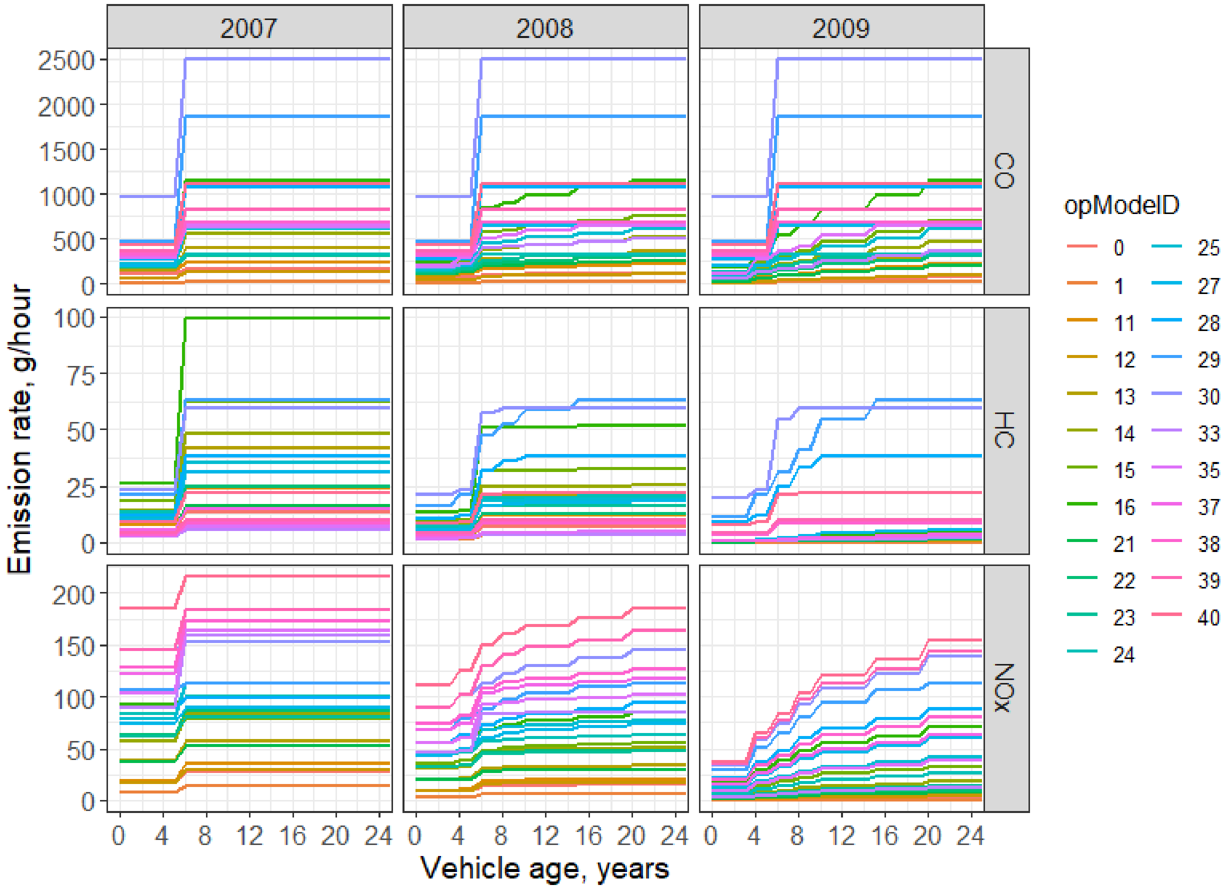

**Figure 3-6. Age Effects for CO, THC, and NO$_x$ Emission Rates for Regulatory Class LHD2b3 (regClassID 41) Vehicles in Running Operating Modes for MY 2007, 2008 and 2009**

Due to limited data on LHD45 vehicles, we applied the LHD2b3 emission rates developed in the previous section to the LHD45 emission rates. The LHD2b3 and LHD45 emission rates are identical for model years 1960-2017.

#### *3.1.1.2.1 MHD and HHD*

Of the onroad heavy-duty vehicles GVWR Class 4 and above, a relatively small fraction are powered by gasoline: about 15 percent are gasoline, as opposed to 85 percent diesel.[dd] The percentage of gasoline-fueled vehicles decreases as the GVWR class increases. Since these vehicles are a small portion of the fleet, there is relatively little data on these vehicles, and therefore, the current 2008 and 2009 model year emission rates are from MOVES2010.[107] The rates are modeled by applying a 70 percent reduction to the MY 2007 running rates starting in MY 2008, which is

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[dd] Negligible portions are run on other fuels. The figures are aggregated from data supplied by Polk.

consistent with the emission standard reduction with the "Heavy-Duty 2007 Rule."[108,ee] The 2008 and 2009 model year emission rates have two age groups (0-5, and 6+) and the same relative multiplicative age effects as the pre-2007 emission rates (Table 3-3).

#### *3.1.1.3 2010-2060 Model Years*[ff]

In MOVES3, we updated the THC, CO, and $NO_x$ emissions rates for MY 2010 and later vehicles for all gasoline heavy-duty regulatory classes. The initial update is described here. Additional analysis to account for the Tier 3 and HD2027 rules are described in Sections 3.1.1.3.1 and 3.1.1.3.2 below. The updated rates are based on analysis of real-world PEMS-based emissions measurement data from two engine-certified and one chassis-certified heavy-duty gasoline vehicles (Table 3-8) with model years between 2015-2017. As explained in the $PM_{2.5}$ section (Section 3.1.2.2), we also conducted chassis-dynamometer laboratory testing on these vehicles, but used the PEMS gaseous emissions data because it better represents emissions in the real-world.

The Ford and Isuzu vehicles used the most popular engine configurations for recent model year heavy-duty gasoline Class 4 vehicles. Each of the HD gasoline vehicles had three-way catalyst (TWC) technology to control THC, CO, and $NO_x$ emissions. However, one key difference compared to light-duty gasoline vehicle TWC configuration is that the engine-certified HD gasoline vehicles do not use a close-coupled TWC. There might also be differences in catalyst precious metal loading and in-cylinder combustion control for maximum TWC efficacy. The reason for these differences is that engine-certified and chassis-certified gasoline spark-ignited vehicles have to meet different standards.

**Table 3-8 Summary of MY 2015-2017 Heavy-Duty Gasoline Vehicles with Real-World PEMS-based Emissions Measurement Data**

| Vehicle | | | | | | Engine | | Test Weight (lbs) | | Cert-ification |
|---|---|---|---|---|---|---|---|---|---|---|
| Make | Model | MY | Odometer (miles) | GVWR (lbs) | GCWR (lbs) | Family | Displ (L) | Low | High | |
| Isuzu | NPR | 2015 | 48,000 | 14,500 | 20,500 | FGMXE06.0584 | 6.0 | 8,620 | 12,940 | Engine |
| Ford | E450 | 2016 | 31,000 | 14,500 | - | GFMXE06.8BWZ | 6.8 | 9,320 | 13,080 | Engine |
| RAM | 3500 | 2017 | 32,000 | 13,300 | 19,900 | HCRXD06.45W0 | 6.4 | 14,557 | 18,020 | Chassis |

The testing was conducted by US EPA over various test cycles in the Ann Arbor, Michigan area. The test matrix covered a range of vehicle operation that included:

1. Two idling tests of 15- or 30-minutes duration
2. Seven on-road driving routes that cover the full range of power demand by including transient low- and medium-speed urban driving to steady-state high-speed highway driving
3. Soak times ranging from zero minutes (hot start) to 720 minutes (cold start)
4. Vehicle weight at low or high (Table 3-8)

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[ee] The engine-certified standards for heavy-duty gasoline were reduced by 93% (THC), 80% ($NO_x$), and 61% (CO) with the MY 2008 standard.

[ff] The additional rate adjustments for MY2018-2060 LHD2b3 and MY2027-2060 LHD45/MHD/HHD vehicles are described in subsections 3.1.1.3.1 and 3.1.1.3.2 respectively.

5. Air conditioning on or off
6. Cabin windows down or up

A total of 202 tests across vehicles and operation modes was available for data analysis. These tests covered about 412,000 seconds of post-QA operation. We removed the effect of warm and cold starts from the operation since the running emissions are intended to be just the hot running operation; details are discussed in Appendix I.1. After removal of vehicle operation related to start emissions, the final data set used for just the hot running emissions rates update was about 390,000 seconds.

The following steps were used to calculate the operating mode-based emission rates for each age and regulatory class of LHD, MHD, and HHD:

1. Assign operating modes as per the method described above for diesel vehicles and calculate the average rate per operating mode per test per vehicle
2. Calculate the average operating mode-based rate per vehicle (using only vehicle specific tests)
3. Estimate emission rates for operating modes with limited or missing data.
4. Calculate the operating mode-based emission rate as the production weighted average of the three test vehicles.
5. Adjust emission rates by vehicle age.

In Step 1, the operating modes (Table 1-4) were assigned to the 1-hz data using the STP equation (Equation 1-6) with road-load coefficients for single-unit short-haul truck (sourceType 52) for the 2014-2020 model year range as defined in the *sourceusetypephysics* table in MOVES3 database. The coefficients for single-unit short-haul trucks are the same for all the regulatory classes within this sourcetype (LHD2b3, LHD45, MHD, and HHD). The road-load coefficient values used are:

rollingTermA = 0.596526 [kW.sec/m]
rotatingTermB = 0 [kW.sec$^2$/m$^2$]
dragTermC = 0.00160302 [kW.sec$^3$/m$^3$]

For vehicle mass, we used the actual test weight (Table 3-8). Road-grade was not available, so it was set to zero. The entire data set was analyzed with the new $f_{scale}$ values (Table 1-3) of 5 (LHD2b3 and LHD45), 7 (MHD), and 10 (HHD). The selection of these new $f_{scale}$ values was based on the diesel HDIUT dataset and is described in Appendix G.

In Step 2, we averaged according to operating mode for each vehicle. In Appendix I.2, we compared the emission rates among the three vehicles by operating mode. Significant differences are observed between the vehicles, however no consistent differences were noted across operating modes and pollutants between the two engine-certified vehicles and the chassis-certified vehicle.

In Step 3, we estimated emission rates for high power operating modes with limited or missing data from regulatory class MHD and HHD, due to the larger $f_{scale}$ values used for these operating modes. In these cases, we aggregated the data across the nearest high-power operating modes with sufficient data, and set the emission rates to be equivalent across the aggregated bins. Additional details and examples are discussed in Appendix I.3.

In Step 4, we calculated a weighted average of the emission rates from the three vehicles using the production volumes of each of the tested engines. Ideally, the emission rates for each regulatory class (LHD2b3, LHD45, MHD, and HHD) would be estimated from test data collected from vehicles of that regulatory class, or estimated separately for the engine-certified (LHD45 and heavier) and chassis-certified vehicles (LHD2b3). However, due to the small sample size (including only one LHD2b3 vehicle), we used the same weighting of the three vehicles for all the regulatory classes. The production volumes of the RAM 3500 vehicle are only a minor fraction of the combined production of the Ford and Isuzu engine volumes. As such, the production weighting is most representative of LHD45 emission rates.[gg]

Because we use the same production volume weighting for all the regulatory classes, the base emission rates for MY 2010+ LHD2b3 and LHD45 are identical. However, the LHD2b3 rates are further modified by applying the Tier 3 reductions phased-in from MY 2018 to 2022 (Section 3.1.1.3.1). The only difference between the LHD45, MHD, and HHD emission rates is the $f_{scale}$ used to estimate the emission rate by operating mode, and methods used to estimate high-power operating modes conducted in Step 4 (Details in Appendix I.3).

In Step 5, we applied the MHD/HHD age effects shown in Table 3-3 to all gasoline heavy-duty regulatory classes, including LHD2b3 and LHD45. We did not use the LHD2b3/LHD45 specific age effects shown in Table 3-2. Both of these age effects tables are based on the same data set (Table 3-1) with the difference being only the $f_{scale}$ used while assigning the data to operating modes. Applying the LHD or LD (Table 3-7) age effects to rates developed using HD data and different $f_{scale}$ ranges could over- or under-estimate the increases in emissions from aging. Ideally, LHD2b3 emission rates and age effects would be derived from chassis-certified heavy-duty gasoline vehicles.

#### *3.1.1.3.1 LHD2b3 2018-2060 Model Years*

The LHD2b3 vehicles are subject to the Tier 3 light-duty standards starting in MY 2018.[hh] To calculate emission rates for MY 2018 and later, we applied reductions representing the Tier 3 phase-in for MY 2018-2022 for LHD2b3 vehicles (as shown in Table 3-9) to the emission rates representing MY 2010-2017 estimated from the above. The reductions for each model year during the phase-in were estimated by extracting the corresponding MOVES rates for MY 2007-2022, and calculating the fractions relative to MY 2017. The basis and rationale for the Tier 3 reductions for gasoline LHD2b3 vehicles developed for the Tier 3 rulemaking are documented in the MOVES2014 heavy-duty exhaust report.[109]

The LHD2b3 MY 2018+ rates contain the same heavy-duty gasoline age effects as were applied to the MY 2010-2017 rates (Table 3-3). The resulting emission rates for THC, CO and $NO_x$ are shown in Figure 3-7 through Figure 3-9.

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[gg] Sales of Class 2b gasoline trucks are much larger than for Class 3, 4, 5, and 6.

[hh] All LHD2b3 chassis-certified complete vehicles are subject to Tier 3. All LHD2b3 gasoline fueled vehicles are chassis-certified complete vehicles.

**Table 3-9 Tier 3 Reductions by Model Year for Gasoline LHD2b3**

| Model Year | THC | CO | $NO_x$ |
|---|---|---|---|
| 2018 | 35% | 38% | 41% |
| 2019 | 44% | 48% | 52% |
| 2020 | 53% | 59% | 63% |
| 2021 | 62% | 68% | 74% |
| 2022-2060 | 71% | 78% | 85% |

#### *3.1.1.3.2 LHD45, MHD, HHD 2027-2060 Model Years*

In order to account for the HD2027 standards in MOVES4, we revised the running exhaust emission rates for $NO_x$, THC, CO, (and $PM_{2.5}$ described later in 3.1.2.3) for MY2027+ heavy-duty (LHD45, MHD, HHD) gasoline vehicles using the methodology described in this section. Unlike the HD2027 standards for diesel vehicles, the rule does not include off-cycle standards for gasoline vehicles. Due to the relatively simple treatment of aging for MOVES HD gasoline vehicles, we did not estimate any impact from the lengthened warranty and useful life periods provisions on the emission rates.

The FTP duty-cycle standards shown in Table 2-9 apply to both heavy-duty compression-ignition engines and heavy-duty spark-ignition engines. 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 3-10 shows the estimated reduction in $NO_x$ emission rates, which is consistent with the ratio of the MY2010 FTP emission standards and the HD2027 final FTP standards shown in Table 3-10.

In addition, we also estimated emission rate reductions due to the HD2027 standards for HC and CO. 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 available data from production HD Spark-ignition (SI) engines and from the heavy-duty gasoline technology demonstration program to estimate our modeled emissions levels.[110] We assumed a 65 percent reduction in THC emissions would occur at a $NO_x$ $NO_x$ standard of 0.1 g/hp-hr. We assumed additional decreases in THC emissions to reflect tighter final $NO_x$ standards in MY 2027. We derived Equation 3-1 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 3-1 to estimate the reductions in THC emissions using the $NO_x$ levels for the control scenarios (Table 3-10).

$$R_{gasoline,THC,NOx\ FTP} = 1 - \left(\frac{NOx\ FTP\ Standard}{0.1\frac{g}{bhp \cdot hr}}\right) \times \left(1 - R_{gasoline,THC,0.1\ NOx\ FTP}\right)$$ **Equation 3-1**

$$= 1 - \left(\frac{NOx\ FTP\ Standard}{0.1\frac{g}{bhp \cdot hr}}\right) \times (1 - 65\%)$$

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 3-10
$NO_x$ *FTP Standard* = HD2027 $NO_x$ FTP standards

We assumed a 60 percent reduction in CO for MY2027+ engines (see Table 3-10) based on EPA testing.

**Table 3-10 Running Emission Rate Reductions From Heavy-duty Gasoline Vehicles Due to HD2027 Standards, $R_{gasoline}$, Across All Heavy-duty Gasoline Regulatory Classes and Operating Modes**

| **Regulatory Class$^A$** | **FTP/SET $NO_x$ standard (g/hp-hr)** | **$NO_x$** | **THC** | **CO** |
|---|---|---|---|---|
| LHD, MHD, HHD | 0.035 | 82.5% | 87.8% | 60% |

$^A$ We applied the same standards to represent the SI engines modeled by the LHD, MHD, and HHD regulatory classes, unlike the final standards for compression-ignition engines

Then Equation 3-2 was used to revise the MOVES emission rates to account for the HD2027 standards. Since spark-ignition engines are not subject to the HDIUT program, 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.

$$ER_{Final\ Standards} = \left(1 - R_{gasoline}\right) \times ER_{MOVES\_baseline}$$ **Equation 3-2**

Where:

$ER_{control}$ = MOVES running exhaust emission rates for HD2027 standards based on the reduction in the FTP duty-cycle standard
$R_{gasoline}$ = percent emission reductions in heavy-duty gasoline emissions from Table 3-10
$ER_{MOVES\ baseline}$ = MOVES running exhaust emission rates before the rate revision

#### *3.1.1.4 Inspection and Maintenance Program Effects for LHD2b3 Gasoline Vehicles*

In MOVES3.1, we updated the meanBaseRateIM values for THC, CO, and $NO_x$ running exhaust emission rates to better reflect our understanding how state and local inspection and maintenance (I/M) programs reduce gaseous emissions from LHD2b3 gasoline vehicles.

As background, in addition to the meanBaseRates described in Section 1, the MOVES emissionRateByAge table includes a field, meanBaseRateIM, that is used to estimate emissions under a relevant I/M program. These calculations are explained in more detail in the MOVES Adjustments report.[63]

In MOVES3.0.4 and earlier versions of MOVES, we set the values of meanBaseRateIM for all HD exhaust rates to equal the associated meanBaseRate—essentially assuming no benefit from HD I/M programs. For MOVES3.1 and later, we reconsidered this choice for gasoline LHD2b3 trucks (regClass 41). Given the similarity of the engine technology and aftertreatment systems between gasoline LHD2b3 and light-duty trucks (regClass 30), and the similarity in the way these trucks are tested in contemporary I/M programs, we updated the gasoline LHD2b3 HC, CO and $NO_x$ running exhaust values for meanBaseRateIM to reflect the same proportional reduction (that is meanBaseRateIM/meanBaseRate) that we model for each operating mode bin and age for the light-duty trucks. For more detail on the meanBaseRate and meanBaseRateIM values for light-duty trucks, see the MOVES3 LD report.

#### *3.1.1.5 Model Year Trends*

Figure 3-7 through Figure 3-9 display the THC, CO, and $NO_x$ non-IM running exhaust emission rates by model year and regulatory class (HHD and Urban Bus). The emission rates are estimated in grams per mile (g/mile) using nationally representative operating mode distributions and average speeds. The model year groups used to estimate the emission rates are evident: 1960-1989, 1990-1997, 1998-2007, 2008-2009, and 2010-2060. Note that not all the changes in the gram per mile emission rates are due to changes in the operating mode specific emission rates. For example, the MY 1995-1997 operating mode specific emission rates are the same as the 1990-1995 emission rates for all regulatory classes. However, there is an observed spike in the HHD gram per mile THC emission rate, which is attributed to a shift in the distribution of HHD gasoline activity among different source types in MOVES.

Figure 3-7 shows that the THC emission rates follow decreasing trends with model year that correspond with tighter emission factors. The drop in emission rates in model year 2008-2009 is attributed to the different methodology used to develop those rates discussed earlier. Even though the increasing trend between 2008-2009 and 2010 and later model year groups may not be intuitive from a technical perspective, we have increased confidence that the MY 2010 and later THC emission rates represent the real-world emissions since they were developed based on in-use testing of MY 2010 and later vehicles.

Emission rates also change starting in MY2027 due to the implementation of the HD2027 standards.

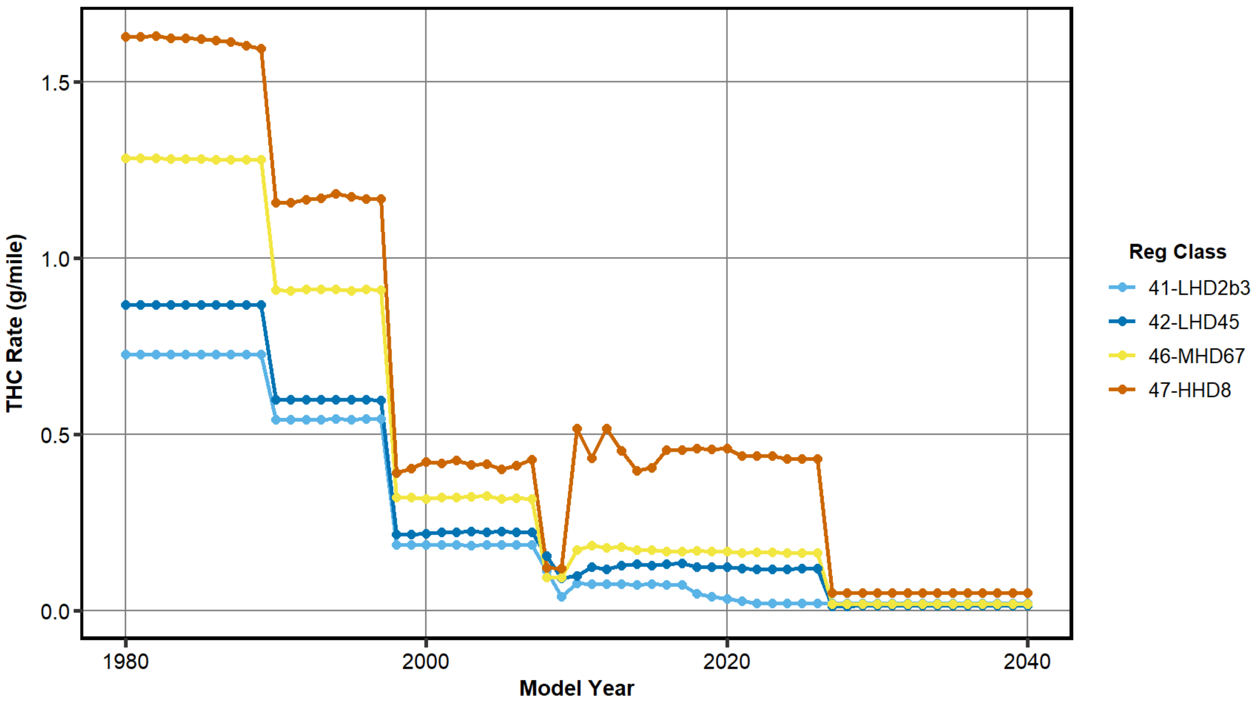

**Figure 3-7. Base running emission rates for THC from age 0-3 gasoline heavy-duty vehicles averaged over a nationally representative operating mode distribution.**

The CO emission rates are shown in Figure 3-7  The CO emission rates for LHD2b3 vehicles (the largest regulatory class of heavy-duty gasoline) follow a generally decreasing trend with model year. The trends for LHD45 and MHD show unexpected variation across model years, including an increase in CO emission rates for LHD45 and MHD vehicles. We have the most confidence in the most recent model year data, and the variability in the model year trends reflects uncertainty in the earlier heavy-duty gasoline emission rates.

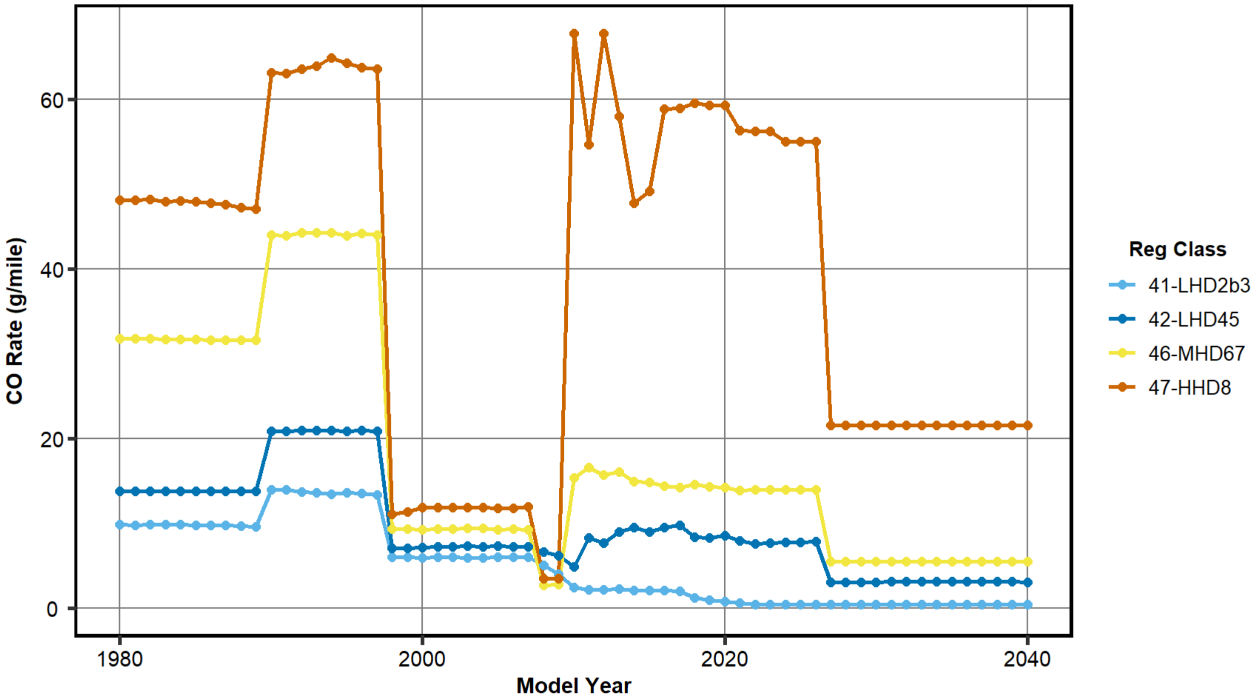

**Figure 3-8. Base running emission rates for CO from age 0-3 gasoline heavy-duty vehicles averaged over a nationally representative operating mode distribution.**

Figure 3-9 shows that the $NO_x$ emission rates follow decreasing trends with model years that correspond with tighter emission standards.

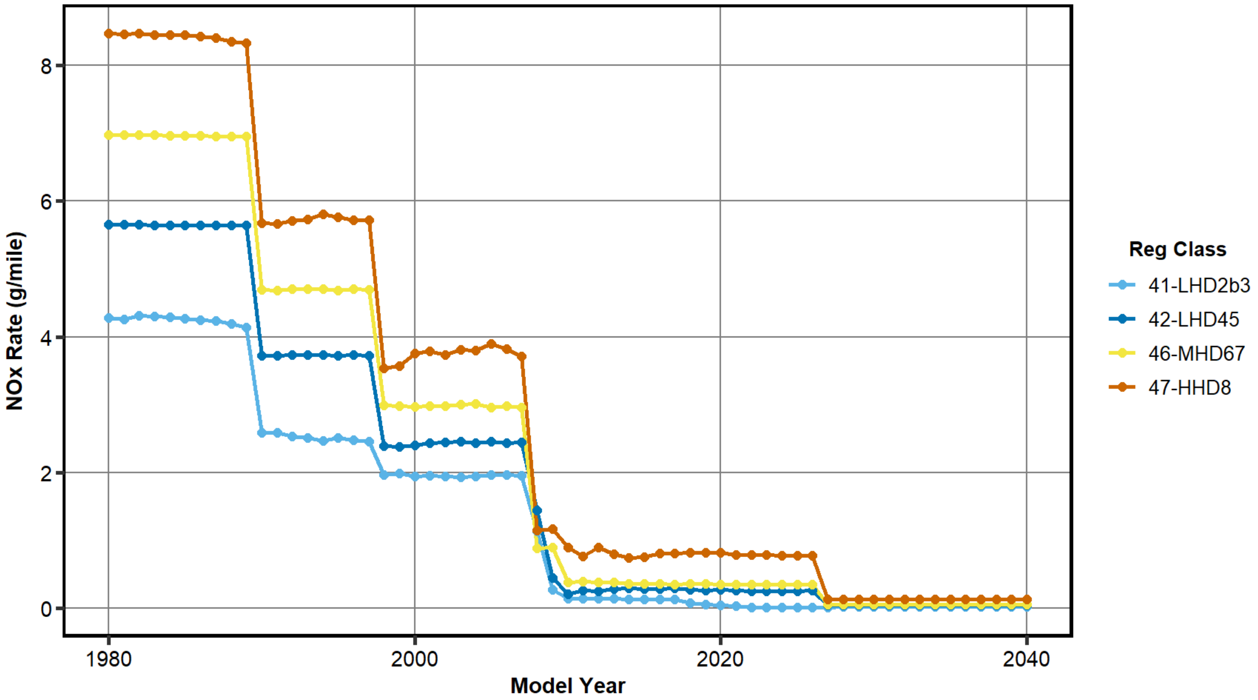

**Figure 3-9. Base running emission rates for $NO_x$ from age 0-3 gasoline heavy-duty vehicles averaged over a nationally representative operating mode distribution**

### *3.1.2 Particulate Matter ($PM_{2.5}$)*

The available studies from which to develop $PM_{2.5}$ emission for heavy-duty gasoline are particularly limited. This includes limitations on second-by-second data from which to develop operating mode specific rates, as well as studies representative of in-use and fleet average emissions. At the same time, heavy-duty gasoline is a relatively small contributor to the total $PM_{2.5}$ emissions inventory when compared to heavy-duty diesel and light-duty gasoline. As a result, the limited analysis conducted for MOVES2010 has been carried over into MOVES3 for the 2009 and earlier vehicles as discussed in Section 3.1.2.1. For MOVES3, we have updated the 2010 and later model year heavy-duty gasoline emission rates to be based on heavy-duty diesel rates as discussed in Section 3.1.2.2.

#### *3.1.2.1 1960-2009 Model Years*

For MOVES, the MY 1960-2009 heavy-duty gasoline $PM_{2.5}$ emission rates were calculated by multiplying the MOVES2010b light-duty gasoline truck $PM_{2.5}$ emission rates by a factor of 1.40, as explained below. Since the MOVES light-duty gasoline $PM_{2.5}$ emission rates comprise a complete set of factors classified by particulate sub-type (EC and nonECPM), operating mode, model year and regulatory class, the heavy-duty $PM_{2.5}$ emission factors are also a complete set. No change to the PM emission rates is made between MY 2003 and 2009, because the HD 2007 Rule PM standards are not expected to change in-use emissions for heavy-duty gasoline vehicles. As presented in the next subsection, the simulated age 0-3 HD gasoline MY 1960-2009 emission rates on the UDDS is ~6.6 mg/mile, while the standard for 2008+ spark-ignition vehicles is 20 mg/mile[108]

##### *3.1.2.1.1 Data Sources*

The factor of 1.4 used to convert light-duty gasoline PM rates to heavy-duty rates was developed based on $PM_{2.5}$ emission test results from the four heavy-duty gasoline trucks tested in the CRC E55-E59 test program. The specific data used were collected on the UDDS test cycle. Each of the four vehicles in the sample received two UDDS tests, conducted at different test weights. Other emission tests using different cycles were also available on the same vehicles but were not used in the calculation. The use of the UDDS data enabled the analysis to have a consistent driving cycle. The trucks and tests are described in Table 3-11.

**Table 3-11 Summary of Data Used in HD Gasoline PM Emission Rate Analysis**

| Vehicle | MY | Age | Test cycle | GVWR [lb] | $PM_{2.5}$ mg/mi |
|---|---|---|---|---|---|
| 1 | 2001 | 3 | UDDS | 12,975 | 1.81 |
| | 2001 | 3 | UDDS | 19,463 | 3.61 |
| 2 | 1983 | 21 | UDDS | 9,850 | 43.3 |
| | 1983 | 21 | UDDS | 14,775 | 54.3 |
| 3 | 1993 | 12 | UDDS | 13,000 | 67.1 |
| | 1993 | 12 | UDDS | 19,500 | 108.3 |
| 4 | 1987 | 18 | UDDS | 10,600 | 96.7 |
| | 1987 | 18 | UDDS | 15,900 | 21.5 |

The table shows the four vehicles, two of which are quite old and certified to fairly lenient standards. A third truck is also fairly old at twelve years and certified to an intermediate standard. The fourth is a relatively new truck at age three and certified to a more stringent standard. No trucks in the sample are certified to the Tier 2 or equivalent standards.

Examination of the heavy-duty data shows two distinct levels: vehicle #1 (MY 2001) and the other three vehicles. Because of its lower age (3 years old) and newer model year status, this vehicle has substantially lower PM emission levels than the others, and initially was separated in the analysis. The emissions of the other three vehicles were averaged together to produce these mean results:

|  |  |  |
|---|---|---|
| Mean for Vehicles 2 through 4: | 65.22 mg/mi | Older Group |
| Mean for Vehicle 1: | 2.71 mg/mi | Newer Group |

#### *3.1.2.1.2 LHD*

To compare these rates with rates from light-duty gasoline vehicles, we simulated UDDS cycle emission rates based on MOVES2010b light-duty gas $PM_{2.5}$ emission rates (with normal deterioration assumptions) for light-duty gasoline trucks (regulatory class LDT). The UDDS cycle represents standardized operation for the heavy-duty vehicles.

The simulated light-duty UDDS results were then compared to the results from the four heavy-duty gas trucks in the sample. Emission rates from the following MOVES model year groups and age groups for light-duty trucks were used:

- MY group 1983-1984, age 20+
- MY group 1986-1987, age 15-19
- MY group 1991-1993, age 10-14
- MY group 2001, age 0-3

The simulated $PM_{2.5}$ UDDS emission factors for the <u>older</u> light-duty gas truck group using MOVES2010b are 38.84 mg/mi (ignoring sulfate emissions which are on the order of $1\times10^{-4}$ mg/mile for low sulfur fuels). This value leads to the computation of the ratio: $\frac{65.22\,\frac{\text{mg}}{\text{mile}}}{38.84\,\frac{\text{mg}}{\text{mile}}} = 1.679$.

The simulated $PM_{2.5}$ UDDS emission rates for the <u>newer</u> light-duty gas truck group are 4.687 mg/mi using MOVES2010b. Ignoring sulfate emissions, which are in the order of $1\times10^{-5}$ mg/mile for low sulfur fuels, this value leads to the computation of the ratio: $\frac{2.71\,\frac{\text{mg}}{\text{mile}}}{4.687\,\frac{\text{mg}}{\text{mile}}} = 0.578$.

The newer model year group produces a ratio which is less than one and implied that large trucks produce less $PM_{2.5}$ emissions than smaller trucks. This result is counter-intuitive and is the likely result of a very small sample and a large natural variability in emission results.

Thus, all four data points were retained and averaged together by giving the older model year group a 75 percent weighting and the newer model year group (MY 2001) a 25 percent weighting. This is consistent with the underlying data sample. It produces a final ratio of:

$$\text{Ratio}_{\text{final}} = \text{Ratio}_{\text{older}}\text{WtFrac} + \text{Ratio}_{\text{newer}}(1 - \text{WtFrac}) = 1.679\times0.75 + 0.578\times0.25 = 1.40$$

**Equation 3-3**

We then multiplied this final ratio of 1.40 by the light-duty gasoline truck $PM_{2.5}$ rates to calculate the input emission rates for heavy-duty gasoline $PM_{2.5}$ rates.

This approach is similar to how the LHD THC, CO, and $NO_x$ emissions for MY 2008 and 2009 were estimated by using the light-duty gasoline truck emissions as the basis, with VSP-based light-duty rates applied as STP-based LHD2b3 emission rates.This assumption was deemed an acceptable approximation because the LHD2b3 gasoline vehicles are chassis certified to distance-based standards (g/mi). Accordingly, the vehicle emissions rates are less dependent on the individual power and weight of the vehicle, and should scale approximately to the the g/mile emission standards.[ii]

###### *3.1.2.1.3 MHD and HHD*

For MHD and HHD regulatory classes, the emission rates are based on a $f_{scale}$ of 17.1. The LHD emission rates are based on the light-duty truck rates, with an $f_{scale}$ of 2.06.

We used an indirect approach to derive MHD and HHD $PM_{2.5}$ emission rates from the LHD emission rates. We assume that the relationship of total hydrocarbon (THC) between emission rates based on an $f_{scale}$ of 2.06 and 17.1 is a reasonable surrogate to map $PM_{2.5}$ emission rates from an $f_{scale}$ of 2.06 and 17.1 because both pollutants are products of incomplete fuel combustion and unburned lubricating oil. For the mapping, we first calculated the emission rate ratio for THC emissions for each operating mode between regulatory class MHD (regClassID 46) and LHD2b3 (regClassID 41). We then multiplied this ratio by the EC and nonEC $PM_{2.5}$ emission rates in regulatory class LHD2b3 (regClassID 41) to obtain EC and nonEC emission rates based on the 17.1 $f_{scale}$ used in the heavier regulatory classes (RegClassID 46 and 47). An example of the regulatory class LHD2b3 EC emission rates, 17.1/2.06 $f_{scale}$ THC ratios, and the calculated 17.1 $f_{scale}$ based EC emission rates are displayed in Table 3-12. No reductions are made between 2003 and 2009, because the 2007 HD rule is not anticipated to cause reductions in heavy-duty gasoline $PM_{2.5}$ emissions.

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[ii] This approximation needs to be revisited in the future now that we have updated the mass of LHD vehicles in MOVES3 to range from 3.5 to 7.8 metric tons**Error! Bookmark not defined.**, which differs from the $f_{scale}$ value of 2.06 metric tons.

[jj] For example, the LHD gasoline $PM_{2.5}$ age 0-3 emission rates for model year 2016 are on average 5.5 mg/mile and 7 mg/mile for LHD2b3 and LHD45, respectively, using nationally representative operating mode distributions (See Figure 3-11). In contrast, the MHD gasoline $PM_{2.5}$ rates are lower than the comparable MHD diesel $PM_{2.5}$ emission rates.

**Table 3-12. Derivation of MHD and HHD Elemental Carbon Emission Rates from LHD2b3 Rates using $f_{scale}$ 17.1/2.06 THC emission ratios. Using Model Year 2001 as an Example**

| opModeID | LHD2b3 EC emission rates (mg/hr) | $f_{scale}$ 17.1/2.06 THC emission ratios | MHD and HHD EC emission rates (mg/hr) |
|---|---|---|---|
| 0 | 0.59 | 1.000 | 0.59 |
| 1 | 0.54 | 1.000 | 0.54 |
| 11 | 0.60 | 1.000 | 0.60 |
| 12 | 0.79 | 2.263 | 1.78 |
| 13 | 1.38 | 3.677 | 5.08 |
| 14 | 2.62 | 5.095 | 13.37 |
| 15 | 5.55 | 5.443 | 30.22 |
| 16 | 64.52 | 5.427 | 350.13 |
| 21 | 8.38 | 1.000 | 8.38 |
| 22 | 2.92 | 1.154 | 3.37 |
| 23 | 2.08 | 2.173 | 4.52 |
| 24 | 2.92 | 2.825 | 8.24 |
| 25 | 10.94 | 4.842 | 52.95 |
| 27 | 20.50 | 7.906 | 162.10 |
| 28 | 126.42 | 8.796 | 1,112.05 |
| 29 | 523.16 | 6.471 | 3,385.32 |
| 30 | 2,366.75 | 7.102 | 16,809.50 |
| 33 | 26.59 | 2.121 | 56.40 |
| 35 | 10.76 | 4.780 | 51.42 |
| 37 | 13.29 | 4.010 | 53.28 |
| 38 | 43.61 | 8.979 | 391.56 |
| 39 | 75.73 | 9.522 | 721.06 |
| 40 | 74.96 | 5.300 | 397.26 |

The resulting $PM_{2.5}$ emissions by regulatory class for LHD, MHD and HHD are shown in Figure 3-10. In general, $PM_{2.5}$ emission rates are of similar magnitude for each regulatory class between model year 1980 and 2009. There is significant variation in the model years, with some unexpected trends (e.g., LHD45 has higher emission rates than HHD and MHD for most of these model years). These unexpected trends and variation in the emission rates across model years and regulatory class reflect uncertainties in deriving the pre-2010 emission rates heavy-duty gasoline from light-duty gasoline data and THC surrogate values.

### *3.1.2.2 2010-2026 Model Years*

The real-world PEMS-based emissions measurement data from two engine-certified and one chassis-certified heavy-duty gasoline vehicles used to update the MY 2010 and later THC, CO, and $NO_x$ emission rates (Section 3.1.1.2.1) did not include $PM_{2.5}$. Lacking appropriate PM data by operating mode, we populated the MY 2010+ HD gasoline $PM_{2.5}$ rates by copying MY 2010+ HD diesel rates.

This decision was supported by analysis of laboratory chassis tests. Gravimetric filter-based $PM_{2.5}$ emissions measured from the three HD gasoline vehicles (described in Section 3.1.1.2.1) over various chassis-dynamometer tests are shown in Table 3-13 The average $PM_{2.5}$ rate over all vehicles and test cycles is 1.35 mg/mi. The average $PM_{2.5}$ emission rate for MY 2016 age 0-3, LHD diesel (comparable to the tested gasoline vehicles) using nationally representative operating mode distributions and average speeds is 1.4 mg/mile (See Figure 2-34). Since those numbers were comparable given the uncertainty of the $PM_{2.5}$ emission rates, and no modal HD gasoline $PM_{2.5}$ data was available, we decided to use the HD diesel $PM_{2.5}$ rates for HD gasoline. These rates also include the tampering and mal-maintenance age effects for model year 2010-2026 (see Appendix B.8).

**Table 3-13 $PM_{2.5}$ Emissions for Lab-Based Cycles for HD Gasoline Vehicles[1]**

| Vehicle | FTP | HWFET | LA92 | Supercycle | Average |
|---|---|---|---|---|---|
| 2015 ISUZU NPR | 1.74 | 0.75 | 1.69 | 2.73 | 1.64 |
| 2016 Ford E450 | 0.53 | 0.55 | 1.55 | 2.51 | 1.17 |
| 2017 RAM 3500 | 1.68 | 0.40 | 1.43 | 1.35 | 1.34 |
| Average | 1.36 | 0.57 | 1.53 | 2.24 | 1.35 |

Note:
[1] The vehicles are described in section 3.1.1.2.1.

The draft diesel LHD2b3 and LHD45 $PM_{2.5}$ rates were copied to the gasoline LHD2b3 and LHD45 rates, respectively, from a MOVES version used for the preliminary HD2027 Rule analysis.[108] Since the diesel MHD rates were notably higher than the diesel LHD and HHD rates, the diesel HHD rates were used for gasoline MHD and HHD. Note that after this analysis, the heavy-duty diesel $PM_{2.5}$ emission rates in MOVES were updated to account for the updated HDIUT sample and model year split described in Section 2.1.2.2. For this reason, the zero-mile $PM_{2.5}$ emission rates from heavy-duty gasoline are constant for 2010 and later model years, whereas the heavy-duty diesel $PM_{2.5}$ emission rates are reduced starting in model year 2013, and the heavy-duty gasoline rates for 2013 and later are generally higher than the comparable heavy-duty diesel rates. [jj] Gasoline engine rates for LHD45 and LHD2b3 are higher than the HHD rates for all 2010 and later years, whereas this trend is only seen in the initial model years (2010-2013) of the heavy-duty diesel $PM_{2.5}$ rates from the HDIUT program (Figure 2-34). We intend to update the HD gasoline rates in a future MOVES version to incorporate any new HD gasoline emissions data, or at least to be consistent with the updated MOVES HD diesel rates.

The gasoline rates were copied from the diesel rates as $PM_{2.5}$, and then allocated to EC and nonECPM using gasoline-specific fractions based on the Kansas City study of light-duty cars and trucks as described in the MOVES3 Speciation Report.[1] Because the diesel EC (9.98 percent) and nonEC (90.02 percent) split of $PM_{2.5}$ differs from gasoline EC (14 percent) and nonEC (86 percent), the EC and nonECPM emissions rates stored in the MOVES database are also quite

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[jj] For example, the LHD gasoline $PM_{2.5}$ age 0-3 emission rates for model year 2016 are on average 5.5 mg/mile and 7 mg/mile for LHD2b3 and LHD45, respectively, using nationally representative operating mode distributions (See Figure 3-11). In contrast, the MHD gasoline $PM_{2.5}$ rates are lower than the comparable MHD diesel $PM_{2.5}$ emission rates.

different than the diesel emission rates. Figure 3-12 shows the EC and nonECPM emission rates for gasoline LHD45 vehicles by model year for age 0-3 vehicles.

The MOVES heavy-duty gasoline $PM_{2.5}$ zero mile emission rates are constant for MY 2013 through 2026. There are differences between the 2010-2012 and 2013-2026 model year groups due to different tampering and mal-maintenance assumptions applied to the diesel emission rates (see Section 2.1.2.3), which primarily impact the ages 4-5 and older ages. The Tier 3 rulemaking sets PM FTP emission standards for Class 2b and Class 3 of 8 mg/mile and 10 mg/mile, respectively, which began phase-in starting with model year 2018 vehicles.[52] We did not model reductions in the gasoline $PM_{2.5}$ emission rates with the phase-in of Tier 3, because the data on the tested heavy-duty gasoline vehicles (Table 3-13) suggests that the heavy-duty gasoline vehicles are well in compliance with the Tier 3 standard. In addition, the diesel rates on which the gasoline rates are based also are well in compliance with the Tier 3 standards as discussed in Section 2.1.1.5.5.

#### *3.1.2.3 2027-2060 Model Years*

In order to account for the HD2027 standards in MOVES4, we revised the $PM_{2.5}$ running exhaust emission rates for MY2027+ heavy-duty (LHD45, MHD, HHD) gasoline vehicles using the methodology described in 3.1.1.3.2 for other criteria pollutants.

To meet the PM standards (5 mg/hp-hr for MY2027+), manufacturers are expected to improve fuel control and limit the need for catalyst protection. Therefore, we assumed a 50 percent reduction in $PM_{2.5}$, consistent with the 50 percent more stringent PM standard and revised the MOVES emission rates using Equation 3-2.

### *3.1.2.4 Model Year Trends*

Figure 3-10 and Figure 3-11 display the $PM_{2.5}$ rates by model year and regulatory class for age 0-3 age group estimated in grams per mile (g/mile) using nationally representative operating mode distributions and average speeds.

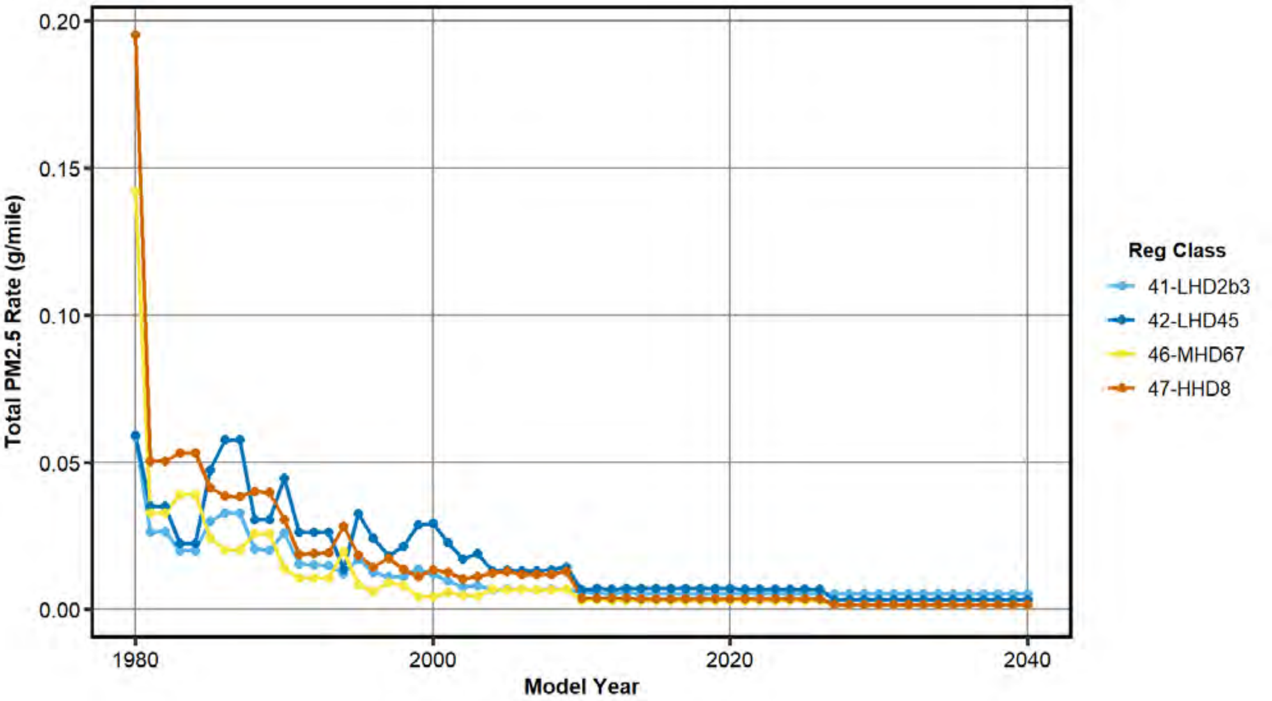

**Figure 3-10. Base running emission rates for $PM_{2.5}$ from age 0-3 gasoline heavy-duty vehicles averaged over a nationally representative operating mode distribution**

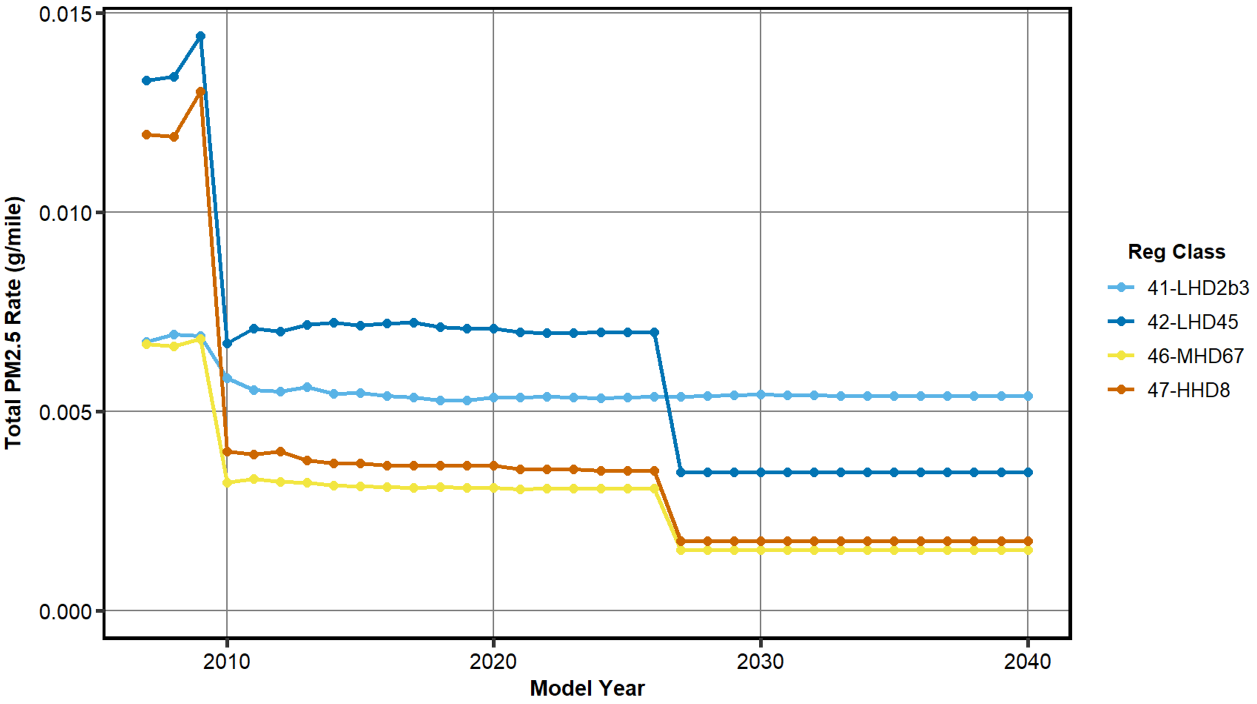

**Figure 3-11 Base running emission rates for $PM_{2.5}$ from age 0-3 gasoline heavy-duty vehicles for MY2007-2040 averaged over a nationally representative operating mode distribution**

Figure 3-12 shows the $PM_{2.5}$ emission rates separated into elemental carbon (EC) and non-elemental carbon (nonEC) fractions for age 0-3 HHD gasoline vehicles using nationally representative operating mode distributions and average speeds. The EC/PM fractions are dominated by the nonEC across all model years.

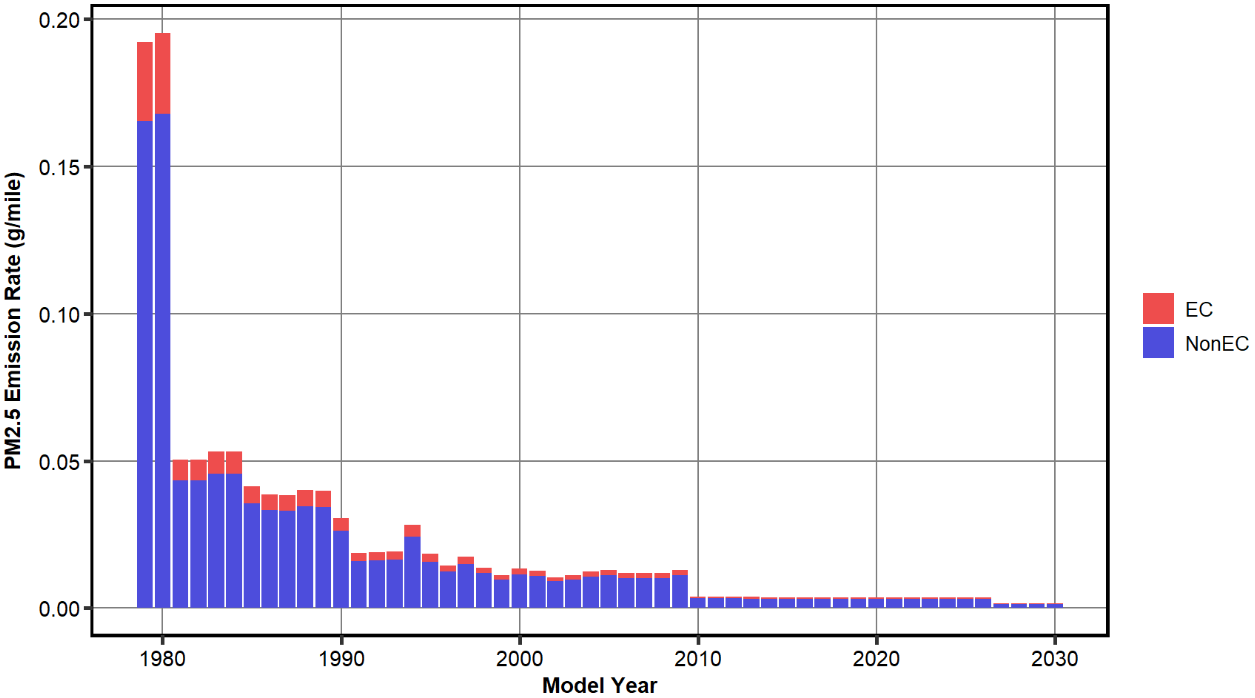

**Figure 3-12 Heavy Duty Gasoline Running Exhaust $PM_{2.5}$ Emission Rates by Elemental Carbon and Non-Elemental Carbon (nonEC) Fractions for the 0-3 Age Group by Model Year and Regulatory Class using Nationally Representative Operating Mode Distributions**

## *3.1.3 Energy*

### *3.1.3.1 1960-2009 Model Years*

#### *3.1.3.1.1 LHD*

The energy rates for gasoline LHD (LHD2b3 and LHD45 regulatory classes) pre-2009 energy rates are unchanged from MOVES2010a. In MOVES2010a, the energy rates for LHD2b3 and LHD45, along with the light-duty regulatory classes, were consolidated across weight classes, engine size and engine technologies, as discussed in the MOVES2010a energy updates report[57].

#### *3.1.3.1.2 MHD and HHD*

The energy rates for gasoline MHD and HHD pre-2009 energy rates are unchanged from MOVES2014. The rates were developed using the same data set we used to develop the THC, CO, and $NO_x$ exhaust emission rates. Similar to the analysis for the diesel running exhaust energy rates, we made no distinction in rates by model year, age, or regulatory class. To calculate energy rates (kJ/hour) from $CO_2$ emissions, we used a heating value (HV) of 122,893 kJ/gallon and $CO_2$ fuel-specific emission factor ($f_{CO2}$) of 8,788 g/gallon for gasoline (see Equation 3-20). STP was calculated using Equation 1-6. Figure 3-13 presents the gasoline running exhaust energy rates in MOVES for these regulatory classes.

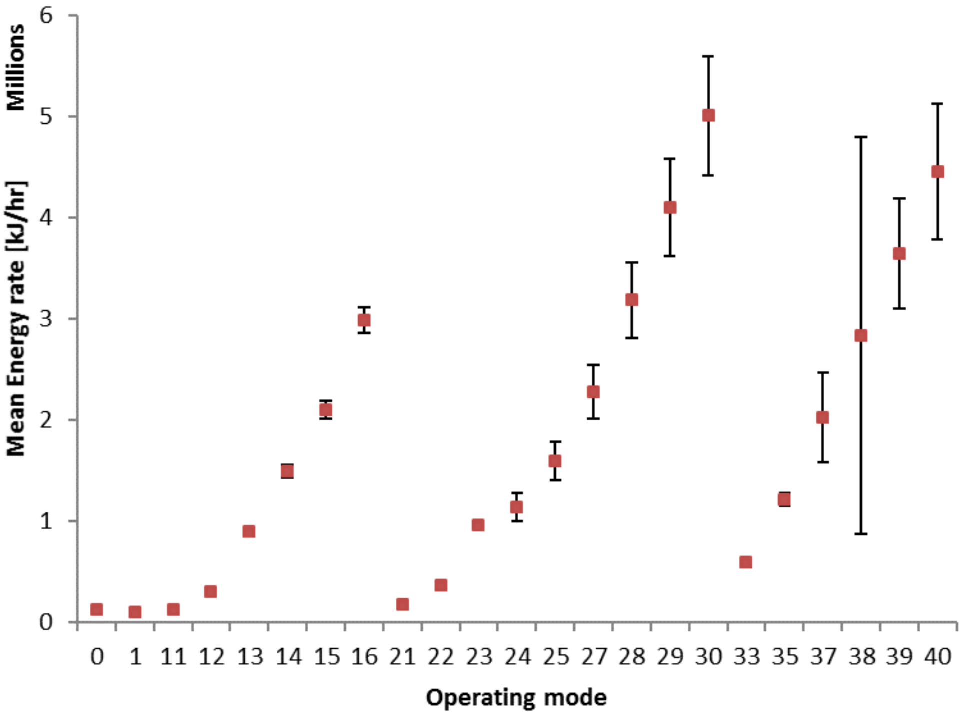

**Figure 3-13. Gasoline Running Exhaust Energy Rates for MHD (1960-2009) and HHD (1960-2009)**

A linear extrapolation to determine rates at the highest operating modes in each speed range was performed analogously to diesel energy and $NO_x$ rates (see Section 2.1.1.4.2).

#### *3.1.3.2 2010-2060 Model Years*

The real-world PEMS-based emissions measurement data from two engine-certified and one chassis-certified heavy-duty gasoline vehicles used to update the THC, CO, and $NO_x$ emission rates (Section 3.1.1.2.1) included $CO_2$ emissions data which was used to update the energy rates. The energy rates are derived using the measured $CO_2$ values and the conventional gasoline specific values for carbon content (0.0196 g/KJ) and oxidation fraction (1.0) and the molecular mass of $CO_2$ (44), and atomic mass of Carbon (12). These values are described in the MOVES GHG and Energy Rates report.[3]

When calculating the operating mode-based energy rates for high-power operating modes with limited or missing data, we extrapolated using STP values using the method described in Section 2.1.1.4.2.

For LHD2b3, the energy rates are identical for MY 2010-2013. For LHD45, MHD, and HHD, the energy rates are identical for MY 2010-2015.

### *3.1.3.2.1 LHD2b3 2014-2060 Model Years*

The LHD2b3 gasoline energy rates are reduced to incorporate the impacts of the Phase 1 and Phase 2 Heavy-duty Greenhouse Gas rules. The LHD2b3 gasoline rates are adjusted from the 2010-2013 model year rates using the gasoline reductions documented in Table 3-14 (Phase 1) and Table 2-33 (Phase 2) in Section 2.1.4.3.

**Table 3-14 Estimated Total Vehicle Reductions in Energy Consumption Rates for LHD2b3 Gasoline Vehicles due to the HD GHG Phase 1 Program**

| Regulatory Class | Model years | Reduction from MY 2013 Energy Rates |
|---|---|---|
| LHD2b3 | 2014 | 1.5% |
|  | 2015 | 2% |
|  | 2016 | 4% |
|  | 2017 | 6% |
|  | 2018-2020 | 10% |

The HD GHG Phase 1 reductions for the affected model years are incorporated into the energy rates in the *emissionRate* table in the MOVES database. The adjustments for HD GHG Phase 2 are applied at run-time using the values in the *emissionRateAdjustment* table in the MOVES database.

### *3.1.3.2.2 LHD45, MHD, and HHD 2016-2060 Model Years*

Updates to the energy rates were made to the heavy-duty gasoline energy rates for model years 2016-2020 based on the Phase 1 Medium and Heavy-Duty Greenhouse Gas Rule[111] discussed in Section 2.1.4.3 and shown in Table 3-15.

**Table 3-15 Heavy-Duty Gasoline Reductions due to the Heavy-Duty GHG Phase 1 Rule[111]**

| **Regulatory Class** | **Model Years** | **$CO_2$ Reduction From 2013 Baseline** |
|---|---|---|
| LHD45, MHD, HHD | 2016-2020 | 5% |

The energy rates for 2021 model year and beyond were updated in MOVES3 to reflect the $CO_2$ emission reductions expected from the Heavy-Duty GHG Phase 2 rule, as shown in Table 3-16, which have separate reductions for vocational and combination trucks.

As noted above, the HD GHG Phase 2 reductions to energy rates are not incorporated into the energy rates in the *emissionRate* table in the MOVES database, but are applied at run-time using the values in the *emissionRateAdjustment* table in the MOVES database.

**Table 3-16 Heavy-Duty Gasoline Reductions due to the Heavy-Duty GHG Phase 2 Rule**[112]

| Source Type (SourceTypeID) | Regulatory Class | Model Years | $CO_2$ Reduction from 2017 Baseline |
|---|---|---|---|
| Other Bus, School Bus, Refuse Truck, Single-Unit Short-Haul, Single-Unit Long-Haul, Motorhomes (41, 43, 51, 52, 53, 54) | LHD45 | 2021-2023 | 6.9% |
| | | 2024-2026 | 9.8% |
| | | 2027+ | 13.3% |
| Other Bus, School Bus, Refuse Truck, Single-Unit Short-Haul, Single-Unit Long-Haul, Motorhomes (41, 43, 51, 52, 53, 54) | MHD and HHD | 2021-2023 | 6.9% |
| | | 2024-2026 | 9.8% |
| | | 2027+ | 13.3% |
| Short-haul Combination Trucks (61) | MHD and HHD | 2018-2020 | 0.6% |
| | | 2021-2023 | 7.4% |
| | | 2024-2026 | 11.9% |
| | | 2027+ | 15.0% |

#### *3.1.3.3 Model Year Trends*

Figure 3-14 and Figure 3-15 display the $CO_2$ (g/mile) emission rates and fuel economy values calculated from the energy rates using the carbon content and energy density conversion factors for conventional gasoline[kk] as documented in the MOVES3 Greenhouse Gas and Energy Report.[3] The $CO_2$ (g/mile) emission rates and fuel economy values are estimated using nationally representative operating mode distribution and average speed values. Figure 3-15 displays the significant decrease in fuel economy in model year 2010 due to the updated data and analysis incorporated for model year 2010 trucks. The large change in fuel economy is not anticipated to be real, but an artifact of the using the updated data and analysis.

The LHD emission rates show substantial variability in the early model years (pre-1985) – we do not expect LHD vehicles to have lower fuel economy than MHD and HHD for these years, but have not revisited these emission rates due to the small number of pre-1985 gasoline vehicles remaining in the onroad fleet. As discussed in Section 2.1.4.1, the detailed methodology used in MOVES2004 (which modeled different emission rates according to vehicle weights, engine technologies, and engine sizes) introduced variability into the energy rates within the current MOVES regulatory class emission rates for pre-2010 LHD.

The figures display that, since model year 2010, there are decreasing trends in $CO_2$ (g/mile) with corresponding increases in fuel economy, due to the lower energy rates as well as lower source

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[kk] Using the energy content of conventional gasoline (E0), the fuel economy is ~4% higher than is estimated using the energy content of E10 gasoline. Note that E10 is estimated to be the dominant gasoline fuel sold in 2008 and later. MOVES has the same carbon content for both fuels, so there is no estimated impact on the $CO_2$ g/mile.

mass values and improved road load coefficients estimated with the Phase 1 and Phase 2 heavy-duty greenhouse gas rulemaking. The energy rates by operating mode are constant for model year 2027-2060. However, some small differences in $CO_2$ (g/mile) or fuel economy values observed within model year groups and regulatory classes with the same energy rates are due to differences in the nationally representative operating modes, which are different across model years due to changing fractions of regulatory classes among different source types.

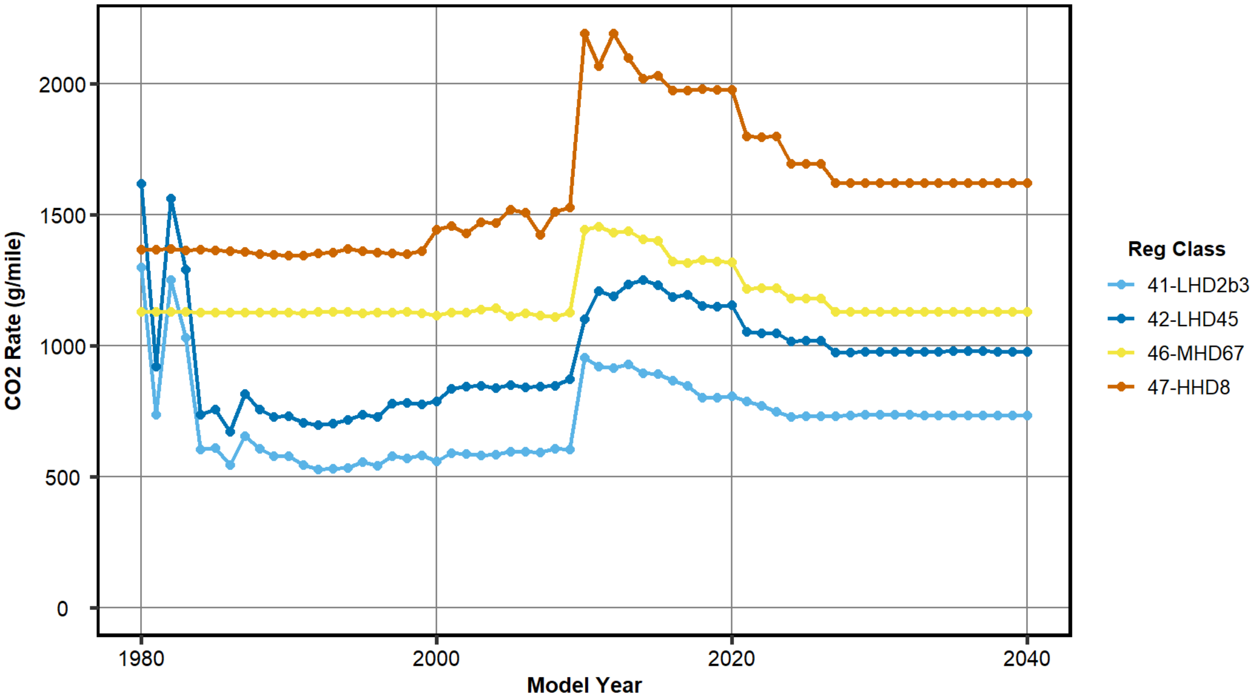

**Figure 3-14. Base running emission rates for $CO_2$ from age 0-3 gasoline heavy-duty vehicles averaged over a nationally representative operating mode distribution**

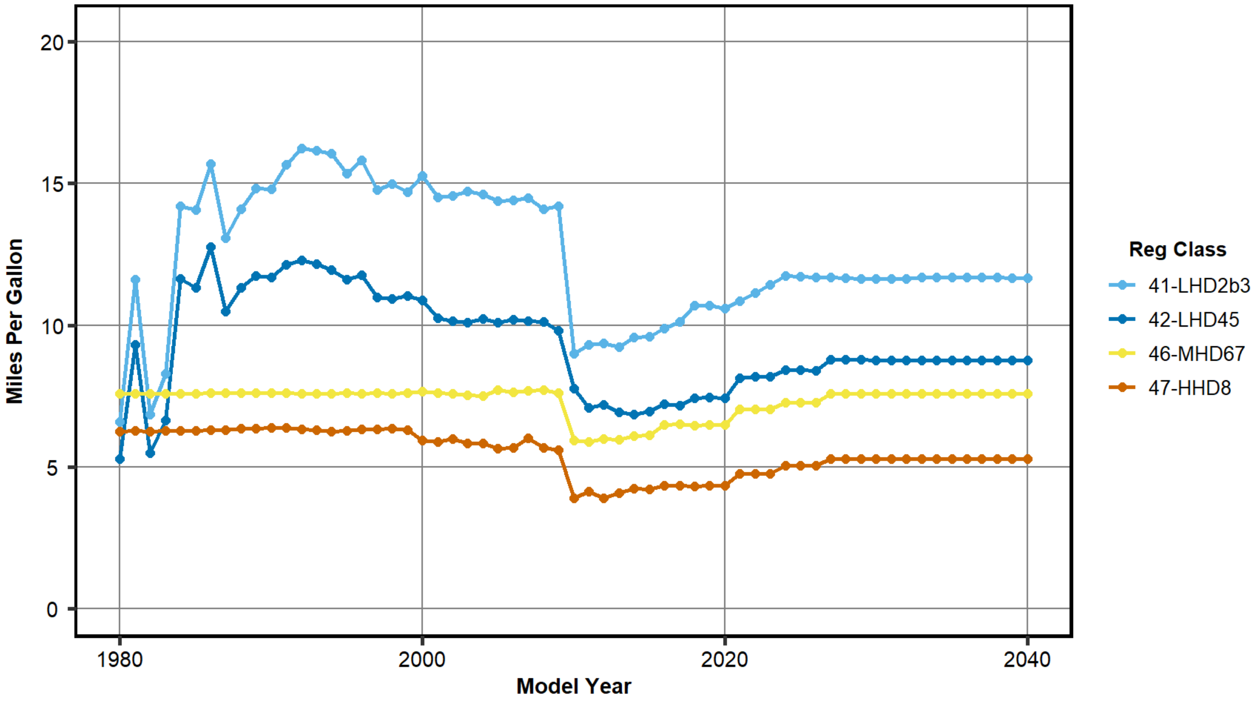

**Figure 3-15. Fuel economy for age 0-3 gasoline heavy-duty vehicles averaged over a nationally representative operating mode distribution**

## *3.2 Start Emissions*

Representative in-use data on vehicle start emissions for heavy-duty gasoline vehicles is even less common than running data. While some data was available (Table 3-18, Table 3-23), the MOVES analysis also relies on deterioration patterns from light-duty vehicles, as well as ratios to the relevant engine emission standards. For LHD2b3 gasoline vehicles, manufacturers comply with chassis (g/mile) emission standards. For the larger regulatory classes, engine emission standards apply. We used the engine emission standards to estimate differences in emissions between the LHD2b3 regulatory class and the heavier regulatory classes. Most of this analysis has been carried over from MOVES2010b and MOVES2014, but the cold start emissions for LHD45, MHD, and HHD gasoline engines of 2008 model year and later have been updated for MOVES3 based on recent certification data.

The heavy-duty spark ignition engine emissions standards[113] for the Federal Test Procedure (FTP) are shown in Table 3-17. Note that the standards for model years 1990 through 2004 for CO and THC vary by weight class, but not by model year, whereas those for $NO_x$ vary by model year, but not by weight class. Also, for model years 2005-2007, a single standard is applied for $NMHC+NO_x$, but by 2008, separate but lower standards are again in effect. Note also that by model year 2008, the standards for the three gaseous pollutants are the same across regulatory class.

**Table 3-17 FTP Standards (g/hp-hr) for Heavy-Duty Gasoline Engines for Model Years 1990-2008+[113]**

| Model-Year Group | GVWR ≤ 14,000 lb (LHD2b3) | | | GVWR > 14,000 lb | | |
|---|---|---|---|---|---|---|
| | CO | NMHC[1] | $NO_x$ | CO | NMHC[1] | $NO_x$ |
| 1990 | 14.4 | 1.1 | 6.0 | 37.1 | 1.9 | 6.0 |
| 1991-1997 | 14.4 | 1.1 | 5.0 | 37.1 | 1.9 | 5.0 |
| 1998-2004 | 14.4 | 1.1 | 4.0 | 37.1 | 1.9 | 4.0 |
| 2005-2007 | 14.4 | 1.01 | | 37.1 | 1.0[2] | |
| 2008+ | 14.4 | 0.14 | 0.20 | 14.4 | 0.14 | 0.20 |

Note:

[1] Non-methane hydrocarbons standard expressed as NMHC + $NO_x$

### 3.2.1 *THC, CO, and $NO_x$*

The heavy-duty gasoline vehicle start emissions for MOVES regulatory class LHD2b3 and LHD45 vehicles are discussed in Section 3.2.1.1. Section 3.2.1.2 discusses the development of the rates for MOVES regulatory class MHD and HHD gasoline vehicles. In Section 3.2.1.3, we summarize and compare the two sets of start emission rates for THC, CO and $NO_x$. Soak time adjustments are detailed in Section 3.2.3.

#### *3.2.1.1 LHD2b3*

For LHD2b3, the gaseous emission rates for MY 1960-2004 are based on data analysis of test data, and the MY 2005+ emission rates are based on ratioing the pre-2005 rates based on the emission standards.

##### *3.2.1.1.1 1960-2004 Model Years*

To develop start emission rates for MY 1960-2004 heavy-duty gasoline-fueled vehicles, we extracted data available in EPA's Mobile-Source Observation Database (MSOD).[104] These data represent aggregate test results for heavy-duty spark-ignition (gasoline powered) engines measured on the Federal Test Procedure (FTP) cycle. The GVWR for all trucks was between 8,500 and 14,000 lbs, placing all trucks in the LHD2b3 regulatory class. The 1960-2004 LHD2b3 start rates are unchanged from LHD2b3 start emission rates in MOVES2010b.

Table 3-18 shows the model-year by age classification for the data. The model year groups in the table were designed based on the progression in $NO_x$ standards between MY 1990 and 2004. Standards for CO and THC are stable over this period, until MY 2004, when a combined NMHC+ $NO_x$ standard was introduced. However, no measurements for gasoline HD trucks were available for MY2004 and later.

Start emissions are not dependent on power, and therefore, the emission rates do not need to be calculated differently to distinguish different $f_{scale}$ values as was done for running exhaust rates. As discussed later, start emission rates are separated by regulatory classes to account for differences in the emission standards and/or available test data.

**Table 3-18 Availability of Emissions Start Data by Model-Year Group and Age Group for LHD2b3 Vehicles**

| Model-year Group | Age Group (Years) | | | | | Total |
|---|---|---|---|---|---|---|
| | 0-3 | 4-5 | 6-7 | 8-9 | 10-14 | |
| 1960-1989 | | | | 19 | 22 | 41 |
| 1990 | | | 1 | 29 | | 30 |
| 1991-1997 | 73 | 59 | 32 | 4 | | 168 |
| 1998-2004 | 8 | | | | | 8 |
| Total | 81 | 59 | 33 | 52 | 22 | 247 |

#### *3.2.1.1.2 Estimation of Mean Rates*

As with light-duty vehicles, we estimated the "cold-start" as the mass from the cold-start phase of the FTP (bag 1) less the "hot-start" phase (Bag 3). As a preliminary exploration of the data, we averaged by model year group and age group and produced the graphs shown in Appendix F. Sample sizes were small overall and very small in some cases (e.g., 1990, age 6-7) and the behavior of the averages was somewhat erratic. In contrast to light-duty vehicle emissions, strong model-year effects were not apparent. This may not be surprising for CO or THC, given the uniformity of standards throughout. This result was more surprising for $NO_x$, but model year trends are no more evident for $NO_x$ than for the other two. Broadly speaking, it appeared that an age trend may be evident.

If we assume that the underlying population distributions are approximately log-normal, we can visualize the data in ways that illustrate underlying relationships. As a first step, we calculated geometric mean emissions, for purposes of comparison to the arithmetic means calculated by simply averaging the data. Based on the assumption of log-normality, the geometric mean ($x_g$) was calculated in terms of the logarithmic mean ($x_l$) as shown in Equation 3-4.

$$\bar{x}_g = e^{\ln \bar{x}_l} \qquad \textbf{Equation 3-4}$$

This measure was not appropriate for use as an emission rate, but was useful in that it represents the "center" of the skewed parent distribution. As such, it was less strongly influenced by unusually high or outlying measurements than the arithmetic means. In general, the small differences between geometric means and arithmetic means suggest that the distributions represented by the data do not show strong skew in most cases. Because evidence from light-duty vehicles suggested that emissions distributions should be strongly skewed, this result implied that these data are not representative of "real-world" emissions for these vehicles. This conclusion appeared to be reinforced by the values in Figure F-3 which represent the "logarithmic standard deviation" calculated by model-year and age groups. This measure ($s_l$), is the standard deviation of natural logarithm of emissions ($x_l$). The values of $s_l$ were highly variable, and generally less than 0.8, showing that the degree of skew in the data was also highly variable as well as generally low for emissions data; e.g., corresponding values for light-duty running emissions are generally 1.0 or greater. Overall, review of the geometric means confirmed the impression of age trends in the CO and THC results, and the general lack of an age trend in the $NO_x$ results.

Given the conclusion that the data as such are probably unrepresentative, assuming the log-normal parent distributions allowed us to re-estimate the arithmetic mean after assuming reasonable values for $s_l$. For this calculation, we assumed values of 0.9 for CO and THC and 1.2 for $NO_x$. These values approximate the maxima seen in these data.

The re-estimated arithmetic means were calculated from the geometric means, by adding a term that represents the influence of the "dirtier" or "higher-emitting" vehicles, or the "upper tail of the distribution," as shown in Equation 3-5.

$$\bar{x}_a = \bar{x}_g e^{\frac{s_l^2}{2}}$$

**Equation 3-5**

For purposes of rate development using these data, we concluded that a model-year group effect was not evident and re-averaged all data by age group alone. Results of the coarser averaging are presented in Figure 3-16 with the arithmetic mean (directly calculated and re-estimated) and geometric means shown separately.

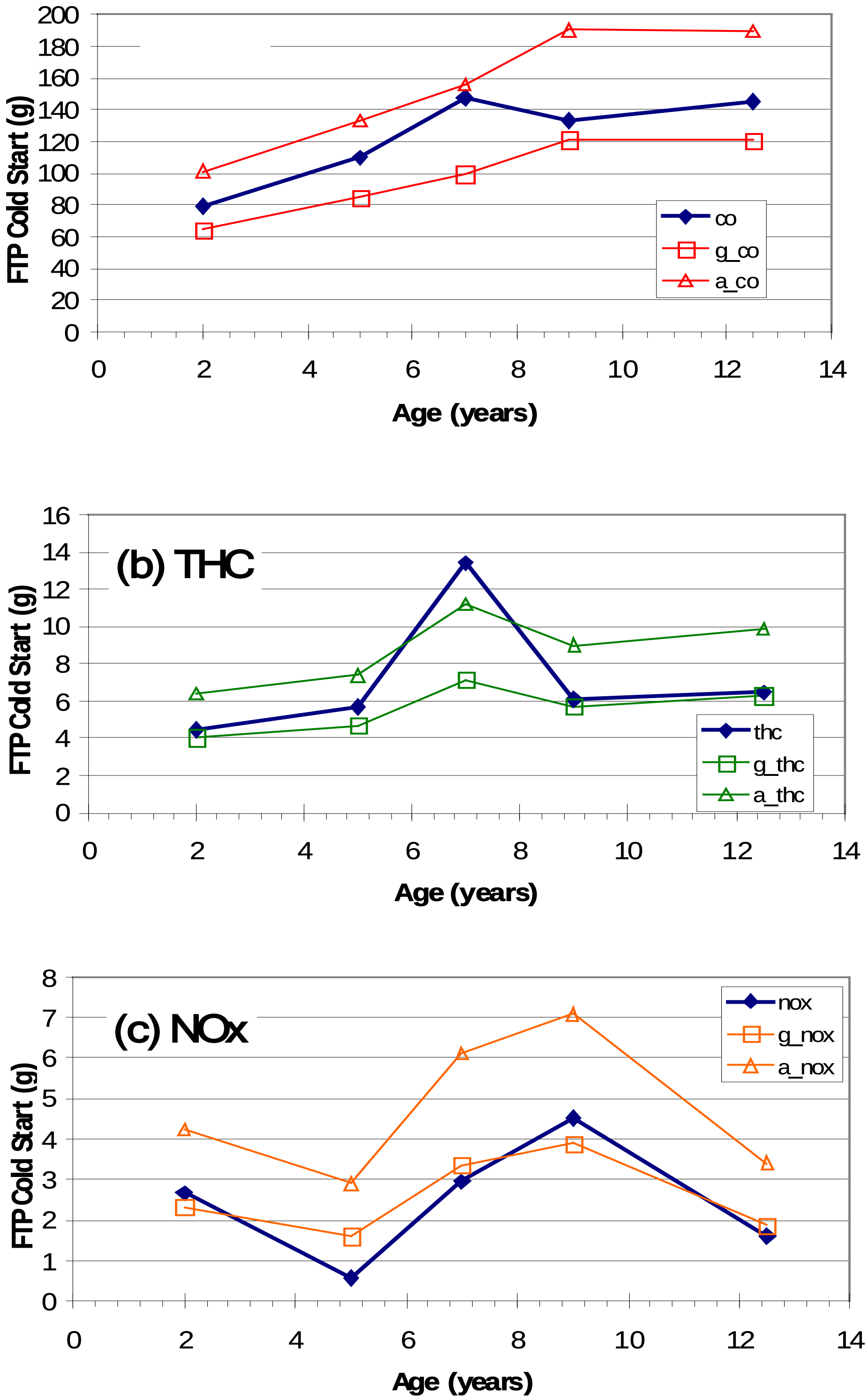

**Figure 3-16. Cold-start FTP Emissions for Heavy-Duty Gasoline Trucks, Averaged by Age Group Only (g = Geometric Mean, a= Arithmetic Mean Recalculated from $x_l$ and $s_l$)**

We then addressed the question of the projection of age trends. As a general principle, we did not allow emissions to decline with age. For THC and $NO_x$, we assumed the emission rates stabilized at the maximum level reached at the 6-7 and 8-9 age groups, respectively as shown in Table 3-19. For CO emissions, we kept the age trends as they were, since there was only a slight decrease in CO emissions after the maximum was reached in the 8-9 age group.

###### *3.2.1.1.3 Estimation of Uncertainty*

We calculated standard errors for each mean in a manner consistent with the re-calculation of the arithmetic means. Because the (arithmetic) means were recalculated with assumed values of $s_l$, it was necessary to re-estimate corresponding standard deviations for the parent distribution $s$, as shown in Equation 3-6.

$$s = \sqrt{x_g^2 e^{s^2}(e^{s^2} - 1)} \qquad \textbf{Equation 3-6}$$

After recalculating the standard deviations, the calculation of corresponding standard errors was simple. Because each vehicle is represented by only one data point, there was no within-vehicle variability to consider, and the standard error could be calculated as $s/\sqrt{n}$. We divided the standard errors by their respective means to obtain CV-of-the-mean or “relative standard error.” Means, standard deviations and uncertainties are presented in Table 3-19 and in Figure 3-17. Note that these results represent only “cold-start” rates (opModeID 108). Soak time adjustments other start opModes are detailed in Section 3.2.3.

**Table 3-19. Cold-Start Emission Rates (g) for Heavy-Duty Gasoline Trucks, by Age Group (Italicized Values Replicated from Previous Age Groups)**

| Age Group | *n* | Pollutant | | |
|---|---|---|---|---|
| | | CO | THC | $NO_x$ |
| *Means* | | | | |
| 0-3 | 81 | 101.2 | 6.39 | 4.23 |
| 4-5 | 59 | 133.0 | 7.40 | 5.18 |
| 6-7 | 33 | 155.9 | 11.21 | 6.12 |
| 8-9 | 52 | 190.3 | *11.21* | 7.08 |
| 10-14 | 22 | 189.1 | *11.21* | *7.08* |
| *Standard Deviations* | | | | |
| 0-3 | | 108.1 | 6.82 | 8.55 |
| 4-5 | | 142.0 | 7.90 | |
| 6-7 | | 166.5 | 11.98 | 12.39 |
| 8-9 | | 203.2 | *11.98* | 14.32 |
| 10-14 | | 202.0 | *11.98* | *14.32* |
| *Standard Errors* | | | | |
| 0-3 | | 12.01 | 0.758 | 0.951 |
| 4-5 | | 18.49 | 1.03 | 1.18 |
| 6-7 | | 28.98 | 2.08 | 2.16 |
| 8-9 | | 28.18 | *2.08* | 1.99 |
| 10-14 | | 43.06 | *2.08* | *1.99* |

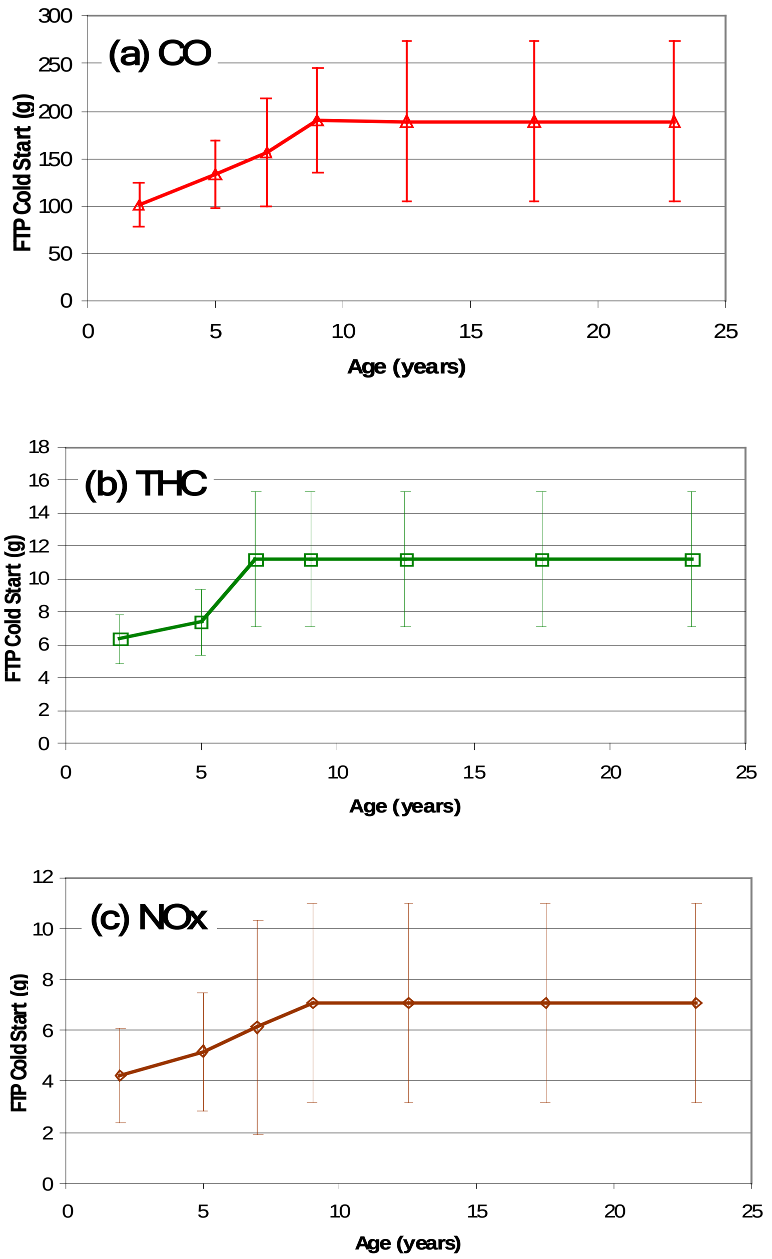

**Figure 3-17. Cold-Start Emission Rates for Heavy-Duty Gasoline Trucks, with 95 Percent Confidence Intervals**

The steps described so far involved reduction and analysis of the available emissions data. In the next step, we describe approaches used to impute rates for model years not represented in these data. For purposes of analysis, we delineated four model year groups: 1960-2004, 2005-2007, 2008-2017 and 2018 and later. The rates above were used for the 1960-2004 model year group. We describe the derivation of rates for the remaining groups below.

#### *3.2.1.1.4 2005-2007 Model Years*

For the 2005-2017 model year emission rates, we applied reductions to the 1960-2004 emission rates, by comparing the standards between the two model year ranges. For CO, the approach was simple. We applied the age zero values in Table 3-19 to the 2005-2007 model year group. The rationale for this approach is that the CO standards do not change over the full range of model years considered.

For THC and $NO_x$, we imputed values for the 2005-2007 and 2008-2017 model-year groups by multiplying the age zero values for the 1960-2004 emission rates in Table 3-19 by ratios expressed in terms of the applicable standards. Starting in 2005, a combined THC+$NO_x$ standard was introduced. It was necessary for modeling purposes to partition the standard into THC and $NO_x$ components. We assumed that the proportions of NMHC and $NO_x$ would be similar to those in the 2008 standards, which separate NMHC and $NO_x$ while reducing both.

We calculated the THC value by multiplying the 1960-2004 value by the fraction $f_{\mathrm{HC}}$ as shown in Equation 3-7.

$$f_{\mathrm{HC}} = \frac{\left(\dfrac{0.14\ \mathrm{g/hp\text{-}hr}}{(0.14+0.20)\ \mathrm{g/hp\text{-}hr}}\right)\left(1.0\ \mathrm{g/hp\text{-}hr}\right)}{1.1\ \mathrm{g/hp\text{-}hr}} = 0.37$$

**Equation 3-7**

This ratio represents the component of the 2005 combined standard attributed to NMHC. We calculated the corresponding value for $NO_x$ as shown in Equation 3-8.

$$f_{\mathrm{NOx}} = \frac{\left(\dfrac{0.20\ \mathrm{g/hp} - \mathrm{hr}}{(0.14+0.20)\ \mathrm{g/hp} - \mathrm{hr}}\right)1.0\ \mathrm{g/hp\text{-}hr}}{4.0\ \mathrm{g/hp\text{-}hr}} = 0.147$$

**Equation 3-8**

For these heavy-duty rates, we neglected the THC/NMHC conversions, to which we gave attention for light-duty.

#### *3.2.1.1.5 2008-2017 Model Years*

For the 2008-2017 model years, the approach to projecting rates was modified to adopt two refinements developed for light-duty rates. First, start emission rates for the LHD2b3 gasoline vehicles were estimated from composite rates by applying the “start split-ratio” shown in Table 3-6 to a set of rates representing light-duty trucks in Tier-2/Bin 8. Second, we updated the deterioration effects for start $NO_x$ exhaust from MOVES2014[114], by applying the ratios shown in Table 3-20.

**Table 3-20. Deterioration Reduction Ratio for 2008-2017 gasoline LHD2b3 $NO_x$ Starts**

| ageGroupID | Deterioration Reduction Ratio |
|---|---|
| 3 | 1.00 |
| 405 | 0.85 |
| 607 | 0.79 |
| 809 | 0.73 |
| 1014 | 0.62 |
| 1519 | 0.62 |
| 2099 | 0.62 |

These ratios were initially developed for LDT in a draft version of MOVES3[115] but the LD age effects were further updated prior to MOVES3 release. [ll]

For THC and CO, the multiplicative age effects are unchanged from the effects from MOVES2014.[116] The resulting multiplicative age effects for start emission rates for LHD2b3 vehicles used in MOVES3 for model years 2009-2017 are shown in Table 3-21. The start emission rates for model year 2008 are estimated by averaging the MY 2007 and 2009 emission rates across all age groups and operating modes assuming a phase-in of 50% of the Tier 2 standards and the HD 2007 Rule in MY 2008 as we assumed for LHD2b3 gasoline running emissions as discussed in Section 3.1.1.2.1. The relative age effects for LHD2b3 MY 2008 and MY 2009-2017 are shown Figure 3-21.

**Table 3-21 Multiplicative Age Effect Used for Start Emissions for Gasoline LHD2b3 Vehicles for 2009-2017 Model Years Adopted from the Deterioration Effects for Light-Duty Trucks**

| ageGroupID | THC | CO | $NO_x$ |
|---|---|---|---|
| 3 | 1 | 1 | 1 |
| 405 | 1.65 | 1.93 | 1.47 |
| 607 | 2.20 | 2.36 | 1.74 |
| 809 | 2.68 | 2.54 | 2.01 |
| 1014 | 3.30 | 3.00 | 2.00 |
| 1519 | 3.66 | 3.35 | 2.26 |
| 2099 | 4.42 | 4.06 | 2.56 |

Using these deterioration rates for starts results in start emission rates for MY 2010+ gasoline LHD2b3 vehicles having a higher relative deterioration than running emission rates (compared to Table 3-3).[mm] We recognize this is inconsistent with our knowledge of light-duty start deterioration.[9] We plan to address this data gap with data collected on LHD2b3 in future versions of MOVES.

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[ll] In MOVES3, we incorporated additional updates to the start deterioration rates (including for $NO_x$) for LDT as documented in the MOVES3 light-duty exhaust emission rate report.[9]

[mm] The updated MY 2010 and later heavy-duty running gasoline rates (including LHD2b3) use the heavy-duty age effects as discussed in Section 3.1.1.2.1 and 3.1.1.3.1.

#### *3.2.1.1.6 Incorporating Tier 3 Standards: 2018 and Later Model Years*

Emission rates representing the phase-in of Tier-3 standards for the start-exhaust process were developed for MOVES2014 as described in gasoline running emissions section of the MOVES2014 heavy-duty exhaust report.[109] Like the MY 2008-2017 rates, the LHD2b3 Tier 3 start rates are based on light-duty truck emission rates scaled to higher emission standards for the LHD2b3 regulatory class. The reduction in start emissions due to Tier 3 is relatively lower than the reductions in running emissions presented in Section 3.1.1.3.1.

The LHD2b3 start rates during and following the Tier 3 phase-in have relatively lower deterioration than the start rates for the model years preceding the onset of the phase-in (MY 2008-2017) as documented in the MOVES2014 light-duty exhaust report.[116,nn] For MOVES3, we adjusted the $NO_x$ start emission rates by applying the deterioration ratios in Table 3-20 to the MOVES2014 $NO_x$ start rates. The multiplicative age effects for LHD2b3 cold start rates for THC, CO and $NO_x$ after the complete phase-in of Tier 3 phase-in model year 2022 are shown below in Table 3-22 The age effects of the phase-in years of Tier 3 (MY 2018-2021) are a weighted average of the MY 2010-2017 and the MY 2022 start emission rates using the phase-in assumptions documented in the MOVES2014 heavy-duty exhaust report.[109]

**Table 3-22 Multiplicative Age Effect Used for Start Emissions for Gasoline LHD2b3 Vehicles for 2022-2060 Model Years**

| ageGroupID | THC | CO | $NO_x$ |
|---|---|---|---|
| 3 | 1 | 1 | 1 |
| 405 | 1.54 | 1.73 | 1.38 |
| 607 | 1.94 | 1.97 | 1.57 |
| 809 | 2.26 | 1.96 | 1.74 |
| 1014 | 2.78 | 2.33 | 1.72 |
| 1519 | 3.09 | 2.59 | 1.95 |
| 2099 | 3.73 | 3.15 | 2.21 |

We do not model any impact of the HD2027 rule on the Gasoline LHD2b3 start emissions because HD2027 standards affect only engine-certified gasoline light-heavy-duty vehicles (modelled as MOVES3 regulatory class LHD45).

#### *3.2.1.1.7 Inspection and Maintenance Program Effects for LHD Gasoline Vehicles*

In MOVES3.1, we updated the meanBaseRateIM values for THC, CO, and $NO_x$ start exhaust emission rates to better reflect the I/M programs for LHD2b3 gasoline vehicles.
Due to a lack of data and analysis, in MOVES3.0.4 and earlier versions of MOVES, we assumed no benefit from I/M programs for starts. However, as explained in for running emissions in Section 3.1.1.3.2, we updated the gasoline LHD2b3 HC, CO and $NO_x$ start values for MeanBaseRateIM in

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[nn] In MOVES3, the deterioration effects for all model year light-duty vehicles were updated on updated data and analysis. The light-duty Tier 3 emission rates no longer have different deterioration values. We plan to update the LHD2b3 start deterioration effects to be consistent with the light-duty vehicles in an upcoming version of MOVES.

MOVES3.1 and later to reflect the same proportional reduction (that is meanBaseRateIM/meanBaseRate) that we model for each operating mode bin and age for the light-duty trucks. For more detail on the meanBaseRate and meanBaseRateIM values for light-duty trucks, see the MOVES3 LD report.[9]

#### 3.2.1.2 *LHD45, MHD, and HHD*

The start emission rates from LHD45, MHD, and HHD gasoline vehicles differ from the rates for LHD2b3. The following two subsections document the emission rates for 1960-2007 model years (Section 3.2.1.2.1) and 2008+ model years (Section 3.2.1.2.2).

##### *3.2.1.2.1 1960-2007 Model Years*

Since bag data were lacking for MY 1960-2007 vehicles in classes LHD45 and MHD, we estimated cold start values relative to the LHD2b3 start emission rates.

For CO and THC, we estimated rates for the heavier vehicles by multiplying them by ratios of standards for the heavier class to those for the lighter class. The value of the ratio for CO based on 1990-2004 model year standards is shown in Equation 3-9.

$$f_{\mathrm{CO}} = \frac{37.1\,\mathrm{g/hp\text{-}hr}}{14.4\,\mathrm{g/hp\text{-}hr}} = 2.58$$ **Equation 3-9**

The corresponding ratio for THC for 1990-2004 model year vehicles is 1.73, as shown in Equation 3-10.

$$f_{\mathrm{HC}} = \frac{1.9\,\mathrm{g/hp\text{-}hr}}{1.1\,\mathrm{g/hp\text{-}hr}} = 1.73$$ **Equation 3-10**

The ratios derived in the previous two equations (2.58 and 1.73) were applied to estimate the start emission rates for 1960-2004 and 2005-2007 model year groups for the LHD45, MHD, and HHD gasoline vehicles (Table 3-25 ). Note that the ratios for CO and THC do not vary by model year group because the standards do not; See Table 3-16.

For MY 1960-2007, $NO_X$ start emission rates for medium and heavy-duty vehicles are equal to the LHD2b3 start emission rates, because the same standards apply to all the HD regulatory classes. The approaches for all three regulatory classes in all model years are summarized in Table 3-25 .

##### *3.2.1.2.2 2008-2060 Model Years*

The cold start emissions for 2008 model year and later LHD45, MHD, and HHD gasoline engines have been updated for MOVES3 based on new data. Similar to the approach taken for light-duty vehicles and for diesel vehicles (see Section 2.2.1.2), the cold start emissions are calculated as the difference in emissions between a test cycle with a cold start and the same test cycle with a hot start. Heavy-duty gasoline engines are certified using the Heavy-Duty Gasoline Engine Federal Test Procedure (FTP) cycle.[117] The test procedure for certification requires that manufacturers run the engine over the FTP cycle with a cold start and then repeat the cycle with a warm start. Starting in model year 2016, EPA began collecting certification data that contained separate cold and hot results for each engine certified. The data that was analyzed for this MOVES3 update includes the following engine families from the 2016 and 2017 model years shown in Table 3-23.

**Table 3-23 Engine Data Analyzed to Revise the Cold Start Emission Rates for HD Gasoline Engines**

| Category | Number of Engines | Manufacturers |
|---|---|---|
| LHD45, MHD, HHD Gasoline | 3 | Ford, GM, Powertrain Integration |

The certification data was used to determine the grams emitted per cold start using Equation 3-11.

$$\begin{aligned}\text{Grams per Start} \\ &= [\text{Cold FTP Emission Results } (g/(hp-hr)) \\ &- \text{Hot FTP Emission Results}(g/(hp-hr))] \\ &* \text{FTP Cycle Work } (hp-hr)\end{aligned}$$

**Equation 3-11**

The amount of work (hp-hr) performed over the FTP cycle is not provided as part of the certification data submitted by the manufacturers to EPA. We only had cycle work data from one 19.3 hp-hr HD gasoline engine. While we acknowledge that FTP cycle work is unique to each engine because it is created based on the engine's maximum speed, curb idle speed, and the maximum torque curve, we estimated cycle work for all HD gasoline engines using our one engine data source.

The analysis of cold and hot start FTP emissions data from three HD gasoline engines determined the grams per start for THC, CO, $NO_x$, and $PM_{2.5}$. The mean and standard deviation of the THC, CO, $NO_x$, and $PM_{2.5}$ emission levels for the three engines are shown in Table 3-24. The MY 2016 and 2017 engines ranged in displacement between 5.4 and 7.2 liters, and ranged in rated power between 297 and 332 HP. The new default cold start emissions values for MOVES3 are the mean values shown in Table 3-24. The THC, $NO_x$ and $PM_{2.5}$ cold start emissions for HD gasoline engines are higher compared to MOVES2014, while the CO emissions are lower.

**Table 3-24 Cold Start Emissions for MY 2008 and Later Heavy-Duty Gasoline Engines**

| Grams per Start | THC | CO | $NO_x$ | $PM_{2.5}$ |
|---|---|---|---|---|
| Mean | 5.57 | 31.5 | 1.88 | 0.084 |
| Standard Deviation | 0.6 | 6.36 | 1.04 | 0.049 |

We applied the same relative age deterioration for the 2008+ model years starts for THC, CO and $PM_{2.5}$ as was used for the previous model year groups (which is based on the gasoline LHD2b3 1960-2004 model years). For $NO_x$, we applied the relative age deterioration as was used for LHD2b3 vehicles for MY 2008 and later vehicles shown in Table 3-21 and Table 3-22.[oo] The start rates for THC, CO, and $NO_x$ for this model year group for each age are graphed in Figure 3-21.

---

[oo] In a future update to MOVES, we intend to update the HD gasoline deterioration to be consistent with the updates made to the LD rates in MOVES3, as well as apply a consistent approach for HD gasoline emissions deterioration for both start and running deterioration and for all pollutants.

We do not model any impact of the HD2027 rule on the Gasoline LHD45, MHD or HHD start emissions due to the lack of sufficient data to model the impact.

### *3.2.1.3 Summary*

Table 3-25 summarizes the data and methods used to estimate THC, CO, and $NO_x$ start emission rates from heavy-duty gasoline vehicles as discussed in Sections 3.2.1.1 and 3.2.1.2. Figure 3-18 through Figure 3-20 displays the cold start (operating mode 108) emission rates across model years for heavy-duty gasoline vehicles.

**Table 3-25 Summary of Cold Start Emission Rates for Heavy-Duty Gasoline Vehicles**

| Regulatory Class | Model Year Group | CO | THC | $NO_x$ |
|---|---|---|---|---|
| LHD2b3 | 1960-2004 | Data analysis, values from Table 3-19 | | |
| | 2005-2007 | Data analysis, values from Table 3-19 | Reduce in proportion to standards from 1960-2004 | |
| | 2008 - 2017 | Section 3.2.1.1.5 Based on Tier 2 Bin 8 LDT rates and deterioration | | |
| | 2018 + | Section 3.2.1.1.6. Based on LDT rates, adjusted to account for Tier 3 standards and assumed lower deterioration. No change for HD2027 rule. | | |
| LHD45, MHD, HHD | 1960-2004 | Increased in proportion to standards from LHD2b3 | | Same values as LHD2b3 |
| | 2005-2007 | Increased in proportion to standards from LHD2b3 | | Same values as LHD2b3 |
| | 2008 + | Updated based on FTP certification data, deterioration based on the 1960-2004 LHD2b3 data. No change for HD2027 rule. | | Updated based on FTP certification data, deterioration based on the 2008 + LHD2b3 vehicles. No change for HD2027 rule. |

Note:
Soak time adjustments are detailed in Section 3.2.3.

The outcomes of the methods described in the table above are summarized graphically in Figure 3-18 through Figure 3-20 for cold-start emissions. The decline in start emissions with the adoption of more stringent standards begins with the reduction in model year 2005 and ends at the completion of the phase-in of Tier 3 standards for LHD2b3 vehicles in model year 2022. Note that there is a slight increase in THC start emissions for LHD45 vehicles in model year 2008, which is the first model year using the new start certification data discussed above in Section 3.2.1.1.5.

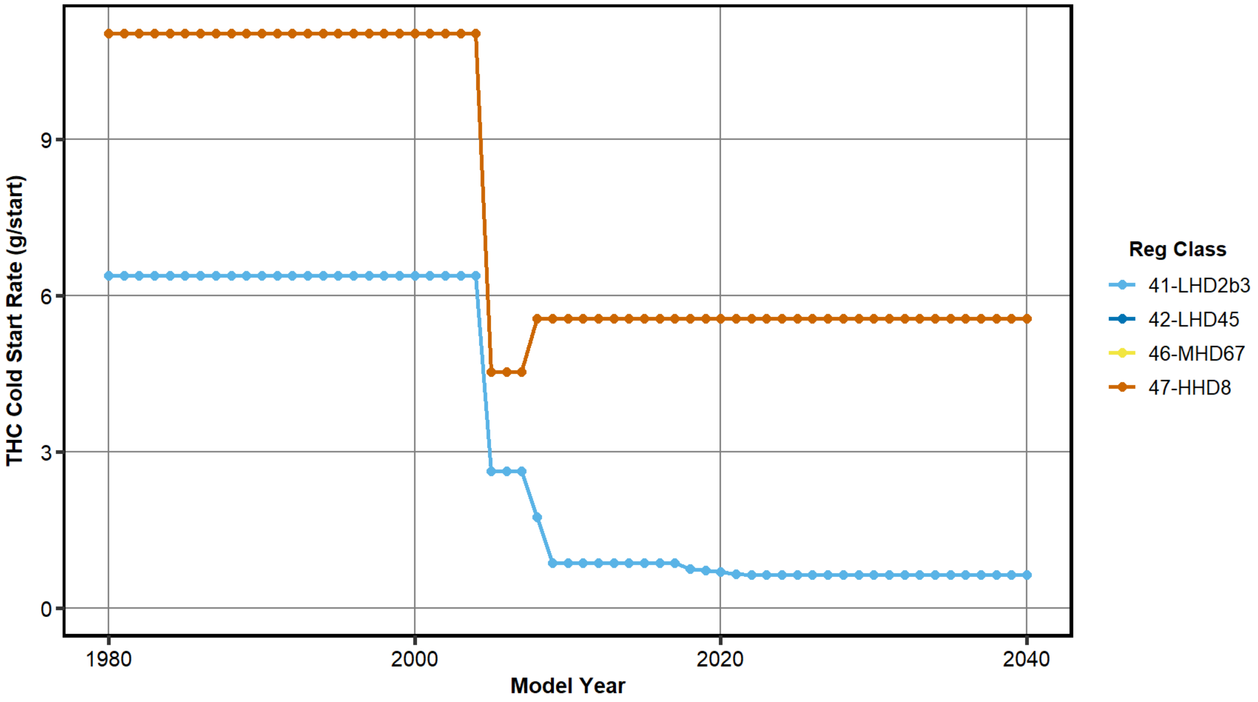

**Figure 3-18 Heavy-duty Gasoline THC Cold-Start Emission Rates (g/start) for Age Group 0-3 By Regulatory Class and Model Year. LHD45, MHD and HHD are equivalent.**

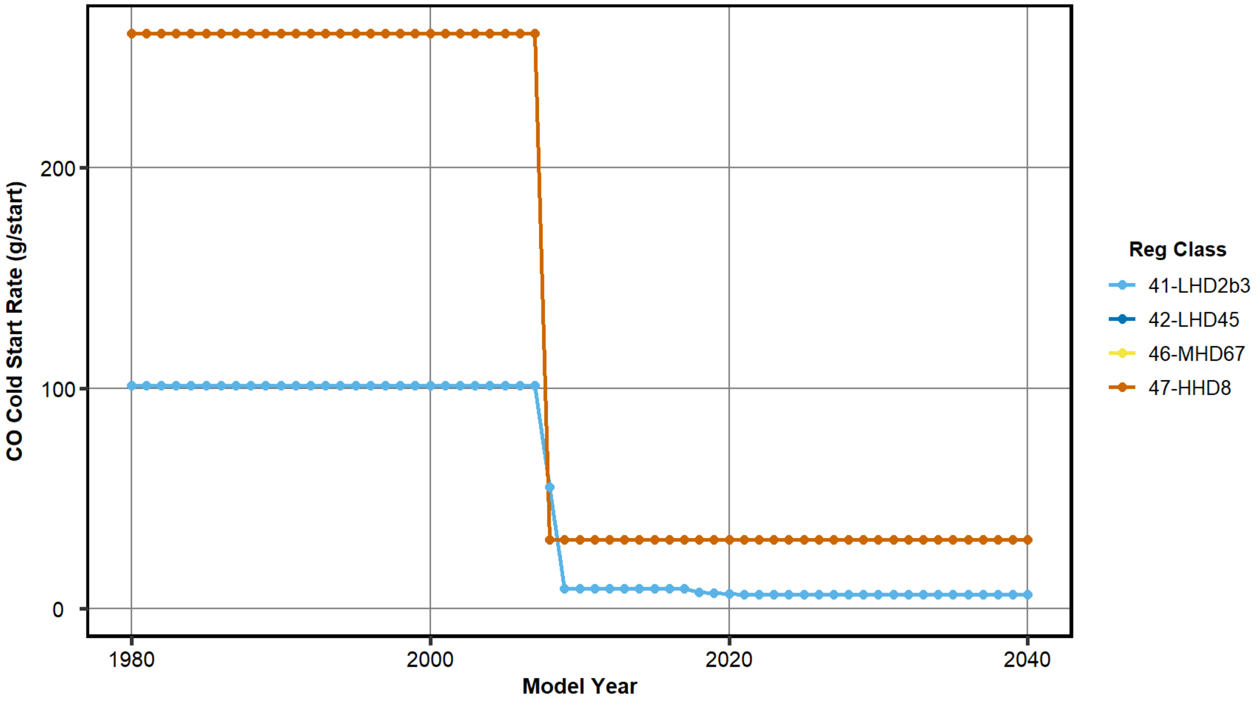

**Figure 3-19 Heavy-duty Gasoline CO Cold-Start Emission Rates (g/start) for Age Group 0-3 By Regulatory Class and Model Year. LHD45, MHD and HHD are equivalent.**

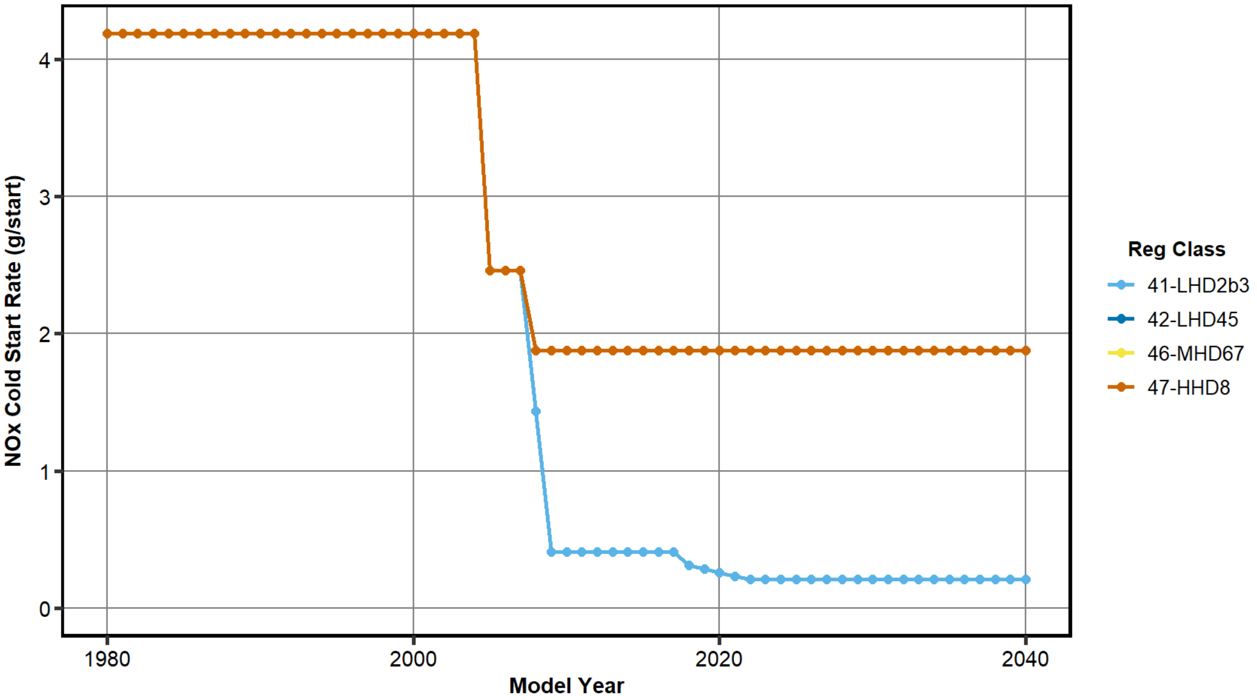

**Figure 3-20 Heavy-duty Gasoline NO$_x$ Cold-Start Emission Rates (g/start) for Age Group 0-3 By Regulatory Class and Model Year. LHD45, MHD and HHD are equivalent.**

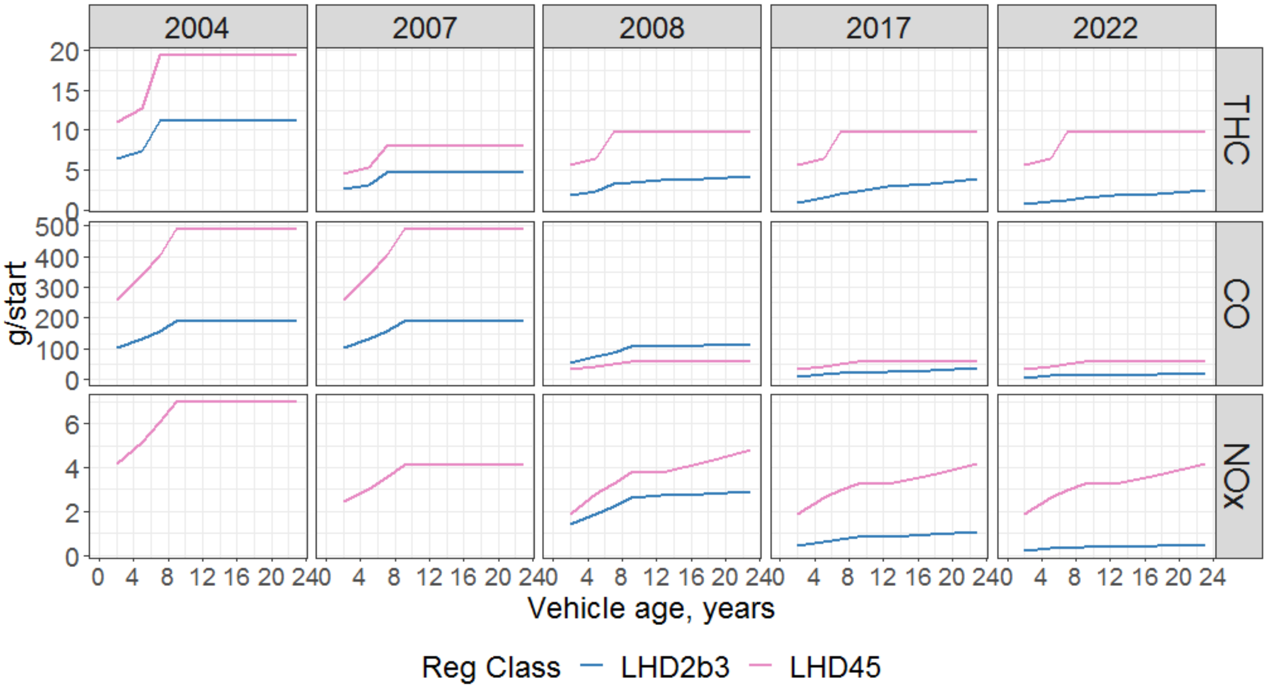

**Figure 3-21 Heavy-duty Gasoline Cold-Start Rates (opModeID 108) vs. Vehicle Age for Select Model Years LHD45, MHD and HHD are equivalent.**

### 3.2.2 Particulate Matter ($PM_{2.5}$)

Data on $PM_{2.5}$ start emissions from heavy-duty gasoline vehicles were unavailable, so these emissions were extrapolated as described below.

#### 3.2.2.1 LHD2b3

For LHD2b3 vehicles, we used the multiplicative factor from the running exhaust emissions analysis of 1.40 (derived in Equation 3-3 in Section 3.1.2.1.2) to scale up start emission rates from light-duty trucks (LDT) for model years 1960-2003.

For 2004+ model years, the LHD2b3 start emission rates are 1.4 times the model year 2003 LDT emission rates. We project constant start emissions using the 2003 model year emission rates rather than scaling to the LDT $PM_{2.5}$ rates with the 2004 and later model years because the LD rates increase due to the updated data on emission rates and sales penetration of gasoline direct injection technology, and subsequently, decrease beginning in model year 2018 with the implementation of the Tier 3 Vehicle Emissions and Fuel Standards Program. We are not confident that such patterns will apply to HD gasoline due to limited data regarding heavy-duty $PM_{2.5}$ rates and uncertainty regarding (a) the expected penetration of gasoline direct injection technology in heavy-duty gasoline vehicles and (b) the impact of Tier 3 on HD gasoline $PM_{2.5}$ emissions (see Section 3.1.2.2). We do not model any impact of the HD2027 rule on the Gasoline LHD2b3 start emissions because HD2027 standards affect only engine-certified gasoline light-heavy-duty vehicles (modelled as LHD45 in MOVES4 regulatory class).

The start $PM_{2.5}$ emission rates for heavy-duty gasoline vehicles exhibit the same relative effects of soak time, and deterioration as the LDT $PM_{2.5}$ start emission rates.

#### 3.2.2.2 LHD45, MHD, and HHD

Due to a lack of $PM_{2.5}$ start data, we use the same $PM_{2.5}$ emission rates for LHD2b3 for all heavy-duty gasoline for MY 1960-2007. For MY 2008 and later, for LHD45, MHD, and HHD, we updated the $PM_{2.5}$ start emissions data using certification data presented in Table 3-24. This causes the start emissions to increase significantly for LHD45, MHD, and HHD between MY 2007 and MY 2008 as shown in Figure 3-22. We do not model any impact of the HD2027 rule on the gasoline LHD45, MHD or HHD start emissions due to the lack of sufficient data to model the impact.

We continue to apply the same age adjustments to the start $PM_{2.5}$ as the LDT emissions due to lack of data. We caution there is considerable uncertainty in the start heavy-duty gasoline $PM_{2.5}$ emission rates, especially for pre-2007 model years.

#### 3.2.2.1 Model Year Summary

Figure 3-22 displays the cold start emission rates across model years for heavy-duty gasoline vehicles. For the LHD45, MHD and HHD vehicles, we have more confidence in the emission rates from the 2010 and later model year groups since they are based on certification results from these engines.

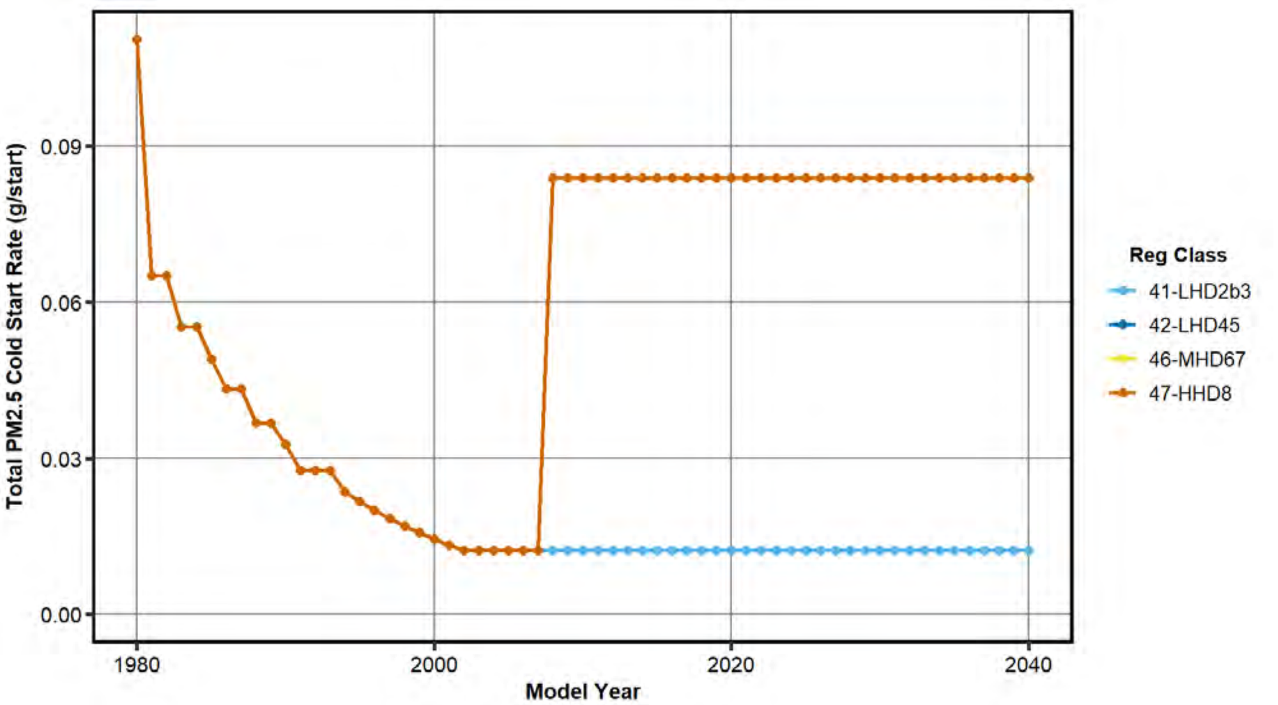

**Figure 3-22. Heavy-duty Gasoline $PM_{2.5}$ Cold-Start Emission Rates (g/start) for Age Group 0-3 By Regulatory Class and Model Year. LHD45, MHD and HHD are equivalent**

### *3.2.3 Soak Time Adjustments*

To estimate the start emissions at various soak lengths, we apply the same soak fractions to the cold start emissions that we apply to 1996-2003 MY light-duty gasoline vehicle as documented in the light-duty emission rate report[9] and shown in Figure 2-61. These are the same adjustments used for heavy-duty gasoline vehicles in MOVES2014.

To evaluate these adjustment ratios for MOVES, we considered recent start emission rate data from one heavy-duty gasoline truck. The data was gathered using PEMS using the procedure and methods discussed in Section 2.2.3.2. The vehicle tested was a 2012 MY box truck with a gasoline engine. Figure 3-23 shows the results from the testing as compared to the MOVES adjustments. Because the trend in the soak time effects is similar to the values used in MOVES2014, and because we only had new data from one truck, MOVES4 retains the start emission adjustment ratios used in MOVES2014.

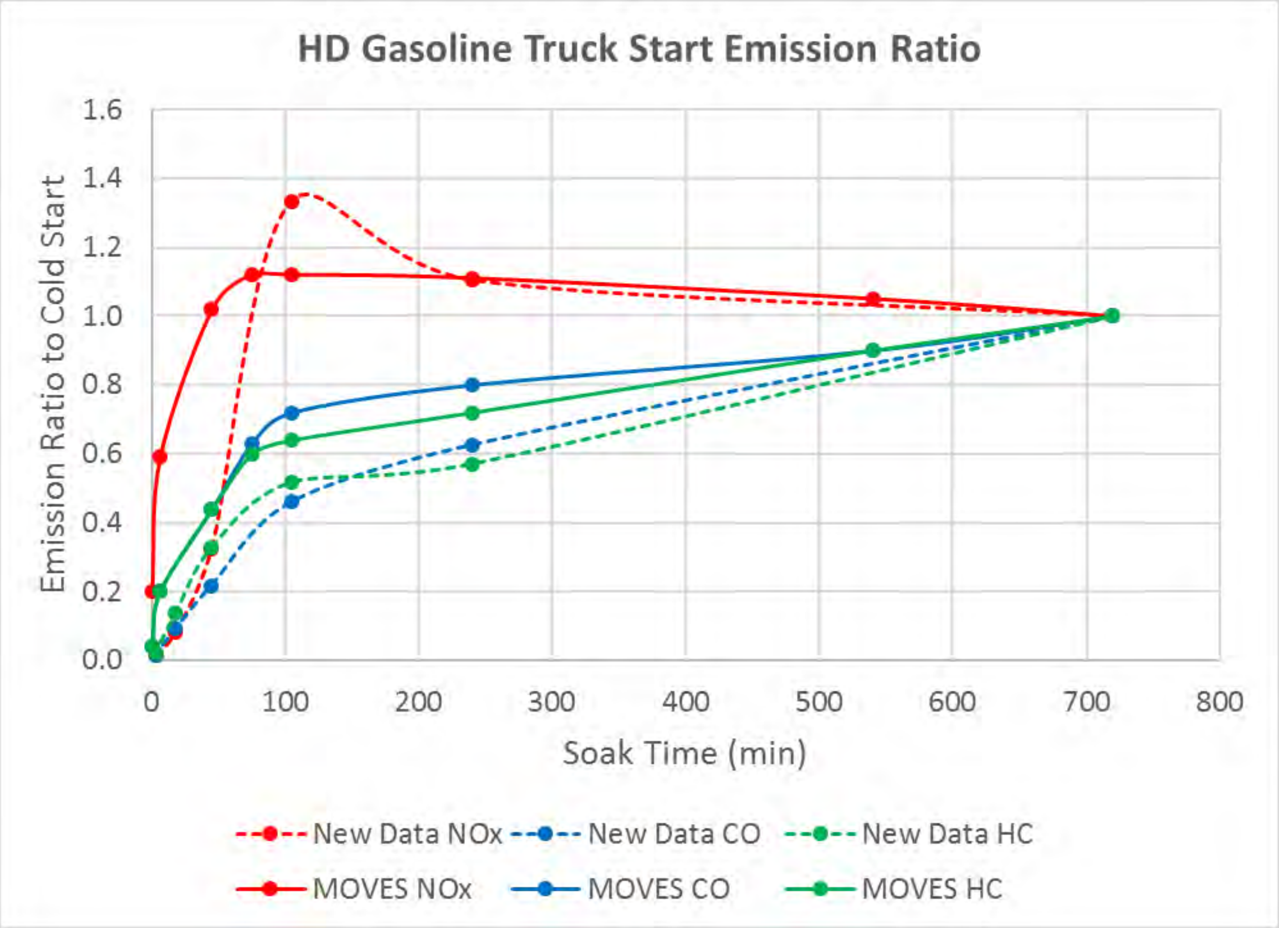

**Figure 3-23 HD Gasoline Start Emission Ratio Compared to Recent Data**

### *3.2.4 Start Energy Rates*

The heavy-duty gasoline start energy rates were originally derived in MOVES2004, and updated in MOVES2010a as described in the corresponding reports.[57] Figure 2-32 displays the $CO_2$ (g/mile) emission rates for cold start (operating mode 108) calculated from the energy rates using the carbon content of conventional gasoline as documented in the MOVES3 Greenhouse Gas and Energy Report.[3] As shown, there is substantial variability in the start rates between 1974 and 2000. As discussed in Section 2.1.4.1, the detailed methodology used in MOVES2004 (which modeled different emission rates according to vehicle weights, engine technologies, and engine sizes) introduced variability into the energy rate within the current MOVES regulatory class emission rates.

Table 3-26 displays the relative contribution of running and start operation to total energy consumption from the heavy-duty gasoline regulatory classes from a national run for calendar year 2016. Like diesel vehicles, starts from gasoline vehicles are estimated to be a relatively small contributor to the total energy demand of vehicle operation. Due to the small contribution to the total energy inventory, we have not prioritized updating the heavy-duty gasoline start emissions rates.

**Table 3-26 Relative Contribution of Total Energy Consumption from Each Pollutant Process by Regulatory Class for Heavy-Duty Gasoline Vehicles in Calendar Year 2016**

| processID | processName | LHD2b3 | LHD45 | MHD | HHD |
|---|---|---|---|---|---|
| 1 | Running Exhaust | 97.8% | 99.2% | 99.0% | 99.2% |
| 2 | Start Exhaust | 2.2% | 0.8% | 1.0% | 0.8% |

The HD gasoline start energy rates are reduced for shorter soak times using the same factors for diesel vehicles, as presented in Table 2-51. The energy rates also increase with cold temperatures using the temperature effects documented in the 2004 Energy Report.[71]

The start energy rates include the projected impact of the Phase 1 Heavy-Duty GHG standards, which began phasing-in in 2014 and have the same reductions as the running energy rates, as presented in Table 2-30 and Table 2-32. As discussed in Section 2.2.4, the start energy rates are not projected to change due to the HD GHG Phase 2 standards.

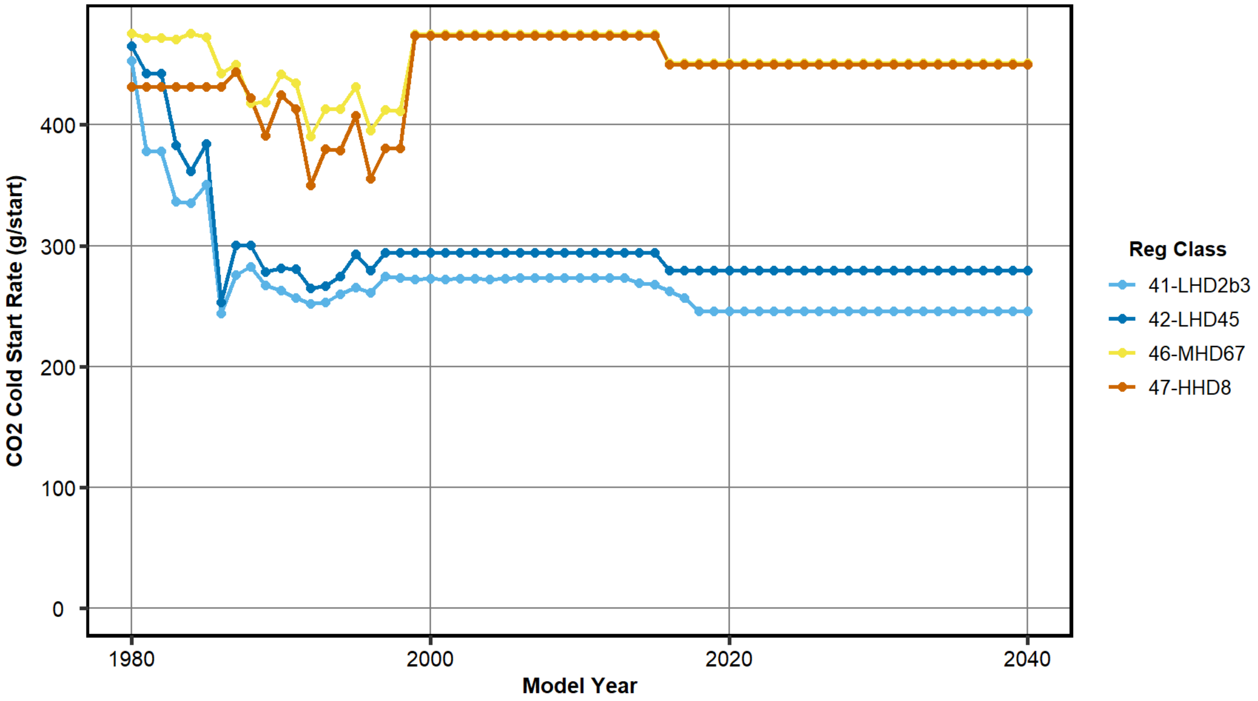

**Figure 3-24 Heavy-Duty Gasoline Cold Start $CO_2$ Emission Rates (g/start) by Model Year and Regulatory Class (OpmodeID 108)**

# 4 Heavy-Duty Compressed Natural Gas Exhaust Emissions

While natural gas lacks the ubiquitous fueling infrastructure of gasoline, compressed natural gas (CNG), propane, and liquefied natural gas have grown as transportation fuels for public transit, government, and corporate fleets. Such fleets typically utilize centralized, privately-owned refueling stations. Fleet vehicles are operated as back-to-base, which means the vehicles return to the same base location each day for refueling. Within this segment, some of the most prevalent use of in CNG vehicles has occurred among city transit bus fleets and in solid waste collection or refuse truck fleets.[118] Figure 4-1 displays the fraction of heavy-duty CNG fueled-vehicles by source type and model year estimated in the default national activity database in MOVES3.[6]

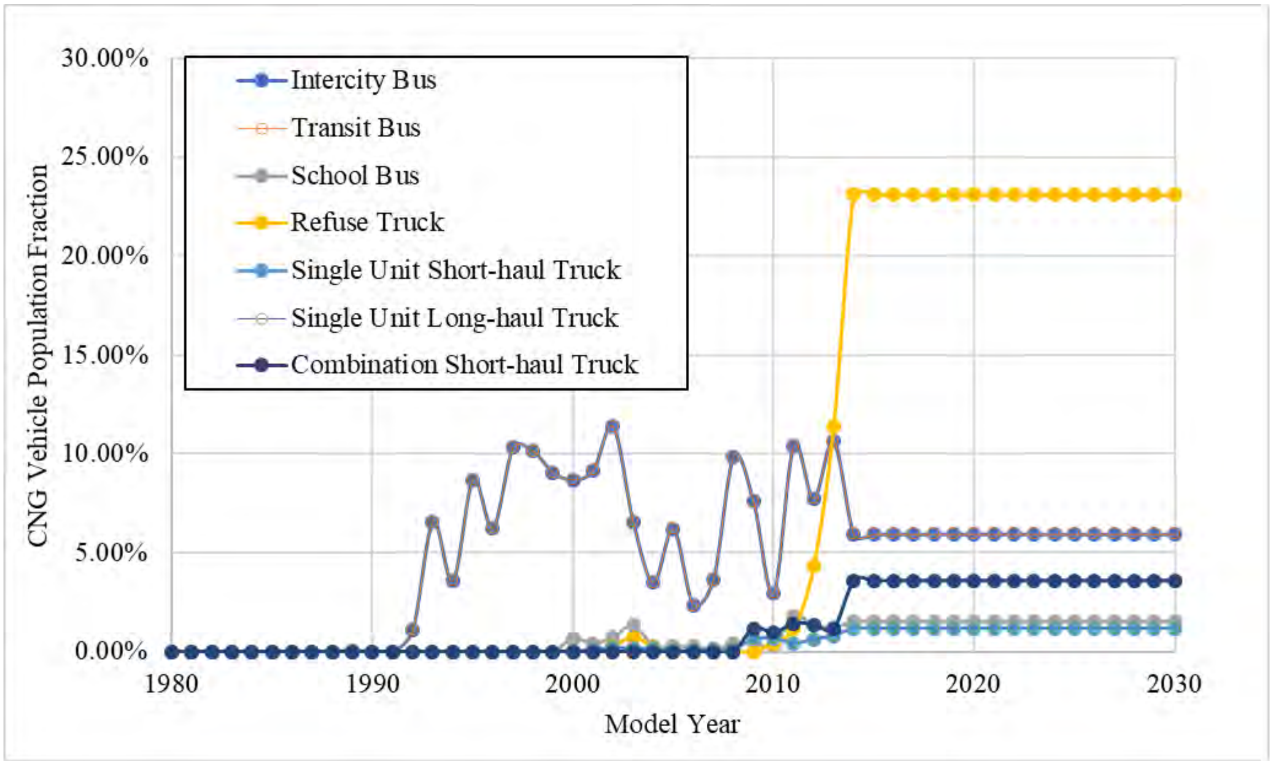

Figure 4-1 Fraction of Heavy-Duty CNG fueled-vehicles in MOVES3 by Source Type by Model Year

MOVES2014 modelled only CNG transit buses. In MOVES3, we allow the modeling of CNG fuel for most heavy-duty source types. Long-haul combination trucks (source type 62) are still diesel-only in MOVES because of the difficulties in accurately modeling hotelling for non-diesel vehicles. We hope to improve this in a future version of MOVES.

The CNG transit buses are mapped to the urban bus regulatory class. The CNG vehicles in other heavy-duty source types are mapped to the HHD regulatory class ). However, the base emission rates for the two regulatory classes are identical. Thus, any differences in CNG emissions between source types is due to differences in population and activity.

Much of the analysis for CNG emissions, especially for older model years, is unchanged from MOVES2014. Important updates in MOVES3 and later versions include:

- Two new model year groups, 2007-2009 and 2010+, to replace the 2007+ emission rates in MOVES2014
- Emissions rates for MY2010+ based on real-world CNG vehicle emissions data.
- For pre-2010 model years, we still estimate emissions using vehicle certification data, but we now use all HD CNG engine emissions data within a model year group. In MOVES2014, the certification emission rate was limited to engine families classified as urban bus.

No updates were made to these rates in MOVES4 since the average $NO_x$ FTP emission level for MY 2010-2017 CNG engine families is already close to the HD2027 0.1 g/hp-hr standard and any further reductions due to the rule are expected to be small.

As noted above for diesel and gasoline vehicles, MOVES methane emissions are not estimated using emission rates. Rather, methane is estimated in relation to THC, using ratios stored in the MethaneTHCratio table in MOVES. The ratios are categorized by fuel type, pollutant process, source type, model-year group, and age group. MOVES multiplies the THC rate by the corresponding ratio from the "methanethcratio" table to calculate the $CH_4$ rate. The methane fraction from CNG vehicles is 89% and 96% for model year groups 1960-2001 and 2002-2060 respectively, as documented in the Speciation report.[1]

These emission rates are dependent on vehicle age, and thus are stored in the emissionRateByAge table.

Total energy consumption is age independent, and therefore, stored in the EmissionRate table. Some of the published studies did not report total energy consumption directly, so it was necessary to compute energy from a stoichiometric equation based on the carbon content in the emitted pollutants or from reported values of miles per gallon equivalent of diesel fuel. In the former case, we used 0.8037 as the carbon fraction coefficient for non-methane hydrocarbons (NMHC) when the bus was equipped with an oxidation catalyst and 0.835 without due to high ethene levels, using speciation profiles from Ayala et al. (2003)[119] discussed later in this section. All other conversion factors to energy were taken from Melendez et al. (2005).[123]

On a similar note, MOVES does not report particulate matter ($PM_{2.5}$ ) as a single rate; it reports one rate for PM from elemental carbon (EC) of 2.5 microns or less, and another rate for non-elemental carbon of 2.5 microns or less. These separate rates for PM (EC) and PM (NonEC) from the emissionRateByAge table are added together for a total $PM_{2.5}$ rate used for comparison to the measurements.

## 4.1 Running Exhaust Emission Rates

The pre-2010 running emission rates are relatively unchanged from MOVES2014[pp], and are based on cycle average rates as discussed in Section 4.1.1. The running exhaust emission rates for model year 2010 and later CNG vehicles using second-by-second in-use emission measurements from heavy-duty vehicles are discussed in Section 4.1.2.

### 4.1.1 1960-2009 Model Years

Ideally, MOVES modal emission rates would be developed through analysis of second-by-second data of vehicles of the appropriate regulatory class, model year, and age. Unfortunately, such data are not readily available for all model years.

In particular, data at multiple ages that can be used to determine emission deterioration, and second-by-second data that can be used to establish STP trends was very limited for MY 2009 and earlier CNG vehicles. Thus, for MOVES, we applied STP and age trends from MHD gasoline vehicles to cycle-based certification results. The following sections describe the available data and the methods to calculate the adjustment ratios.

#### 4.1.1.1 CNG Chassis Dynamometer Measurements

Chassis data was collected from programs that were conducted at several research locations around the country on heavy-duty chassis dynamometer equipment. In our analysis for MOVES2014, we compiled 34 unique dynamometer measurements. Data from newer studies such as Clark et al. (2007)[130] would provide further validation and refinement to the rates discussed in this report, however they have not been incorporated here.

The data considered consisted of distance-specific running emissions rates for each of the following pollutants and total energy:

1. oxides of nitrogen ($NO_x$)
2. carbon monoxide (CO)
3. particulate matter (EC + non-EC)
4. total hydrocarbons (THC)
5. methane ($CH_4$)
6. total energy consumption

This data was collected on two driving cycles, the Central Business District (CBD) and Washington Metropolitan Area Transit Authority (WMATA).

The CBD cycle is defined as a driving pattern with constant acceleration from rest to 20 mph, a short cruise period at 20 mph, and constant deceleration back to rest, repeated for 600 seconds (see

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[pp] The only change was to limit the certification data used to derive the 2007-2009 model year emission rates to the 2007-2009, rather than 2007-2017 as discussed in Section 4.1.1.2.3.

Figure 4-2).[120] The WMATA cycle was developed using GPS data from city buses in Washington, DC, and has higher speeds and greater periods of acceleration than the CBD cycle (see Figure 4-3).

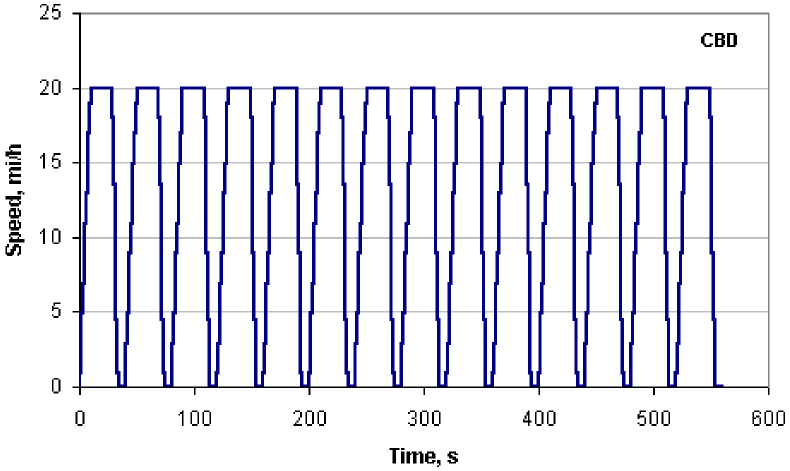

**Figure 4-2 Driving Schedule Trace of the Central Business District (CBD) Cycle[121]**

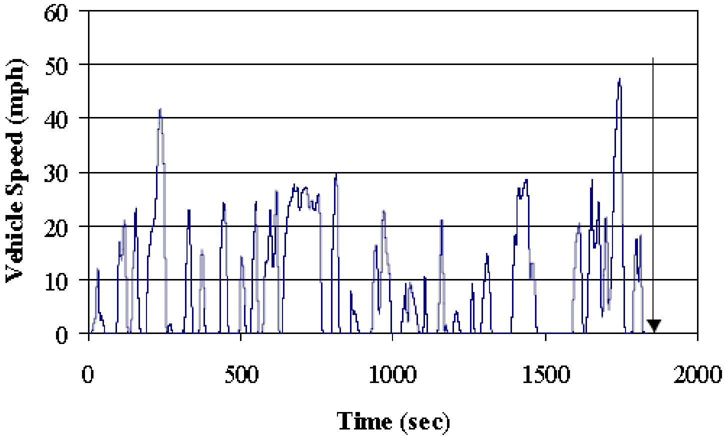

**Figure 4-3 Driving Schedule Trace of the Washington Metropolitan Area Transit Authority (WMATA) Cycle[123]**

Table 4-1 shows a summary of the number of unique CNG bus measurements by driving cycle for each study. Navistar published a similar study of CNG and diesel buses in 2008, and this analysis shares many of the same sources.[122] All of the vehicles were in service with a transit agency at the time of testing. The number of unique measurements are typically equal to the number of vehicles tested and the measurements were typically reported as averages based on multiple runs with the same vehicle and configuration over a specific driving cycle with the exception of measurements reported by Ayala et al. (2002)[125] and Ayala et al. (2003).[119] In the Ayala et al. (2002) study the 2000 model year CNG bus was tested and then retested after approximately two months of service, which we treated as independent measurements. Ayala et al. (2003) retested the same 2000 CNG bus as in their previous study; however, the bus had accumulated an additional 35,000 miles and was serviced by the OEM to be equipped with an oxidation catalyst that was later removed for baseline testing. Ayala et al. (2003) conducted duplicate tests under each vehicle/aftertreatment configuration, which we considered four independent measurements.

**Table 4-1. Summary of External Emissions Testing Programs by Driving Cycle and Number of Unique Measurements and their Corresponding Model Years**

| Paper/Article | Lead Research Unit | Driving Cycle(s) | Model Year (Number of Measurements) |
|---|---|---|---|
| Melendez 2005[123] | National Renewable Energy Laboratory (NREL) | WMATA | 2001 (4),<br>2004 (3) |
| Ayala 2003[119] | California Air Resources Board (CARB) | CBD | 2000 (4),<br>2001 (2) |
| LeTavec 2002[124] | Atlantic Richfield Company (ARCO) | CBD | 2001 (1) |
| Ayala 2002[125] | CARB | CBD | 2000 (2) |
| Lanni 2003[126] | New York Department of Environmental Conservation | CBD | 1999 (3) |
| McKain 2000[127] | West Virginia University (WVU) | CBD | 1999 (3) |
| Clark 1997[128] | WVU | CBD | 1996 (10) |
| McCormick 1999[129] | Colorado School of Mines | CBD | 1994 (2) |
| TOTAL | | | (34) |

### *4.1.1.2 Determining Model Year Groups*

Model year groups are intended capture differences in vehicles over time while still being manageable from a computational viewpoint. Model year groups are defined based on availability of measurement data (see Table 4-1), emissions standards, and/or new vehicle technologies that affect real-world emissions.

#### *4.1.1.2.1 1994-2001 Model Years*

We evaluated the measured $NO_x$, CO, $PM_{2.5}$ , and THC emission rates to establish model year groups and chose to group all the CBD measurements from the literature into one model year group, spanning from MY 1994 to MY 2001. Note that we decided to exclude one of the studies that had four MY 2001 buses tested on the WMATA cycle from this part of the analysis. This was done because inclusion increased the complexity of analysis by having to deal with two driving cycles within a model year group while providing only an incremental increase in sample size.

#### *4.1.1.2.2 2002-2006 Model Years*

Of the surveyed data, only one study had vehicles newer than MY 2001.[qq,130] This paper, a joint study between NREL and WMATA, had three MY 2004 vehicles. The MY 2004 vehicles have a visibly different emissions profile than the other vehicles. While these buses were only tested on the WMATA cycle, they were all equipped with oxidation catalysts and had substantially lower emissions, particularly for $PM_{2.5}$, compared to the 1994-2001 buses tested on the CBD cycle. As a result, we created a model year group from MY 2002 to MY 2006 based on the MY 2004 buses tested on the WMATA cycle. This MY group ends before MY 2007 when a new series of stringent emission standards went into effect, as described below.[131]

#### *4.1.1.2.3 2007-2009 Model Years*

MOVES2014 had a single set of emissions for 2007-and later buses. In MOVES3, we created two groups, MY 2007-2009 and MY 2010+ (noted as MY 2010-2017 when comparing certification data). We decided to split the groups in this way because: (a) changes to $f_{scale}$ values starting MY 2010 (see Appendix G) requires rates to be re-analyzed using 1 hz data; (b) the HDIUT data set includes real world data on MY 2010+ CNG vehicles; (c) certification data showed a significant difference between the average emissions rates for $NO_x$ and CO between these two model year groups (but note that certification data is not used in developing the rates for MY2010+), and (d) this allows for better representation of differences in combustion and aftertreatment technology, such as stoichiometric-combustion with three-way catalysts (TWC) that became more prevalent starting year 2010.

Certification emission data for natural gas heavy-duty vehicles are publicly available by model year on the EPA's Office of Transportation and Air Quality website.[132] Analysis of these data showed that from MY 2002 to MY 2017, there have been changes in average certification levels for all the pollutants considered in this report. In particular, $NO_x$ and $PM_{2.5}$ levels have dropped dramatically. This effect is largely attributable to increasingly stringent emission standards, which have affected both diesel and CNG engines.

Emission rates from analysis of certification data and number of CNG engine families in the certification data are shown in Table 4-2 below. The current, and historically most stringent, heavy-duty compression-ignition $NO_x$ standard of 0.20 g/bhp-hr was fully phased in by 2010 and MY 2010+ heavy-duty CNG engines are required to meet this standard (even if they are not compression-ignition). Thus, the average $NO_x$ certification value for the MY 2010-2017 group is considerably lower compared to the MY 2007-2009 group. At the same time, and mostly to meet the new $NO_x$ standard, heavy-duty CNG engines transitioned from lean-burn to stoichiometric-combustion with TWC. This technology transition is the likely reason for the increase in THC and CO certification emissions rates from MY 2007-2009 to MY 2010-2017.

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[qq] Several papers have discussed more recent vehicles. Examples include Clark et al. (2007).[129] Data from these newer studies would provide further validation and refinement to the rates discussed in this report, however, time and resources were not available to complete a re-analysis for MOVES3.

The differences in MOVES emission rates across all model years are discussed below in Section 4.1.3.

**Table 4-2 Model Year Group Based Certification Emission Rate for Heavy-Duty CNG Engine Families**

| Model Year Group | Number of Engine Families[a,b] | Certification Emission Rate (g/bhp-hr)[c] | | | |
|---|---|---|---|---|---|
| | | $NO_x$ | CO | $PM_{2.5}$ | NMHC[d] |
| 2002-2006 | 22 | 1.208 | 1.355 | 0.0078 | 0.147 |
| 2007-2009 | 30 (24 for $PM_{2.5}$ ) | 0.6123 | 1.940 | 0.0042 | 0.063 |
| 2010-2017[e] | 159 for $NO_x$ and CO, 153 for THC, and 120 for $PM_{2.5}$ | 0.1051 | 4.413 | 0.0028 | 0.044 |

Notes:

[a] For MY 2002-2006, the number of engine families is based on HD CNG urban bus regulatory class. For MY 2007-2009 and MY 2010-2017, the number of engine families is based on all HD CNG engine families.

[b] Some engine families did not report emission data for THC and/or $PM_{2.5}$ .

[c] MY 2002-2006 group emission rates are projected sales weighted average of HD CNG urban bus certification emission rates. MY 2007-2009 and 2010-2017 group emission rates are simple average of all HD CNG certification emission rates (no weighting for projected sales).

[d] Certification data has measurements of organic material non-methane hydrocarbon equivalent (OMNMHCE). For this analysis they were treated as NMHC values.[133]

[e] Only shown for comparison. Certification data for MY 2010-2017 is not used in developing MY 2010+ rates, which are based on MY 2010+ CNG vehicles in the HDIUT data set.

#### *4.1.1.3 Creating Comparable MOVES Gasoline Emissions*

Section 1.6 explains how MOVES operating modes relate to scaled tractive power (STP). Because we lacked data on age and STP trends for pre-2010 CNG vehicles, we applied adjustments based on the rates for gasoline MHD vehicles. To do this, we compared CNG emission data collected on the CBD and WMATA cycles to what MOVES estimated for MHD gasoline vehicles on those same cycles.

Because the pre-2009 CNG vehicles form a small and diminishing portion of the MOVES3 fleet, we have not updated this analysis which relied on emissions, vehicle and activity information from MOVES2010b.

This approach requires converting activity on the CBD and WMATA bus driving cycles to MOVES operating mode distributions, and then simulating MHD gasoline emissions on those same operating mode distributions.

##### *4.1.1.3.1 Operating Mode Distributions for Transit Bus Drive Cycles*

The MOVES2010b project level importer was used to input the second-by-second drive cycle for the CBD and WMATA drive cycles. For each, a single link was created, with the test cycle entered as a drive trace. Running MOVES2010b generated the operating mode distribution, which is created by allocating the time spent in each operating mode according to the cycle speed and acceleration, as shown in Figure 4-4 and Figure 4-5. The derivation of scaled tractive power (STP) and operating mode attribution for heavy-duty vehicles are discussed earlier in this report, in Section 1.5. Road grade is set to zero because these are chassis dynamometer runs.

Since STP is dependent on mass (among other factors), the average vehicle inertial test mass for each cycle was inserted into the MOVES2010b sourceUseType table in place of the default transit bus mass to ensure a more accurate simulation-- 14.957 metric tons for the CBD and 16.308 metric tons for the WMATA, compared to the MOVES2010b default of 16.556 metric tons. The STP calculations used the road-load coefficients from MOVES2010b for transit buses, assuming the coefficients (*A*, *B*, and *C*) were similar to those of the tested buses.

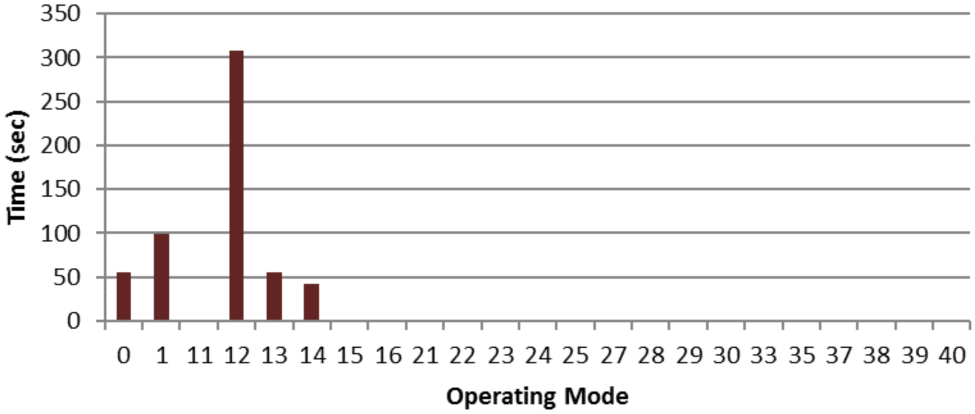

**Figure 4-4 Operating Mode Distribution for the CBD Cycle**

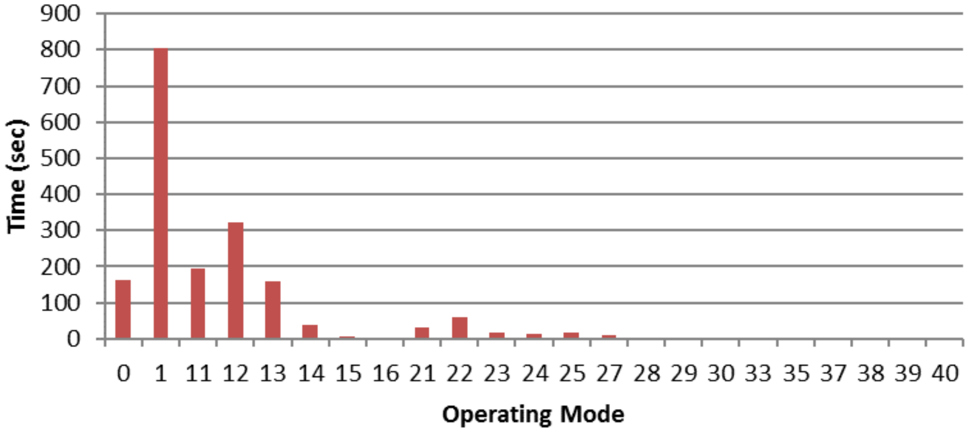

**Figure 4-5 Operating Mode Distribution for the WMATA Cycle**

#### *4.1.1.3.2 Simulating Cycle Average Emission Rates*

With the operating mode distributions determined above, and the emission rates in the MOVES2010b database, we simulated the gasoline MHD emissions for each pollutant for each cycle. Dividing by the cycle total distance we calculated the simulated cycle-average distance-specific rate for that cycle ($E_{simcycle}$, g/mile), as shown in Equation 4-1. Using this method, the simulated cycle emission aggregates were calculated as a function of the following parameters:

- fuel type,
- driving cycle,
- age group,
- regulatory class,
- model year, and
- pollutant and process.

$$\mathbf{E_{p,simcycle}} = \frac{\sum_{\mathbf{OM}} \mathbf{R_{p,OM}} * \mathbf{T_{OM,cycle}}}{\mathbf{D_{cycle}}}$$ **Equation 4-1**

Where:

$D_{cycle}$ = distance of the cycle, in miles
$R_{p,OM}$ = emission rate of pollutant p in operating mode OM, in g/hr
$T_{OM,cycle}$ = time spent in operating mode OM for given cycle, in hr

We compared the MOVES2010b simulated MHD gasoline rates with the published chassis dynamometer measurements. We also specified the age group and model year to match individual vehicles in the testing programs from the literature on CNG transit buses.

#### *4.1.1.4 Emissions Rates by Model Year Group*

To estimate emission rates for pre-2010 CNG vehicles, we applied STP and age trends from MHD gasoline vehicles to cycle-based CNG certification results. Mathematically, this is the same as applying a CNG adjustment to MHD gasoline emission rates, which is how the analysis is described in the sections below.

Due to limited data on older vehicles in the literature, the ratios (shown in Table 4-3) developed using vehicles in the 0-3 age group have been applied to all other age groups. In addition, we assumed that CNG vehicles exhibit the same deterioration trend as medium heavy-duty gasoline trucks (Table 3-3 in Section 3.1.1.1.2 for THC, CO and $NO_x$, and Section 3.1.2.1.3 for $PM_{2.5}$ ).

##### *4.1.1.4.1 1960-2006 Model Years*

The operating mode based emissions rates for MOVES2010b[rr] MHD gasoline vehicles were adjusted by the ratio of cycle-average emissions rates from chassis dynamometer measurements to simulated cycle modeling (see Section 4.1.3). For MY 1994-2001 and MY 2002-2006, the adjustment ratios were based on the CBD cycle and WMATA cycle, respectively.
For each model year group, a central model year was selected as the source for the MHD gasoline operating mode based rates. For MY group 1994-2001, we used MHD gasoline rates from MY 1997 because it is one of the median years in the group. Alternatively, we could have used the other median year, MY 1998. Even though the average rate for MY 1998 was significantly lower (44 percent of that of MY 1997), based on Equation 4-2, we expect minimal differences in the final estimated CNG rates ($R_{CNG}$ term) whether we use MY 1997 or MY 1998 as the median year since the lower operating mode rates ($R_{MDG}$ term) will lead to lower simulated cycle-average rate ($E_{MDG}$ term), which in turn will lead to larger adjustment ratio ($E_{CNG}/E_{MDG}$). For MY group 2002-2006,

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[rr] The PM exhaust emission rates were subsequently updated from MOVES2010b for MHD gasoline vehicles for pre-2010 model years.

we used MHD gasoline rates from MY 2004 because that was the model year of the engine in each of the CNG vehicles measured on the chassis dynamometer (the MY 2001 vehicles were not included in this group). See Equation 4-2 and Equation 4-3 for MY groups 1994-2001 and 2002-2006, respectively.

We assumed that the MY 1993 and earlier CNG vehicles have the same emission rates as MY group 1994-2001.

$$R_{CNG,OM,1994-2001} = R_{MDG,OM,1997} * \frac{E_{CNG,CBD,1994-2001}}{E_{MDG,simCBD,1997}}$$ **Equation 4-2**

$$R_{CNG,OM,2002-2006} = R_{MDG,OM,2004} * \frac{E_{CNG,WMATA,2004}}{E_{MDG,simWMATA,2004}}$$ **Equation 4-3**

Where:

$R_{CNG,OM,MYG}$ = operating mode based emissions rate for CNG vehicles for model year group (MYG) 1994-2001 or MY 2002-2006, in g/hr

$R_{MDG,OM,MY}$ = operating mode based emissions rate for MHD gasoline vehicles for model year 1997 or 2004 (corresponding to MYG), in g/hr

$E_{CNG,Cycle,MYG}$ = Chassis dynamometer cycle-average emissions rate for MY 1994-2001 or 2004 CNG buses tested on a CBD or WMATA cycle, respectively, in g/mile. See Table 4-3.

$E_{MDG,simCycle,MY}$ = Simulated cycle-average emissions rate for MY 1997 or 2004 MHD gasoline vehicles for CBD or WMATA cycle, respectively, in g/mile. This cycle-average rate is calculated using the $R_{MDG,OM,MY}$ operating mode rates. See Table 4-3.

#### *4.1.1.4.2 2007-2009 Model Years*

Due to lack of published data on MY 2007-2009 in-use vehicles, we used certification emissions rates, shown in Table 4-2, to scale the operating mode based emissions rates. Certification emissions rates are reported in grams per brake horsepower-hour (g/bhp-hr) and are not directly used in formulating MOVES emission rates because they do not include real-world effects such as deterioration[134] which were present in the chassis dynamometer measurements used to estimate emissions rates for MY 1994-2001 and MY 2002-2006. So, we created scaling factors that we could apply to the MY 2002-2006 emissions rates to estimate rates for MY 2007-2009. This scaling factor is the right-most term in Equation 4-4 shown below.

$$R_{CNG,OM,2007-2009} = R_{MDG,OM,2004} * \frac{E_{CNG,WMATA,2004}}{E_{MDG,simWMATA,2004}} * \frac{C_{CNG,2007-2009}}{C_{CNG,2002-2006}}$$ **Equation 4-4**

Where:

$C_{CNG,2007-2009}$ = Average certification emission rate of all heavy-duty CNG engine families of model year MY 2007-2009 in g/bhp-hr

$C_{CNG,2002-2006}$ = Projected sales weighted average certification emission rate for CNG urban bus engine families in MY 2002-2006, in g/bhp-hr

The adjustment ratio for energy consumption for MY 2002-2006 (Equation 4-3) is applied to all model years in 2007-2009. For MY 2007+, we did not scale the energy consumption rates like we did for other pollutants (Equation 4-4) because even though we have certification data on $CO_2$ emission rates for 2007-2009 model years, we do not have certification data on $CO_2$ emission rates for MY 2002-2006. As a result, MY 2007-2009 energy consumption rates are identical to the MY 2002-2006 rates.

#### *4.1.1.4.3 Ratio Summary*

**Table 4-3 Ratios Applied to MHD Gasoline Rates to Compute CNG Rates**

| $E_{CNG}$, Cycle-Average Chassis Dynamometer Measurement Rates (g/mile) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| MY | Age Group | Cycle | $NO_x$ | CO | PM_NonEC | PM_EC | THC | TOTAL ENERGY (BTU/mi) |
| 1994-2001 | 0-3 | CBD | 20.8 | 9.97 | 0.037 | 0.0038 | 13.2 | 42782 |
| 2002-2006 | 0-3 | WMATA | 9.08 | 2.17[a] | 0.0039 | 0.0005 | 11.2 | 40900 |
| $E_{MDG}$ , Simulated Cycle-Average Medium Heavy-Duty Gasoline Rates (g/mile) | | | | | | | | |
| MY | Age Group | Simulated Cycle | $NO_x$ | CO | PM_NonEC | PM_EC | THC | TOTAL ENERGY (BTU/mi) |
| 1997 | 0-3 | CBD | 9.63 | 62.4 | 0.0024 | 0.0002 | 1.84 | 31137 |
| 2004 | 0-3 | WMATA | 5.45 | 18.9 | 0.0035 | 0.0003 | 1.43 | 35489 |
| Ratios Applied to the Medium Heavy-Duty Gasoline Rates to Create CNG Rates | | | | | | | | |
| MY | Age Group | MHD Gasoline MY[b] | $NO_x$ | CO | PM_NonEC[f] | PM_EC | THC | TOTAL ENERGY |
| 1994-2001[c] | all | 1997 | 2.16 | 0.160 | 15.5 | 21.6 | 7.17 | 1.37 |
| 2002-2006[c] | all | 2004 | 1.67 | 0.115 | 1.09 | 1.87 | 7.79 | 1.15 |
| 2007-2009[d] | all | 2004 | 0.842 | 0.157 | 0.587 | 1.01 | 3.34 | 1.15 |
| 2010+[e] | Age 0- 3 (and 4-5) rates are based on analysis of 1 hz data from MY 2010+ CNG vehicles in the HDIUT data set. Ages 6+ apply deterioration factors to age 0-3 rates as described in main text. | | | | | | | |

Notes:

[a] The measured CO rate (0.14 g/mi) was uncharacteristically low and thus determined to be an outlier and not used. Each of the three post-2001 vehicles in this study had the same MY 2004 engine (John Deere 6081H). This engine's CO certification rate was a full order of magnitude lower than certification rate of other MY 2004 engine models, and was not supported by additional test results. We adjusted the WMATA chassis dynamometer CO rate by the ratio between the sales-weighted average CO certification level of all MY 2004 CNG engine models and the CO certification level for the MY 2004 John Deere 6081H engine.

[b] Model year of the medium heavy-duty gasoline operating mode rates to which the pollutant-specific ratios are applied

[c] The ratios are calculated using Equation 4.2 or Equation 4.3 and the ECNG and EMDG values in this table

[d] The ratios are calculated using Equation 4.4, the $E_{CNG}$ and $E_{MDG}$ values in this table, and the $C_{CNG}$ values in Table 4.2

[e] Energy consumption rates for MY 2014-2017 and MY 2018+ are reduced as per heavy-duty GHG Phase 1 and Phase 2 rules, respectively. See main text for details.

[f] The $PM_{2.5}$ exhaust emission rates have been subsequently updated in MOVES3 from MOVES2010b for MHD gasoline vehicles for MY 1997. The ratios presented here are applicable to the MOVES2010b MHD gasoline rates and the MOVES3 CNG emission rates.

### *4.1.2 2010-2060 Model Years*

Running emission rates for MY 2010 and later CNG vehicles were based on information from in-use trucks, and thus, unlike the calculations for earlier model years, the rates by operating mode could be calculated directly. We then applied factors to account for deterioration with vehicle age, and adjustments to energy rates to account for the phase-in of heavy-duty greenhouse gas standards.

#### *4.1.2.1 Base Emission Rates*

Running emission rates for MY 2010 and later CNG vehicles were based on information from in-use trucks. To develop MY 2010+ emissions rates (for THC, CO, $NO_x$, and $PM_{2.5}$) and energy consumption rates, we used the MY 2010+ CNG vehicles in the HDIUT data set. At the time of analysis, there were five MY 2011 CNG vehicles and six MY 2014 vehicles. These 11 vehicles are all stoichiometric-combustion with TWC and are certified at or below the 0.20 g/bhp-hr standard.

After quality assurance, the 1 Hz data set included about 310,000 seconds of operation. Operating modes (Table 1-4) were assigned to the 1 Hz data using the method to calculate STP described in section 2.1.1.3. The analysis used updated $f_{scale}$ values described in section 2.1.1.4.2 and Appendix G and thus, there was no need for hole-filling of missing operating modes. The operating mode-based rates were calculated using $f_{scale} = 10$. The rates for regClass 47 and 48 are identical.

Unlike the analysis method for HD diesel (described in section 2.1.1.5), the method for HD CNG did not use the $NO_x$ FEL based grouping since all 11 vehicles are in the same $NO_x$ FEL group. As a result, the zero-mile (age 0) THC, CO, $NO_x$, and $PM_{2.5}$ rates for CNG are identical for all model years starting 2010 (unlike HD diesel where they change for each model year in 2010-2015 based on production volume differences between the $NO_x$ FEL groups).

#### *4.1.2.2 Age-based deterioration factors*

THC, CO, and $NO_x$ age-based deterioration factors for MY 2010+ CNG vehicles in MOVES3 are unchanged from MOVES2014. In MOVES2014, these factors were set as equal to the factors for MY 2010+ HD gasoline vehicles, which in turn are identical to and based on MY 1960-2007 HD gasoline vehicles. There is no deterioration for age groups 0-3 and 4-5 and the deterioration factor (per operating mode) is same across age groups for ages 6+ but varies between operating modes within an age group. These deterioration factors are described in Table 3-3 in Section 3.1.1.1.2.

For $PM_{2.5}$, in MOVES3, ages 0-3 and 4-5 have no deterioration and the MOVES2014 light-duty $PM_{2.5}$ deterioration factor for age 6-7 is applied to all CNG $PM_{2.5}$ emission rates for ages 6+, thus making the $PM_{2.5}$ and gaseous pollutant methods more (but not fully) aligned. Note that, unlike the factor for gaseous pollutants, the MOVES $PM_{2.5}$ deterioration factor does not vary between operating modes for a given age group. See Section 3.1.2.1.3 for more details and Table 4-4 for a comparison between MOVES3 and MOVES2014.

**Table 4-4 Age-based Deterioration Factor for $PM_{2.5}$ Emission Rates for HHD and Urban Bus CNG Vehicles in Model Year 2010+**

| Age | MOVES2014 | MOVES3[1] |
|---|---|---|
| 0-3 (Baseline) | 1.00 | 1.00 |
| 4-5 | 1.57 | 1.00 |
| 6-7 | 1.75 | 1.75 |
| 8-9 | 1.96 | 1.75 |
| 10-14 | 2.38 | 1.75 |
| 15-19 | 3.14 | 1.75 |
| 20+ | 4.15 | 1.75 |

Note:

[1] When recreating the deterioration factor, for age 6+, from the age-group based default emissions rates in the MOVES database, the ratios will not be exactly 1.75 because the final rates (with deterioration factors already applied) are rounded to a set precision before submission to the database.

#### *4.1.2.3 Application of Heavy-Duty Greenhouse Gas Phase 1 and Phase 2 Rules*

To model energy consumption in MOVES3, we split the CNG MY 2010+ group into MY 2010-2013, MY 2014-2017, and MY 2018+ groups. The MY 2010-2013 energy consumption rates are identical across these model years and based solely on the HDIUT data set analysis. For MY 2014-2017, the CNG energy consumption rates of MY 2013 are reduced by the percentage reduction assigned to HHD vehicles in the Greenhouse Gas Emissions Standards and Fuel Efficiency Standards for Medium and Heavy-Duty Engines and Vehicles Phase 1 rule[59] (see Table 2-30). Similarly, for MY 2018 and later, using MY 2017 rates as base year, the energy consumption rates of CNG vehicles are further reduced as per the Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium and Heavy-Duty Engines and Vehicles — Phase 2 rule[61] (see Table 2-31). Note that the Phase 1 reduction for CNG vehicles is identical across all allowed source type and regulatory class combinations. However, for the Phase 2, different reductions for CNG vehicles are applied by source type and regulatory class (see Table 2-31). The anticipated improvements in fuel efficiency from the Phase 2 rules are stored in the EmissionRateAdjustment table.

The GHG Phase 1 and 2 reductions reflect the percent improvements projected from the rules based on engine technology improvements to diesel engines. In making these projections, we assumed the HD GHG rules lead to the same reductions in the energy rates for CNG vehicles as for heavy-duty diesel. In reality, manufacturers of CNG vehicles can meet the standards by lowering both $CH_4$ and $CO_2$ emissions, and the reductions in fuel consumption (and $CO_2$ emission rates) between CNG and diesel vehicles will likely differ. Future MOVES versions may update the energy consumption rates and $CH_4$ emission rates with data from MY 2015 and later CNG vehicles that comply with the GHG standards.

### *4.1.3 Model Year Trends*

Figure 4-6 through Figure 4-10 display the THC, CO, $NO_x$, $PM_{2.5}$, and $CO_2$ running exhaust emission rates by model year and regulatory class (HHD and Urban Bus). The emission rates are estimated in grams per mile (g/mile) using nationally representative operating mode distributions and average speeds. The change in emissions at MY 2010 coincides with both a change in our analysis methodology and a shift in the CNG vehicle fleet from lean-burn combustion to stoichiometric combustion with a three-way catalyst.

Figure 4-6 shows a significant increase in the THC emissions between the MY 2007-2009 and MY 2010 and later vehicles. Because MOVES uses the same methane fraction for 2002 and later CNG vehicles, the $CH_4$ and non-methane hydrocarbons (NMHC) emissions follow the same trend. The significant increase in THC, $CH_4$, and NMHC starting in MY 2010 with the increased penetration of CNG vehicles with stoichiometric-combustion engines and three-way catalyst (TWC) is not supported by the certification data presented in Table 4-2 nor in recent studies comparing stochiometric and lean-burn combustion CNG engines.[135,136] The differences in the methodologies and limitations in the pre-2010 data likely contributed to apparent increase in THC emissions starting in 2010 model year in MOVES.

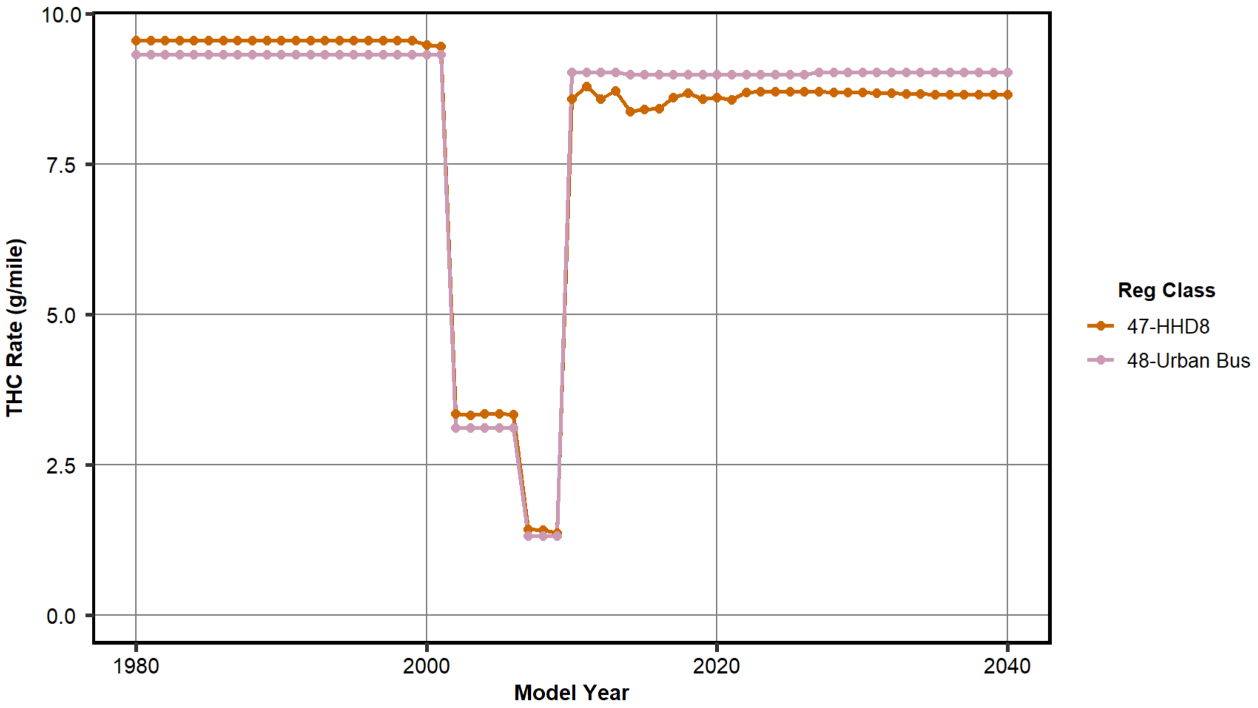

**Figure 4-6. Base running emission rates for THC from age 0-3 CNG heavy-duty vehicles averaged over a nationally representative operating mode distribution**

Like THC, CO also shows a significant increase in emission rates with the updated analysis of the MY 2010+ vehicles (See Figure 4-7). However, the increase in CO is supported by certification data (Table 4-2) and in more recent testing comparing stoichiometric-combustion with TWC based CNG buses.[135,136]

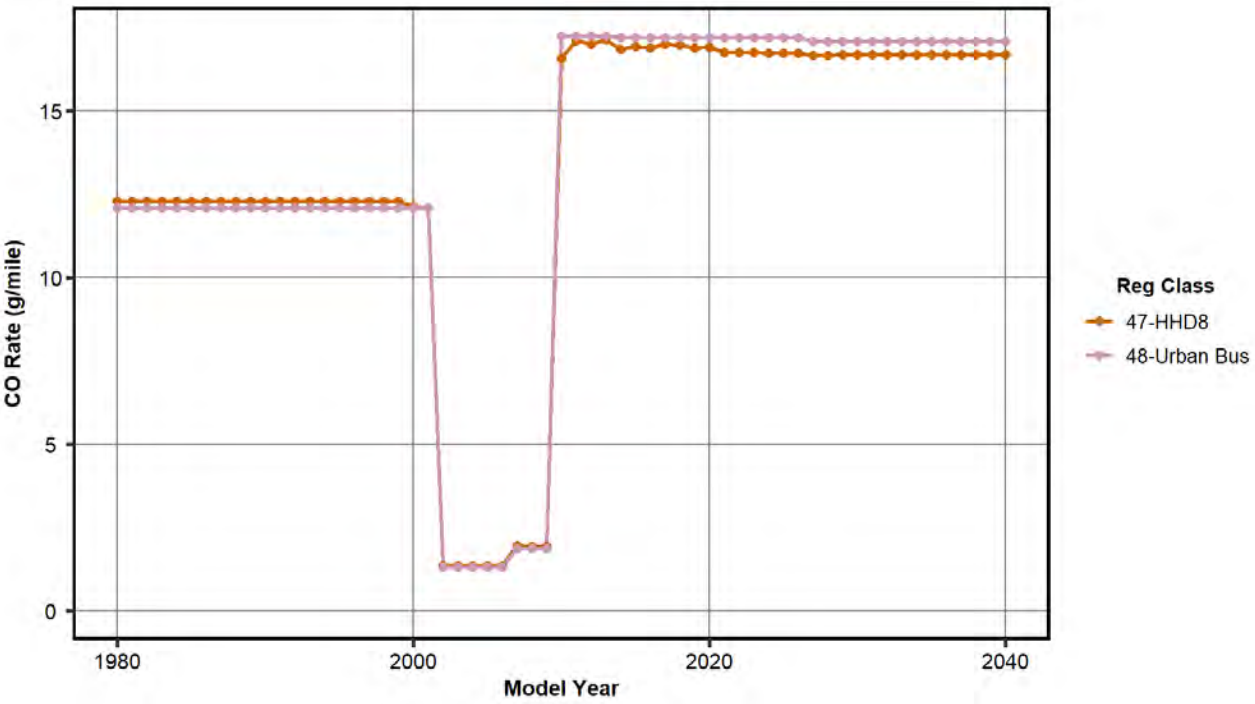

**Figure 4-7. Base running emission rates for CO from age 0-3 CNG heavy-duty vehicles averaged over a nationally representative operating mode distribution**

Figure 4-8 shows consistent decreases in $NO_x$ emission rates from older to new model years. The trends in $NO_x$ emissions are consistent with the certification data (Table 4-2) and recent studies.[135,136]

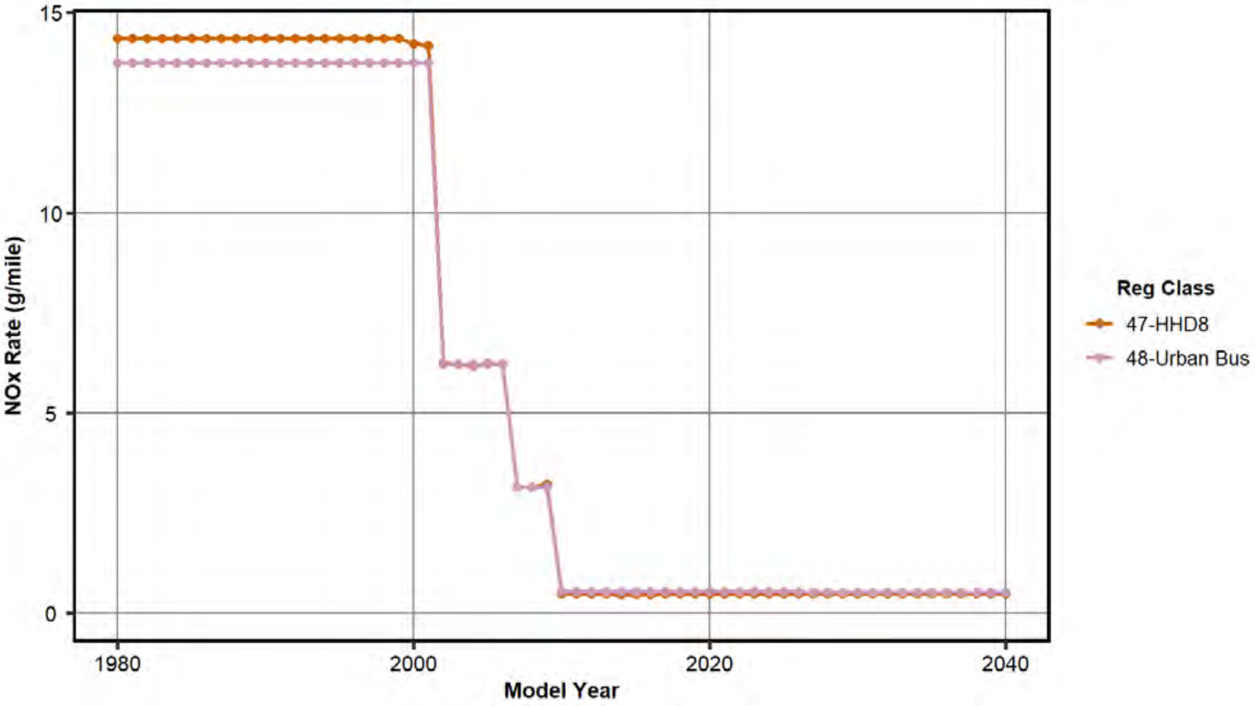

**Figure 4-8. Base running emission rates for $NO_x$ from age 0-3 CNG heavy-duty vehicles averaged over a nationally representative operating mode distribution**

Figure 4-9 shows significant decreases in the $PM_{2.5}$ emission rates between the 2001 and 2002 model year emission rates based on the chassis-cycle average $PM_{2.5}$ emission rates. An increase in $PM_{2.5}$ emission rates is shown from model year 2009 and 2010, which is inconsistent with the certification data (Table 4-2). The two studies evaluating stoichiometric and lean-burn showed mixed results, with one study showing stoichiometric engines with TWC emitting lower $PM_{2.5}$ emissions[136] and the other study showing stoichiometric engines emitting higher $PM_{2.5}$ rates.[135]

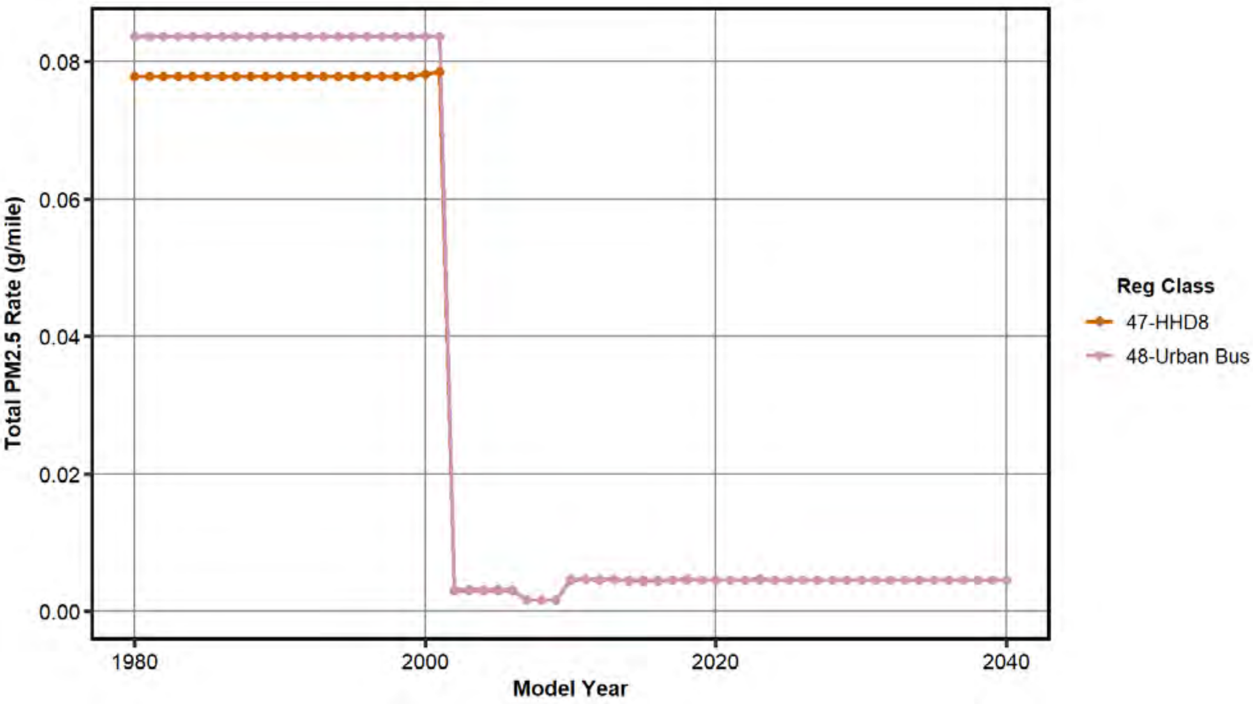

**Figure 4-9. Base running emission rates for $PM_{2.5}$ from age 0-3 CNG heavy-duty vehicles averaged over a nationally representative operating mode distribution**

Figure 4-10 shows general decreases in the $CO_2$ emission rates across model years, including the impact of the HD GHG Phase 1 and Phase 2 rules discussed in 4.1.2.3.

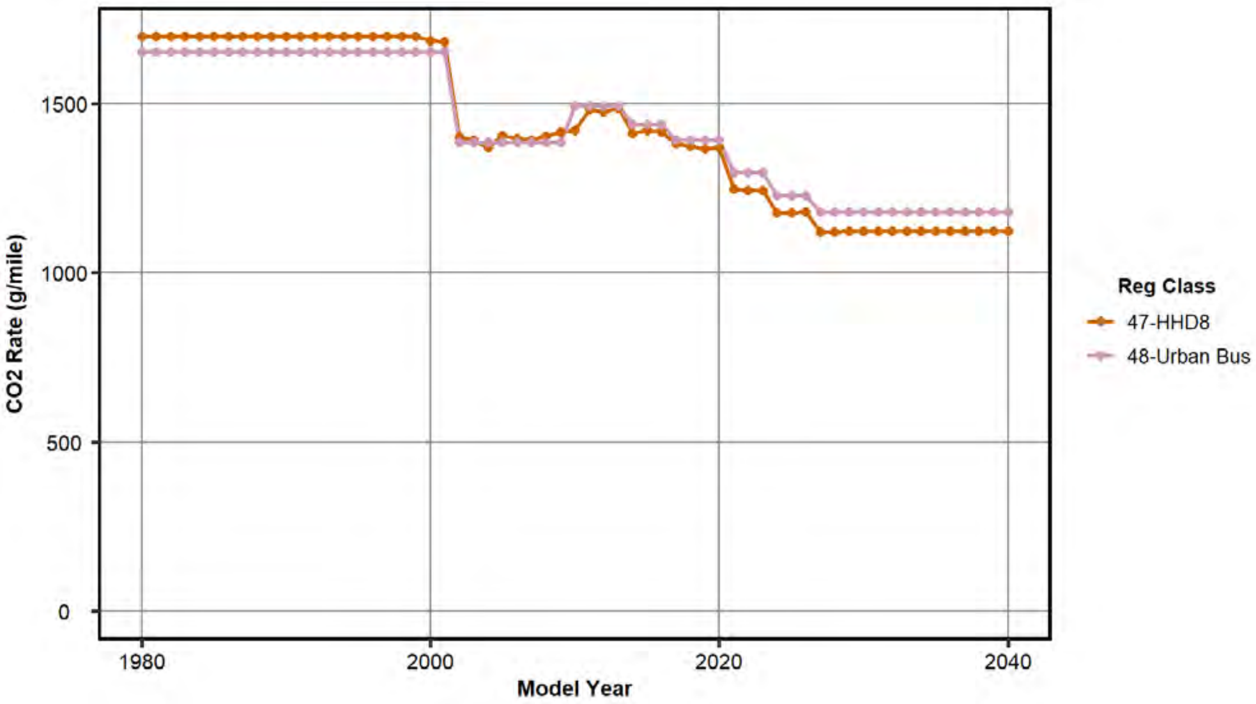

**Figure 4-10. Base running emission rates for $CO_2$ from age 0-3 CNG heavy-duty vehicles averaged over a nationally representative operating mode distribution**

We have more confidence in the model year 2010 and later emission rates because the emissions rates are derived directly from in-use second-by-second data. Unfortunately, the differences in the methodology likely contributed to the differences in emission rates for THC and possibly $PM_{2.5}$ that are not explained by shift to stoichiometric TWC vehicles for 2010 and later vehicles. Future updates to MOVES could revisit the pre-2010 CNG exhaust running emission rates to address these inconsistencies.

## *4.2 Start Exhaust Emission Rates*

In the absence of any measured start exhaust emissions from CNG vehicles, their start rates are copied from the pre-2010 model year heavy-duty diesel start rates for all pollutants including energy rates. MOVES still estimates that the majority of emissions from CNG vehicles are from running emissions, which are based on CNG test programs. We acknowledge that the diesel start rates may not accurately represent CNG start emissions.

## *4.3 Extended Idle Exhaust Emission Rates*

Like starts, there is an absence of data regarding extended idle emissions from CNG vehicles. Therefore, all extended idle rates are copied from the idle operating mode (opModeID 1) for the running process, which we assume to be a reasonable proxy for extended idle emissions. The running idle rates for some pollutants, such total hydrocarbons and CO, deteriorate with age, but extended idle emissions do not. In this case, the emission rate for a new CNG vehicle is used to represent the extended idle rate for all ages.

# 5 Heavy-Duty Ammonia Emissions

The ammonia ($NH_3$) running exhaust emission rates for heavy-duty diesel, heavy-duty gasoline, and heavy-duty compressed natural gas fueled vehicles have been updated in MOVES4. We do not estimate $NH_3$ emissions from starts. Extended idle emission rates are only estimated for gasoline and CNG as discussed in the following sections.

## *5.1 Heavy-Duty Diesel*

Ammonia is not formed during typical combustion processes in diesel engines but is emitted as a undesirable byproduct of selective catalytic reduction (SCR) aftertreatment systems present on model year 2010 and later heavy-duty diesel vehicles to meet the 2010 $NO_x$ emission standards.

The SCR system functions by injecting aqueous urea into the exhaust flow, which then thermally decomposes to $NH_3$ and $CO_2$ (Equation 5-1). $NO_x$ is then reduced to $N_2$ by reactions shown in Equation 5-2 through Equation 5-4.[137]

$$\mathrm{CO(NH_2)_2 + H_2O \rightarrow 2NH_3 + CO_2} \qquad \textbf{Equation 5-1}$$

$$\mathrm{4NH_3 + 4NO + O_2 \rightarrow 4N_2 + 6H_2O} \qquad \textbf{Equation 5-2}$$

$$\mathrm{4NH_3 + 6NO \rightarrow 5N_2 + 6H_2O} \qquad \textbf{Equation 5-3}$$

$$\mathrm{2NH_3 + NO + NO_2 \rightarrow 2N_2 + 3H_2O} \qquad \textbf{Equation 5-4}$$

Excessive urea injected into the exhaust stream can lead to ammonia passing through the aftertreatment system into the atmosphere, referred to as ammonia slip. $NH_3$ oxidation (AMOX) catalysts can be used to reduce ammonia slip but may not eliminate the emissions entirely.[138,93]

Consistent with previous versions of MOVES, we estimate zero heavy-duty diesel $NH_3$ start emissions. We also estimate zero $NH_3$ extended idle emissions. $NH_3$ emissions during extended idling should be minimal, due to little or no dosing of urea in the SCR system because current technology diesels cannot maintain the required operational exhaust temperature at extended low loads.[51] We do not estimate $NH_3$ emissions from auxiliary power unit exhaust, which are not expected to have SCR systems. The remainder of this section discusses ammonia running emissions.

Ammonia measurements were not part of the HDIUT program we used to estimate the heavy-duty diesel and CNG THC, CO, $NO_x$, and $PM_{2.5}$ emission rates as described in Section 2.1.1.1 As such, we relied on other data sources for developing heavy-duty $NH_3$ emission rates for diesel vehicles. We compared fleet-average heavy-duty vehicle $NH_3$ emission rates reported in the literature to in-use studies as summarized in Table 5-1.

**Table 5-1. Fleet-average fuel-based $NH_3$ emission rates (± 95% Confidence Intervals) from heavy-duty vehicles reported from recent studies**

| Study | Study Year | Location | Number of vehicles | Heavy-duty vehicle fleet average $NH_3$ emission rate (g/kg-fuel) |
|---|---|---|---|---|
| Preble et al. (2019)[139] | 2018 | Caldecott Tunnel near Oakland, CA | 1,186 | 0.10 ± 0.03 |
| Haugen et al. (2018)[142] | 2017 | Peralta Weigh Station near Anaheim, CA | 1,844 (HDV)<br>471 (MDV)<br>1,408 (high)<br>907 (low) | 0.09 ± 0.02 (HDV)<br>0.06 ± 0.05 (MDV<br>0.08 ± 0.02 (high)<br>0.06 ± 0.05 (low) |
| Bishop et al. (2022)[143] | 2020 | Perry Weight Station Salt Lake City, UT | 1,591 (HDV)<br>103 (MDV)<br>1,053 (high HDV)<br>538 (low HDV) | 0.08 ± 0.06 (HDV)<br>0.22 ± 0.23 (MDV)<br>0.009 ± 0.009 (high HDV)<br>0.23 ± 0.02 (low HDV) |
| Wang et al. (2019)[144] | 2015 | Fort McHenry Tunnel, Baltimore, Maryland | NA | 0.10 ± 0.07 (winter)<br>0.03 ± 0.08 (summer) |

Preble et al. (2019)[139] measured $NH_3$ emissions rates from heavy-duty vehicles at the Caldecott Tunnel near Oakland, California in 2018. They sampled the concentrations of $NH_3$ and $CO_2$ from the exhaust plumes of individual heavy-duty vehicles as they entered the tunnel at a 4% grade traveling between 30 and 75 mph. From the $NH_3$ and $CO_2$ concentrations, they estimated $NH_3$ fuel-based emission rates using the carbon content of diesel fuel. By matching license plate images to state truck registration databases, they were able to obtain vehicle information, including engine model year and aftertreatment system. The average emission rates by different mode year and aftertreatment groups are shown in Table 5-2.

Preble et al. (2019) measured $NH_3$ emissions from 2010 and later trucks equipped with SCR systems. They were able to collect over 900 diesel truck $NH_3$ emissions measurements identified by engine model year and aftertreatment system. Collecting a large sample is important for capturing the fleet-average emision rates, because 10% of trucks contributed 95% of the total fleet $NH_3$ emissions. The Preble et al. (2019) study measured a large number of model year 1994-2006 retrofit DPF trucks due to the large number of drayage trucks servicing the nearby Port of Oakland. Between 2010 and 2012, all California drayage trucks were required to be equipped with diesel particulate filters.[140] The average ammonia emission rates for the pre-2010 model year groups are low and uncertain, which is consistent with measurements of heavy-duty ammonia emissions made from the Caldecott Tunnel in 2006.[141] The fleet-average heavy-duty diesel emission rates for Preble et al. (2019) are shown in Table 5-1. The sample size is larger than that listed in Table 5-2 because the fleet-average includes all heavy-duty diesel vehicles measured, including trucks that were not matched to the vehicle registration database.

**Table 5-2. Fuel-based $NH_3$ emission rates (± 95% Confidence Intervals) from heavy-duty vehicles by aftertreatment and engine model year measured at the Caldecott Tunnel by Preble et al. (2019)[139]**

| Aftertreatment | Engine Model Year | $NH_3$ (g/kg) fuel-based emission rate | Number of vehicles | Model year ranges used in MOVES |
|---|---|---|---|---|
| DPF + SCR | 2010-2018 | 0.18 ± 0.07 | 547 | 2010-2060 |
| DPF | 2007-2009 | 0.00 ± 0.01 | 181 | 2007-2009 |
| Retrofit DPF | 1994-2006 | 0.01 ± 0.01 | 114 | Not used |
| No DPF | 2004-2006 | 0.00 ± 0.01 | 24 | 2004-2006 |
| No DPF | 1965-2003 | 0.02 ± 0.02 | 62 | 1960-2003 |

The University of Denver's research group has conducted two studies of heavy-duty diesel emissions measured using their remote sensing device called the Fuel Efficiency Automobile Test (FEAT) system that measures pollution concentrations across the roadway. Haugen et al. (2018)[142] measured $NH_3$ emissions from heavy-duty vehicles at the exit ramp of the Peralta Weigh Station near Anaheim, California. They separately sampled emissions from heavy-duty vehicles with the elevated exhaust pipes ("high" in Table 5-1), and ground-level exhaust pipes ("low" in Table 5-1). Additionally, they classified samples into medium-duty (defined as vehicles with GVWR < 26,000 lbs, or class 2 through 6 vehicles), and heavy-duty vehicles (GVWR > 26,000 lbs, or Class 7 and 8 vehicles). The "low" sample has a high percentage of medium-duty vehicles which had lower $NH_3$ emission rates, and newer heavy-duty vehicles which have higher than average $NH_3$ emission rates. The heavy-duty and medium-duty vehicles measured in Haugen et al. (2018), are over 99% and 92% diesel vehicles, respectively, with the remainder being compressed natural gas vehicles. The research measured a large increase in fleet-average $NH_3$ emissions in the 2017 campaign compared to previous measurements made at the Peralta Weight Station in 2008, 2009, 2010 and 2012, due the penetration of SCR-equipped vehicles into the in-use fleet. The average for the 2010 and later chassis model years from this study was 0.14 g/kg/fuel, while the older model year vehicles had $NH_3$ rates near zero.

Bishop et al. (2022)[143] measured emissions from heavy-duty vehicles at the Perry, Utah Port of Entry (~50 miles north of Salt Lake City) in December 2020. Bishop et al. (2022) separately measured heavy-duty vehicles with "high" and "low" exhaust pipe positions. In this study, the "low" exhaust tailpipe trucks were almost exclusively 2011 and later heavy-duty vehicles trucks, which had significantly higher $NH_3$ than the older trucks included in "high" exhaust tailpipe group. The "low HDV" group had a mean emission rate similar to that estimated from Preble et al. 2019 for DPF+SCR equipped trucks. Bishop et al. (2020) measured a smaller number of Class 4, 5, and 6 vehicles, for which the mean estimate was highly uncertain.

Wang et al. (2019)[144] measured fleet average NH3 emissions for a week in both February and July/August, 2015 from the Fort McHenry Tunnel, which is along the I-95 corridor with a traffic volume of ~55,000 vehicles per day. They measured emission concentrations from two of the four bores that contain heavy-duty vehicle traffic. The tunnel includes a -1.8% down grade, followed by a 3.3% positive grade to the exit of the tunnel. Using the measured concentration and the fraction of heavy-duty vehicles, they estimated fuel-based $NH_3$ emission rates for both light-duty and heavy-duty vehicles. Because this was the earliest study conducted, we would expect the $NH_3$ emission rates to be lowest from this study due to a smaller fraction of SCR-diesel vehicles present in the fleet. The summer measurements are lower than the other studies, however, the winter measurements are similar. In addition, the difference is not statistically significant due to the large confidence intervals of the mean.

Despite the different measuring systems, locations, and sampling years, the fleet-average emission rates are statistically similar among the different studies. This provides confidence that the fuel-based emission rates reported from the studies, are not strongly impacted by measurement methods, or the sampling conditions of the location.

We developed heavy-duty $NH_3$ emission rates in MOVES using the reported fuel-based emission factors by model year and aftertreatment class from Preble et al. (2019) reported in Table 5-2. We chose to use Preble et al. (2019) because they reported the emission rates exclusively for heavy-duty vehicles by model year ranges. In addition, we also used the Preble et al. (2019) study to update the MOVES NO/NO2 fractions (Section 7.1) and $N_2O$ emission rates.[3]

To develop MOVES heavy-duty diesel emission rates by regulatory class, model year, and operating mode, we multiplied the MOVES3 heavy-duty diesel vehicle fuel-consumption rates by regulatory class, model year, operating mode $\left(Fuel\ Rates_{Reg,MY,op}\right)$ by the Preble et al. (2019) fuel-based $NH_3$ emission rates $\left(\overline{FER}_{Model\ Year\ Group}\right)$ from Table 5-1 shown below in Equation 5-5.

$$\overline{ER}_{Reg,MY,age,op} = Fuel\ Rates_{Reg,MY,op} \times \overline{FER}_{Model\ Year\ Group} \qquad \textbf{Equation 5-5}$$

Figure 5-1 shows example $NH_3$ emission rates for the LHD2b3 and HHD regulatory class for model year 2017. Even though the fuel-based emission rate is the same, the gram per hour rate is larger for the HHD regulatory class due to higher fuel consumption rates.

We replicated the $NH_3$ emission rates for each heavy-duty regulatory class and model year across all vehicle age (ages 0 to 30). This differs from the ammonia rates for light-duty gasoline $NH_3$ where we had a much larger data sample and were able to estimate age effects. Preble et al. (2019) collected measurements of $NH_3$ in only their most recent campaign. Haugen et al. (2018) collected several measurement campaigns at the Peralta Weight station, but had a limited number of vehicles from which to estimate both model year and age specific emission rates. We recommend future studies to evaluate the impact of aging, deterioration and mal-maintenance on $NH_3$ from heavy-duty diesel vehicles.

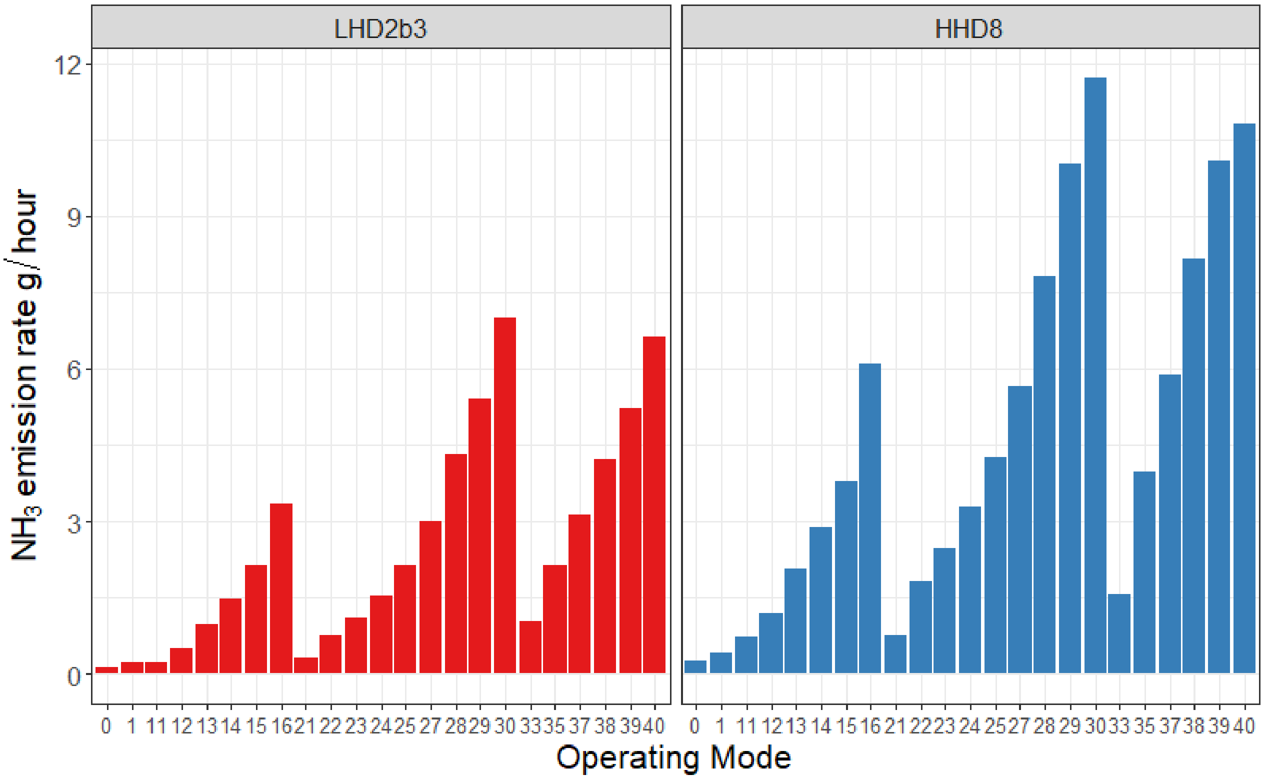

**Figure 5-1. $NH_3$ emission rates (g/hour) by operating mode for regulatory class LHD2b3 and HHD and Model Years 2017 for all ages**

We used the fuel-specific $NH_3$ emission rates reported in Table 5-2 by the model year ranges consistent with the measured data. We did not use the “DPF Retrofit MY 1994-2006” emission rates from Table 5-2 in MOVES, because these are representative of California drayage trucks, but not of the national heavy-duty vehicle fleet represented in MOVES. We used the fuel-based emission rates to develop emission rates for all heavy-duty regulatory classes (LHD2b3, LHD45, MHD, HHD, Urban Bus). As shown in Table 5-1, there are inconsistent results comparing medium and heavy-duty vehicles emission rates between the Haugen et al. (2018), and Bishop et al. (2022) study, with medium duty vehicles having both lower and higher emission rates. The fleet-average differences are not statistically significant in both studies. In MOVES, the differences in ammonia rates by regulatory class are impacted by the different fuel consumption rates. For all model years of glider vehicles (regClassID 49), we used the 1965-2003 model year group to estimate $NH_3$ emission rates. A summary of the $NH_3$ emission rates from MOVES across different regulatory classes is shown in Section 5.4.

## *5.2 Heavy-Duty Gasoline*

Like diesel vehicles, we estimate ammonia emissions only for the running emission process.

### 5.2.1 1960-1980 Model Years

The model year 1960-1981 heavy-duty gasoline ammonia emission rates are unchanged from MOVES2010 and documented in a MOVES2010 technical report.[145] These rates were estimated by scaling the light-duty gasoline ammonia emission rates by the ratio of light-duty gasoline emission rates from model year 1981-1991 and heavy-duty gasoline vehicles measured in a 1983 EPA study.[146]

### 5.2.2 1981-2060 Model Years

In MOVES4, the heavy-duty gasoline vehicle emission rates were updated based on the new fuel-based emission rates for light-duty trucks. We assume that the fuel-based ammonia emission rates are similar between light-duty and heavy-duty gasoline vehicles because the same ammonia formation pathway is present for both vehicles types. In modern gasoline vehicles, ammonia is formed from the catalytic reduction of NO in the three-way catalytic converter during fuel-rich conditions.

Limited data is available to evaluate this assumption. Livingston et al. (2009) [147] measured ammonia emissions from vehicles recruited in southern California. On average, they measured higher gram per mile ammonia rates from the six medium-duty gasoline vehicles than the 35 light-duty vehicles. They attributed the higher ammonia emission rates from the medium-duty vehicles due to:

1) Larger exhaust volumes produced by the medium-duty vehicles
2) Less stringent emission standards, which would lead to higher precursor exhaust emissions of $NO_x$ and CO
3) Potentially different catalyst activity

By estimating heavy-duty gasoline emission rates from light-duty gasoline vehicle fuel-based emission rates, and heavy-duty gasoline fuel rates, we account for the larger exhaust volumes produced by heavy-duty gasoline vehicles. While, we do not account for items 2) and 3), which could lead to higher fuel-based emission rates from heavy-duty gasoline vehicles, we believe our approach is reasonable given that heavy-duty gasoline vehicles are anticipated to be a minor contributor of ammonia emissions in comparison to light-duty gasoline vehicles.

The light-duty truck fuel-based ammonia emission rates are documented in the light-duty exhaust emission rate report.[9] The fuel-based emission rates are estimated for light-duty vehicles and light-duty trucks by model year and vehicle age.

We estimated the ammonia emission rate for heavy-duty gasoline vehicles by multiplying the light-duty truck fuel-specific emission rates by regulatory class, model year group, and age $\left(\overline{LDT\ FER}_{MY,age}\right)$ by the MOVES3 heavy-duty gasoline vehicle fuel-consumption rates by regulatory class, model year, operating mode $\left(HDG\ Fuel\ Rates_{Reg,MY,op}\right)$ as shown in Equation 5-6.

$$\overline{HDG\ ER}_{Reg,MY,age,op} = HDG\ Fuel\ Rates_{Reg,MY,op} \times \overline{LDT\ FER}_{MY,age} \qquad \textbf{Equation 5-6}$$

Example $NH_3$ emission rates in MOVES for LHD2b3 and LHD45 gasoline vehicles for model year 2017 and ages 0-3 are shown in Figure 5-2

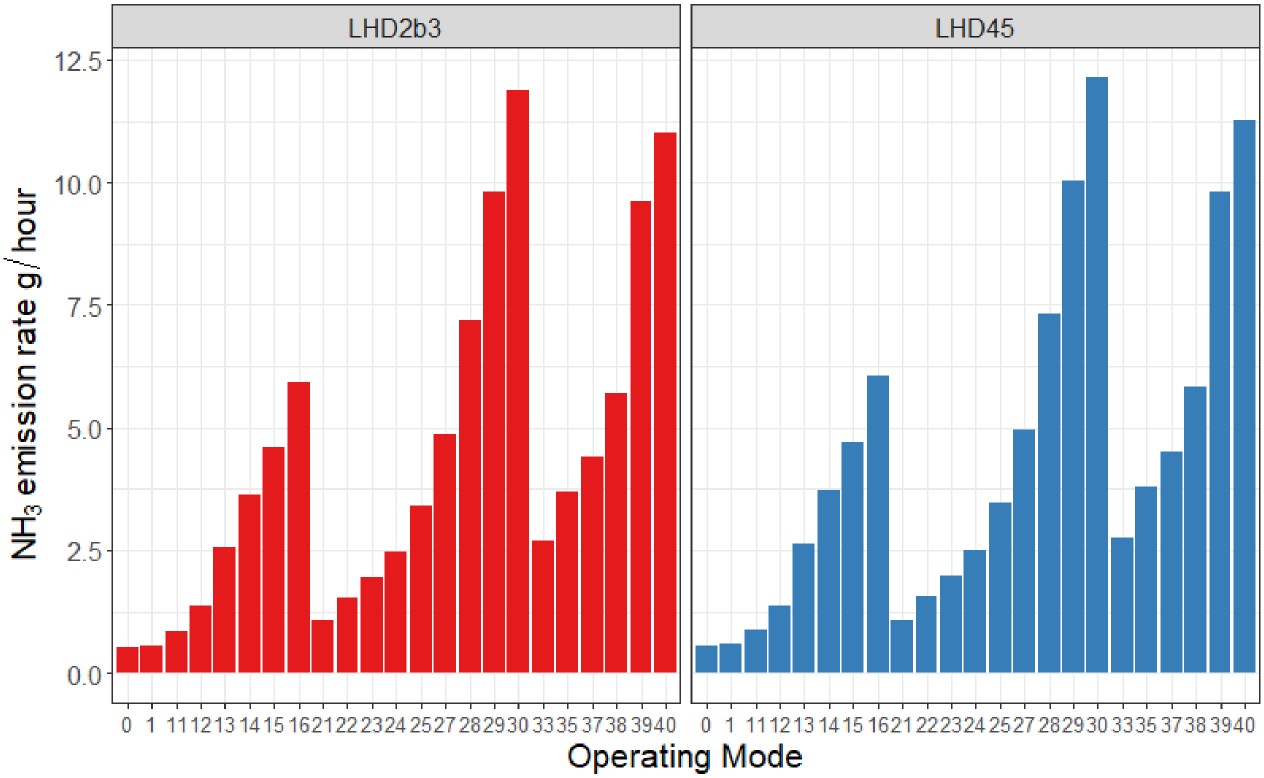

**Figure 5-2. $NH_3$ emission rates (g/hour) by operating mode for regulatory class LHD2b3 and LHD45 and Model Years 2017 for ages 0-3.**

## *5.3 Heavy-Duty Compressed Natural Gas*

CNG vehicles with stoichiometric three-way catalysts have been shown to emit higher ammonia emissions than CNG vehicles with lean-burn combustion.[135,136] Since ammonia measurements were not part of the HDIUT program used to update CNG emission rates described in Section 4.1.2, the ammonia emission rates for CNG vehicles were set equal to the ammonia emission rates from heavy-duty gasoline vehicles by regulatory class, model year, operating mode, and vehicle age. The extended idle emission rates for CNG vehicles are set equal to the running idle rates.

Two studies have demonstrated that stoichiometric emission rates from CNG vehicles can be significantly higher than those from heavy-duty gasoline vehicles.[148],[149] However, one recent study by CE-CERT has shown more moderate $NH_3$ emissions from CNG vehicles.[150] These data have yet to be incorporated into MOVES.

## *5.4 Summary*

Figure 5-1 displays the age 0-3 ammonia emission rate for heavy-duty vehicles by regulatory class and fuel type.

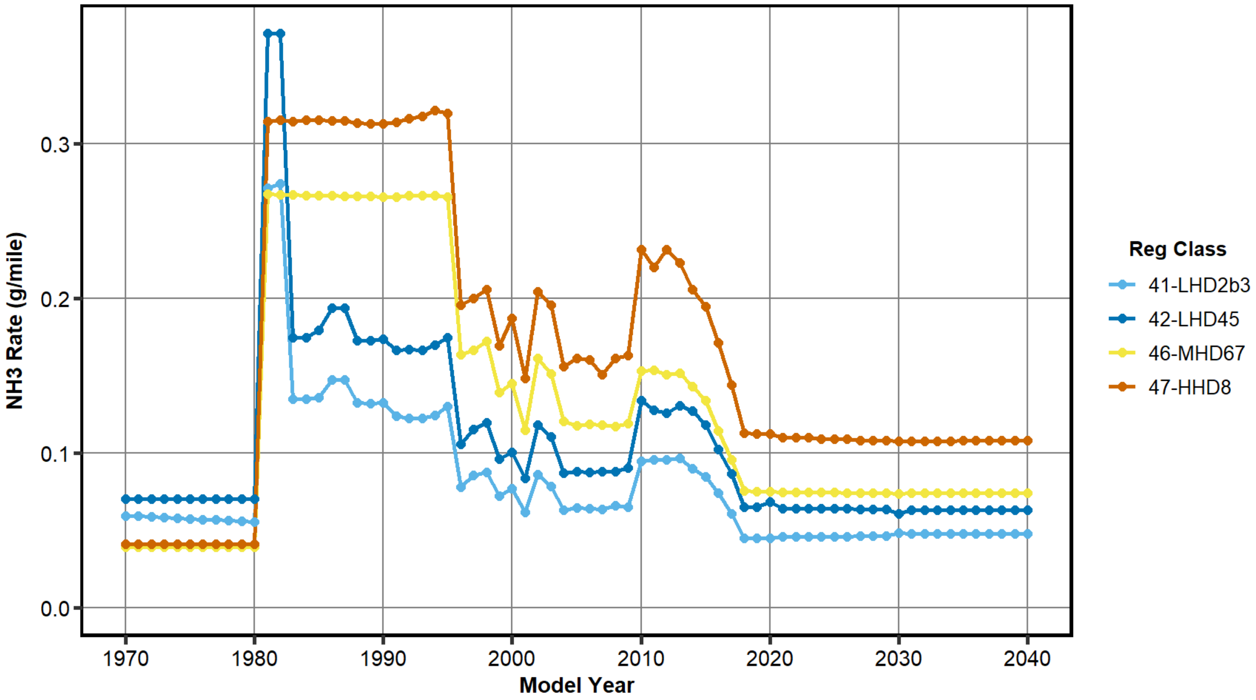

**Figure 5-3: Base running emission rates for $NH_3$ from age 0-3 gasoline heavy-duty vehicles averaged over a nationally representative operating mode distribution**

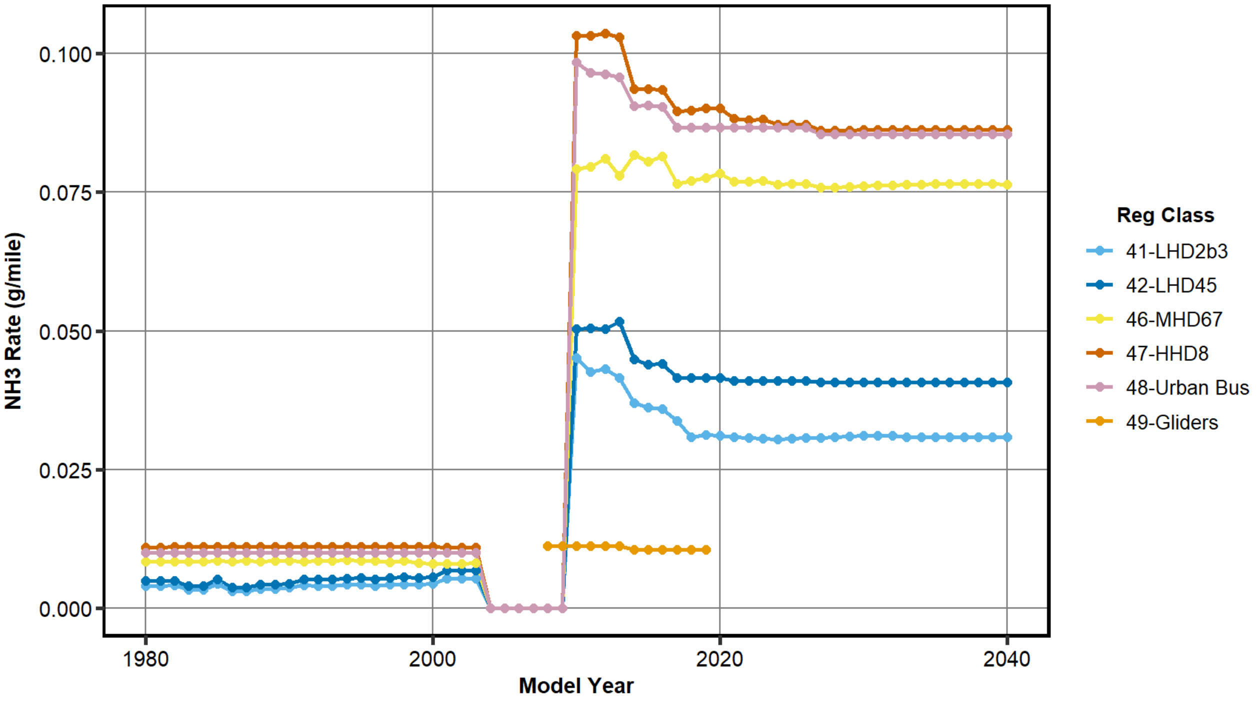

**Figure 5-4: Base running emission rates for** $NH_3$ **from age 0-3 diesel heavy-duty vehicles averaged over a nationally representative operating mode distribution**

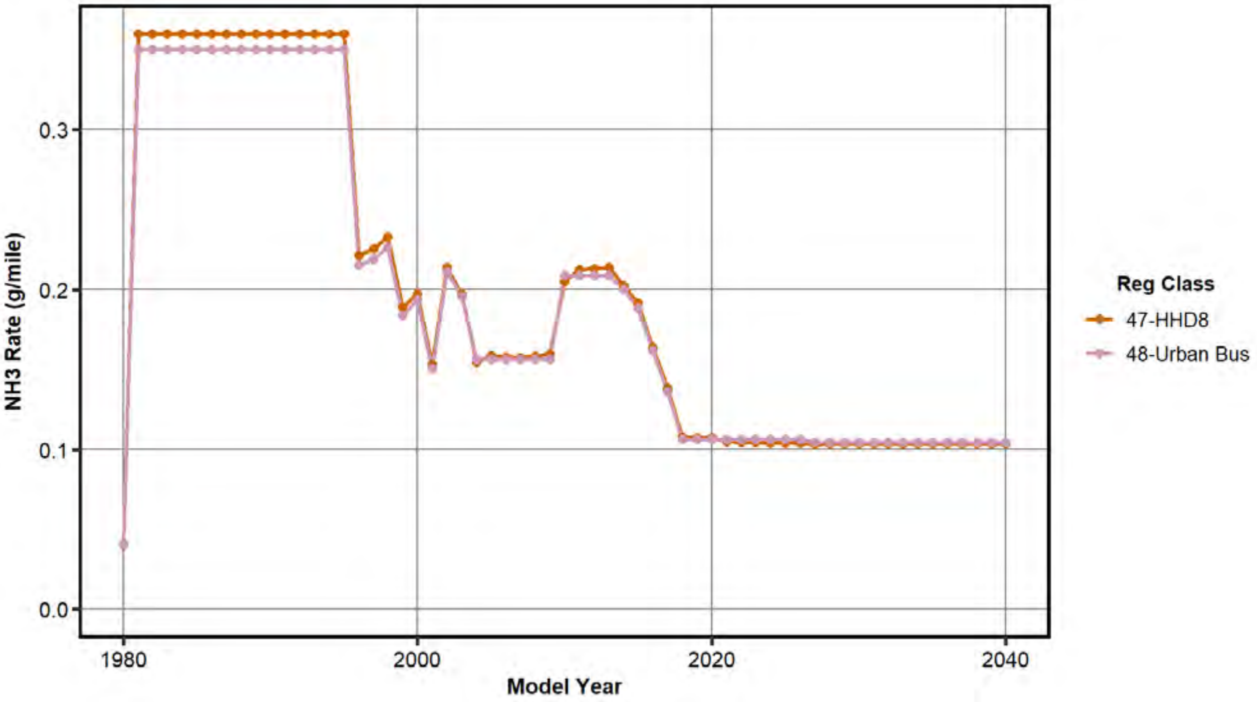

Figure 5-5: **Base running emission rates for** $NH_3$ **from age 0-3 CNG heavy-duty vehicles averaged over a nationally representative operating mode distribution**

# 6 Heavy-Duty Crankcase Exhaust Emissions

Crankcase exhaust emissions, also referred to as crankcase blowby, are combustion gases that pass the piston rings into the crankcase and are subsequently vented to the atmosphere. Crankcase blowby includes oil-enriched air from the turbocharger shaft, air compressors, and valve stems that enters the crankcase. The crankcase blowby contains combustion generated pollutants, as well as oil droplets from the engine components and engine crankcase.[151]

## *6.1 Modeling Crankcase Emissions in MOVES*

MOVES calculates crankcase emissions using two code modules: a gaseous and a particulate matter crankcase emission calculator. Within these calculators, crankcase emissions are calculated in relationship to tailpipe exhaust emissions. In MOVES, the tailpipe exhaust processes are running exhaust, start exhaust, and extended idle exhaust (processID 1, 2, 90). The corresponding crankcase emission processes are crankcase running exhaust, crankcase start exhaust, and crankcase extended idle exhaust (processID 15, 16, 17).

The gaseous crankcase calculator chains calculation of the crankcase emission rates to the tailpipe exhaust emission rates for gaseous pollutants, but it does not change the tailpipe exhaust emission rates. On the other hand, the particulate matter calculator has the ability to divide the particulate matter exhaust emission rates stored in the emissionratebyage and emissionrate table into components representing the contributions from tailpipe exhaust and crankcase emissions. Thus, the particulate ratios may be used to adjust the particulate matter tailpipe exhaust emission rates to account for the crankcase contribution, as was done in previous versions of MOVES. In MOVES4, however, the particulate matter tailpipe exhaust emission rates only include tailpipe emissions and the exhaust ratios are set equal to one as shown in the subsequent sections for all model years, fuel types, regulatory classes and source types. More details on the particulate matter crankcase calculator are provided in the MOVES Speciation Report.[1]

The crankcase ratios for non-methane hydrocarbons (NMHC), $NO_x$, and $PM_{2.5}$ are used to estimate the crankcase emissions for each subspecies that is chained to their respective primary pollutant as shown in Table 6-1. The crankcase emission ratios for both gaseous and particulate matter pollutants are stored in the crankcaseEmissionRatio table. The table stores the crankcase emission rates by pollutant, process, model year, source type, regulatory class, and fuel type. Regulatory class was added as a primary field in MOVES4, and the crankcase emission ratios were updated according to regulatory class. The table structure and code retain the ability to model separate crankcase emission ratios by source type, but we use the same crankcase emission ratios across different source types within the same fuel type, regulatory class and model year.

The $PM_{10}$ crankcase emission rates are subsequently estimated from the $PM_{2.5}$ exhaust and crankcase emission rates using $PM_{10}/PM_{2.5}$ emission ratios as documented in the MOVES Speciation Report.[1]

**Table 6-1 Speciation of Chained Crankcase Pollutants from the Primary Pollutants**

| Primary Pollutant | Chained Crankcase Pollutant |
|---|---|
| Non-methane hydrocarbons (NMHC) | Benzene, Dibenzo(a,h)anthracene gas, 1,3-Butadiene, Fluoranthene gas, Formaldehyde, Acenaphthene gas, Acetaldehyde, Acenaphthylene gas, Acrolein, Anthracene gas, 2,2,4-Trimethylpentane, Benz(a)anthracene gas, Ethyl Benzene, Benzo(a)pyrene gas, Hexane, Benzo(b)fluoranthene gas, Propionaldehyde, Benzo(g,h,i)perylene gas, Styrene, Benzo(k)fluoranthene gas, Toluene, Chrysene gas, Xylene, Fluorene gas, non-methane organic gas (NMOG), Indeno(1,2,3,c,d)pyrene gas, volatile organic carbon (VOC), Phenanthrene gas, Naphthalene gas, Pyrene gas |
| $NO_x$ | NO, $NO_2$, HONO |
| $PM_{2.5}$ | EC, $SO_4$, $H_2O$(aerosol), NonECNonSO$_4$PM |

By using crankcase to tailpipe emission ratios to estimate crankcase emission rates, MOVES implicitly assumes that any increase in emissions due to aging and deterioration also occurs for crankcase emissions. The data sets used to derive the crankcase emission rates for 2007 and later heavy-duty diesel engines are based on engines and vehicles with relatively low miles and no expected deterioration in the emission control system. If crankcase emissions do not exhibit the same increase in deterioration as tailpipe emissions, this method would lead to an overestimation of crankcase emissions in older vehicles.

## 6.2 Heavy-Duty Diesel Crankcase Emissions

Crankcase emissions from pre-2007 diesel engines were typically vented to the atmosphere using an open unfiltered crankcase system, referred to as a 'road draft tube'.[151] Researchers have found that crankcase emissions vented to the atmosphere can be the dominant source of diesel particulate matter concentrations measured within the vehicle cabin.[152,153,154]

Starting in model year 2001, federal regulations require closed crankcase systems for chassis-certified diesel vehicles.[155] Federal regulations permit 2006-and-earlier engine-certified diesel vehicles equipped with "turbochargers, pumps, blowers, or superchargers" to vent crankcase emissions to the atmosphere.[156] Starting in model year 2007, federal regulations no longer permit crankcase emissions to be vented directly to the atmosphere, unless they are included in the certification exhaust measurements.[156] Many heavy-duty diesel manufacturers have adopted open crankcase filtration systems in model year 2007 and later engines.[151] These systems vent the exhaust gases to the atmosphere after the gases have passed a coalescing filter which removes oil and a substantial fraction of the particles in the crankcase blowby.[151] In the ACES Phase 1 program, four MY 2007 diesel engines from major diesel engine manufactures (Caterpillar, Cummins, Detroit Diesel, and Volvo) all employed filtered crankcase ventilation systems.[157]

A summary of published estimates of diesel crankcase emissions as percentages of the total emissions (tailpipe + crankcase) are provided in
Table 6-2. For the pre-2007 diesel technologies, hydrocarbon and particulate matter emissions have the largest contributions from crankcase emissions. There is a substantial decrease in $PM_{2.5}$ emissions beginning with the 2007 model year diesel engines. The aftertreatment technologies required for 2007-and-later engines reduces the tailpipe emissions more than the crankcase

emissions, resulting in an increase in the relative crankcase contribution for THC, CO, and $PM_{2.5}$ emissions.

**Table 6-2 Literature Review on the Contribution of Crankcase Emissions to Diesel Exhaust (Tailpipe + Crankcase)**

| Study | Model Year | Tailpipe Exhaust Aftertreatment | # Engines or Vehicles | THC | CO | $NO_x$ | PM |
|---|---|---|---|---|---|---|---|
| Hare and Baines, 1977[160] | 1966,<br>1973 | None | 2 | 0.2%-3.9% | 0.01%-0.4% | 0.01%-0.1% | 0.9%-2.8% |
| Zielinska et al. 2008[152]<br>Ireson et al. 2011[153] | 2000,<br>2003 | None | 2 | | | | 13.5% - 41.4% |
| Clark et al. 2006[159]<br>Clark et al. 2006[158] | 2006 | None | 1 | 3.6% | 1.3% | 0.1% | 5.9% |
| Khalek et al. 2009[47]<br>("ACES Phase 1") | 2007 | DPF-equipped | 4 | 84.6% | 33.5% | 0.007% | 44.4% |
| NVFEL Testing | 2015,<br>2018 | SCR-DPF | 2 | 19.0%-57.8% | 14.2%-76.7% | 2.3%-7.5% | Not measured |

Note:
The crankcase ratios shown here are a fraction of the total tailpipe and crankcase exhaust. The crankcase ratios used in MOVES are a ratio of crankcase to tailpipe exhaust.

As discussed in the following subsections, we developed crankcase emission ratios by regulatory class and model years groups using the available studies in
Table 6-2, and additional information on requirements for closed crankcase systems.

The data on crankcase emissions are limited. The gaseous crankcase emission rates for heavy-duty diesel vehicles are based on three studies in
Table 6-2, totaling only seven vehicles. As such, the rates have considerable, but unquantified, uncertainties.

### 6.2.1 LHD2b3 Crankcase Emissions

After 2001, all chassis-certified vehicles, including diesel vehicles, are required to avoid venting crankcase emissions into the atmosphere.[155] All LHD2b3 vehicles in MOVES4 are chassis-certified vehicles because the small number of engine-certified LHD2b3 vehicles are re-classified as LHD45 vehicles as discussed Section 1.4.

MOVES uses two model year groups for crankcase emissions from LHD2b3 diesel vehicles. Model year 1960 to 2000 vehicles use the open crankcase ratios estimated for engine-certified vehicles as detailed in Section 6.2.2.1. For model year 2001 to 1960 we estimate zero crankcase ratios because all chassis-certified diesel vehicles are required to have closed crankcase systems.

## 6.2.2 *LHD45, MHD and HHD Crankcase Emissions*

Diesel vehicles within the LHD45, MHD, and HHD regulatory classes are composed of 100% engine-certified vehicles, which are permitted to emit crankcase emissions after model year 2007 if they are accounted for in the engine-certification results. The crankcase emission rates for the engine-certified vehicles are estimated by regulatory class and model year groups, to capture differences in crankcase emission ratios reported from different studies, account for differences in the crankcase control in 2007 and later model years, and to account for changes in tailpipe exhaust emissions which impact the crankcase to tailpipe emission ratios.

### *6.2.2.1 1960-2006 Model Years*

Table 6-3 displays the crankcase/tailpipe emission ratios used for pre-2007 diesel exhaust. For THC, CO, and $NO_x$, we selected the values measured on the MY 2006 diesel engine reported by Clark et al. 2006.[159] These values compare well with the previous HC, CO, $NO_x$ values reported much earlier by Hare and Baines (1977),[160] which represent much older diesel technology. The similarity of the crankcase emission ratios across several decades of diesel engines suggests that for pre-2007 diesel engines, crankcase emissions can be reasonably well represented as a fraction of the exhaust emissions. The THC crankcase ratios presented in Table 6-3 are also used for methane, total organic gases (TOG), non-methane hydrocarbons (NMHC) and all the pollutants chained to NMHC listed in Table 6-1.

For $PM_{2.5}$ emissions, we use a crankcase/tailpipe ratio of 20 percent. The 20 percent ratio falls within the range of observations from the literature on diesel PM emissions. Zielinska et al. 2008[152] and Ireson et al. 2011[153] reported crankcase contributions to total $PM_{2.5}$ emissions as high as 40 percent. Jääskeläinen (2012)[151] reported that crankcase can contribute as much as 20 percent of the total emissions from a review of six diesel crankcase studies. Similarly, an industry report estimated that crankcase emissions contributed 20 percent of total particulate emissions from 1994-2006 diesel engines.[161] The crankcase emission ratios shown Table 6-3 are applied to running, start and extended idle exhaust to estimate the corresponding crankcase exhaust emissions.

**Table 6-3 LHD45, MHD, and HHD 1960-2006 Diesel Crankcase Ratios for HC, CO, $NO_x$, and $PM_{2.5}$**

| Pollutant | Crankcase/Tailpipe Ratio (MOVES inputs) | Crankcase/(Crankcase + Tailpipe) Ratio |
|---|---|---|
| THC | 0.037 | 0.036 |
| CO | 0.013 | 0.013 |
| $NO_x$ | 0.001 | 0.001 |
| $PM_{2.5}$ | 0.200 | 0.167 |

Note:
MOVES uses a crankcase/tailpipe ratios. We also calculated the crankcase to total exhaust ratio (crankcase + tailpipe) to compare the MOVES inputs to the values reported in the literature

As outlined in the MOVES Speciation Report, MOVES does not apply the crankcase/tailpipe emission ratio in Table 6-3 to the total exhaust $PM_{2.5}$ emissions. MOVES applies crankcase/tailpipe emission ratios to $PM_{2.5}$ subspecies: elemental carbon $PM_{2.5}$, sulfate $PM_{2.5}$, aerosol water $PM_{2.5}$, and the remaining PM (nonECnonSO4PM). This allows MOVES to account for important differences in the PM speciation between tailpipe and crankcase emissions. Tailpipe exhaust from pre-2007 diesel engines is dominated by elemental carbon emissions from combustion of the diesel fuel, while crankcase emissions are dominated by organic carbon emissions largely contributed by the lubricating oil.[152,153] Zielinska et al. 2008[152] reported that the EC/PM fraction of crankcase emissions from two pre-2007 diesel buses is 1.57 percent.

To account for the different speciation of exhaust and crankcase emissions, the crankcase emission factors for PM species shown in Table 6-4 have been back-calculated such that the total crankcase $PM_{2.5}$ emissions are 20 percent of the $PM_{2.5}$ exhaust measurements (consistent with Table 6-3) and have an EC/PM split of 1.57 percent. The start and extended idle crankcase ratios are the same, because the pre-2007 start and extended idle exhaust EC/PM are the same ( both 46.4% as documented in Section 2.2.2 and Section 2.3.1). The running exhaust EC/PM ratio is 79% (Section 2.1.2.1.8).

The tailpipe exhaust fractions are set equal to 1 because the tailpipe emission rates are not assumed to include any crankcase emissions. In other words, the crankcase emissions are estimated in addition to the tailpipe emissions.

**Table 6-4. LHD45, MHD, and HHD Exhaust and Crankcase Ratios for 1960-2006 Diesel by Pollutant, Process, and Model Year Group for $PM_{2.5}$ Species**

| Pollutant | Process | Start | Running | Extended Idle |
|---|---|---|---|---|
| EC | Tailpipe Exhaust | 1 | 1 | 1 |
| nonECnon$SO_4$PM | | 1 | 1 | 1 |
| $SO_4$ | | 1 | 1 | 1 |
| $H_2O$ | | 1 | 1 | 1 |
| EC | Crankcase | 0.007 | 0.004 | 0.007 |
| nonECnon $SO_4$PM | | 0.367 | 0.937 | 0.367 |
| $SO_4$ | | 0.367 | 0.937 | 0.367 |
| $H_2O$ | | 0.367 | 0.937 | 0.367 |

#### *6.2.2.2 2007-2009 Model Years*

As discussed in the background section above, the 2007 heavy-duty diesel emission regulations impacted the technologies used to control exhaust and crankcase emissions. The regulations also expanded the types of emissions data included in certification tests by including crankcase emissions in the regulatory standards which previously included only tailpipe emissions. Because heavy-duty diesel engine manufacturers are using open-filtration crankcase systems, the crankcase emissions are included in the emission certification results. In MOVES, the base exhaust rates for 2007 to 2009 diesel engines are based on certification test results for $PM_{2.5}$ as discussed in this section.

The crankcase ratios for 2007-2009 HDD emissions are based on the ACES Phase 1 study[157], which tested four MY 2007 engines from different manufactures (Caterpillar, Cummins, Detroit Diesel and Volvo). The ACES Phase 1 engines and exhaust control systems were new, and underwent 125 hours of "degreening" before the test program. Thus, they represent low-mileage, properly functioning heavy-duty diesel engine emissions. In reporting the emission rates, the engines were anonymized as A, B, C, D and a backup engine B’ which was tested at a secondary site. The B’ backup engine is the same make, model as engine B. The ACES study conducted hot FTP cycles that sampled tailpipe exhaust emissions and repeat tests that sampled combined tailpipe and crankcase exhaust. The crankcase emission rates for each engine were estimated by calculating the difference between the average emissions measured with and without crankcase emissions routed into the sampling system as shown in Equation 6-1, where average emissions are the total mass divided by the testing time.

$$\mathrm{CC_{emissions,i}} = \mathrm{Exhaust_{withCC,i}} - \mathrm{Exhaust_{w/oCC,i}}$$ **Equation 6-1**

Where:

$\mathrm{CC_{emissions,i}}$= crankcase emissions (grams per hour) for engine i

$\mathrm{Exhaust_{withCC,i}}$=hot-FTP cycle average emission emissions (grams per hour) for each engine i with the crankcase routed into the sampling system

$\mathrm{Exhaust_{w/oCC,i}}$= hot-FTP cycle average emission emissions (grams per hour) for each engine i without the crankcase

Then the crankcase emission rates were averaged together in Equation 6-2 with the backup engine being treated as additional tests of engine B.

$$\mathrm{CC_{ACESavg}} = \frac{\left(\mathrm{CC_{engineA}} + \frac{\mathrm{CC_{engineB}} + \mathrm{CC_{engineB',site1}} + \mathrm{CC_{engineB',site2}}}{3} + \mathrm{CC_{engineC}} + \mathrm{CC_{engineD}}\right)}{4}$$ **Equation 6-2**

Since ACES Phase 1 hot-FTP contained a hot-start we assume starts are accounted for in the running values, and thus for these model years, the crankcase ratio for starts is zero. Note that for similar 2010+ vehicles, where cold start crankcase emissions were measured, positive crankcase starts were measured for only for CO as discussed in Section 6.2.2.3. And, for extended idle, based upon data from 2010+ HDD vehicles using the same crankcase technology that show the crankcase emission rates for extended idling are similar to the running rates, we use the hot-FTP rates from ACES Phase 1 for the crankcase extending idling rates. The crankcase rates for running, starts and extended idle are listed in Table 6-5.

Equation 6-3 is used to calculate TOG crankcase emissions from the methane and NMHC crankcase values, using the MOVES NMOG/NMHC value for 2007-2009 MY diesel exhaust.[1]

$$\mathrm{TOG}\left(\frac{\mathrm{g}}{\mathrm{hr}}\right) = \mathrm{CH_4}\left(\frac{\mathrm{g}}{\mathrm{hr}}\right) + \mathrm{NMHC}\left(\frac{\mathrm{g}}{\mathrm{hr}}\right) * \frac{\mathrm{NMOG}}{\mathrm{NMHC}}$$ **Equation 6-3**

Where each pollutant rate is in g/hr and the ratio of NMOG/NMHC is 1.343 from the hcspeciation table in MOVES.[1]

**Table 6-5 The MY 2007 crankcase exhaust rates ($CC_{ACESavg}$) from ACES Phase 1 FTP cycle used for running and extended idling (g/hr)**

| CO | $NO_x$ | THC | $CH_4$ | NMHC | TOG | Total $PM_{2.5}$ |
|---|---|---|---|---|---|---|
| 8.15 | 0.79 | 1.76 | 0.38 | 1.37 | 2.23 | 0.04 |

The crankcase ratios for the ACES program in Table 6-2 are calculated using Equation 6-4 where the $\text{Exhaust}_{\text{ACES}}$ is calculated using Equation 6-2, but using $\text{Exhaust}_{\text{w/oCC,i}}$ in place of the crankcase values.

$$CC_{\text{ACES ratio}} = \frac{CC_{\text{ACESavg}}}{CC_{\text{ACESavg}} + \text{Exhaust}_{\text{ACES}}}$$ **Equation 6-4**

We then calculated the crankcase ratios for use in MOVES using the MOVES MY 2007-2009 exhaust base rates for all diesel HHD vehicles (regClass 47) weighted by the activity of short and long-haul single-unit and combination trucks (sourcetypes 52,53,61,62) in each operating mode estimated from a preliminary MOVES3 national scale run. The values for $\text{Exhaust}_{\text{MOVES}}$ are listed in Table 6-6. The extended idle rates are based on a single operating mode in MOVES. We used the HHD diesel emission rates to match the HHD engines tested in the ACES Phase 1 program.

**Table 6-6: The MY 2007-2009 MOVES exhaust base rates (g/hr) for running (weighted by operating mode activity) and extended idling**

| | CO | $NO_x$ | THC | $CH_4$ | NMHC | TOG | Total $PM_{2.5}$ |
|---|---|---|---|---|---|---|---|
| Running Exhaust | 11.46 | 288.51 | 2.93 | 1.73 | 1.20 | 3.34 | 0.88 |
| Extended Idle Exhaust | 39.26 | 100.45 | 8.49 | 5.00 | 3.49 | 9.69 | 0.087 |

We then used Equation 6-5 to estimate the base crankcase to tailpipe exhaust ratio for 2007-2009 HD vehicles.

$$CC_{\text{ratio,base}} = \frac{CC_{\text{ACESavg}}}{\text{Exhaust}_{\text{MOVES}}}$$ **Equation 6-5**

We assume that crankcase emissions are proportional to the tailpipe exhaust emissions across regulatory classes and source types. As such, we use the $CC_{\text{ratio,base}}$ to derive the crankcase ratio for all heavy-duty diesel regulatory classes and source types. The heavy-duty base crankcase ratios are shown in Table 6-8.

As mentioned in the background section, many manufactures employ an open crankcase ventilation system with a coalescing filter, but a substantial fraction opt for a closed crankcase system where the crankcase vapors are either routed into the engine with the fuel injection or into the exhaust stream upstream of the aftertreatment. For developing crankcase emission ratio estimates, we model heavy-duty diesel closed crankcase systems as having zero crankcase emissions, and reduce the base open crankcase emission ratios to account for the fraction of open crankcase systems in the vehicle fleet.

Available certification data on the prevalence of open and closed crankcase systems are incomplete, but the available data suggests that most manufacturers use either open or closed systems for all their engines in a given model year. We assumed that any engine family listed in the certification data with missing crankcase information was of the same type as all other engine families in that model year for that manufacturer. This was our best assumption based on the available data, despite finding one conflict.[ss] We then used manufacturer production volume data from 2016-2018 (complete data for earlier years was not available) to weight the number of open and closed systems within each regulatory class as shown in Table 6-7. In these model years, there were between 9 and 10 engine manufacturers which produced heavy-duty engines, with between 34 and 41 certified engine families. Using this method, we estimated that 0% of LHD engines, 90.5% of medium heavy-duty and 67% of HHD engines have open crankcase systems. The average value across the 2016-2017 model years and by regulatory classes was used for all 2007 and later engines.[tt]

**Table 6-7 Fraction of Engines with Open Crankcase Systems by Vehicle Regulatory Class and Model Year**

| Model Year | LHD | MHD | HHD |
|---|---|---|---|
| 2016 | 0 | 0.912 | 0.725 |
| 2017 | 0 | 0.919 | 0.635 |
| 2018 | 0 | 0.884 | 0.640 |
| average | 0 | 0.905 | 0.666 |

Finally, to estimate the MY 2007-2009 crankcase emission ratios for MOVES, we assume that crankcase emissions are proportional to the exhaust emissions across each of the engine-certified regulatory classes and source types. To estimate the crankcase emission ratio for each regulatory class, we multiplied the open crankcase ratio, $\mathrm{CC}_{\mathrm{ratio,base}}$, by the open crankcase fraction of each heavy-duty regulatory class, $\mathrm{OpenCC}_{\mathrm{frac,regClass}}$ as shown in Equation 6-6.

$$\mathrm{CC}_{\mathrm{ratio,regClass,modelyear}} = \mathrm{CC}_{\mathrm{ratio,base}} * \mathrm{OpenCC}_{\mathrm{frac}} \qquad \textbf{Equation 6-6}$$

Where

$\mathrm{CC}_{\mathrm{ratio,regClass,model\ year}}$= the crankcase ratio used in MOVES by regulatory class and model year
$\mathrm{CC}_{\mathrm{ratio,base}}$= the heavy-duty open crankcase ratio calculated from Equation 6-5
$\mathrm{OpenCC}_{\mathrm{frac,regClass}}$= the fraction of open crankcase systems by regulatory class determined from certification data and manufacture production volume as shown in Table 6-7

The MOVES 2007-2009 crankcase ratios for THC, $CH_4$, NMHC, TOG, $NO_x$, CO, and $PM_{2.5}$ for each crankcase process for LHD45, MHD, HHD and Urban Bus regulatory classes are shown in Table 6-8.

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[ss] One of the engine manufacturers that we assumed produced closed crankcase systems for all of its 2007 and later model year engines based on certification data produced one of the open crankcase MY 2007 engine tested in the ACES Phase 1 program.

[tt] We recognize the uncertainties in applying open crankcase values from model year 2016-2018 engines to model year 2007-2009 engines. However, the larger uncertainty in the crankcase emission rates is driven by the measured crankcase emission rates. Assuming an HHD open crankcase percentage of 67% decreased the crankcase tailpipe emission rates by roughly one third, which is well within the range of variability of emissions observed in the ACES Phase 1 crankcase emission results.

**Table 6-8 Crankcase/Tailpipe Ratios for Model Year 2007-2009 Engine-certified Vehicles by Heavy-duty Diesel Regulatory Class**

| Process | Pollutant | HD baseline (Equation 6-5) | Crankcase/Tailpipe ratio by regulatory class (Equation 6-6) | | | |
|---|---|---|---|---|---|---|
| | | | LHD45 | MHD | HHD | Urban Bus |
| Running | THC | 0.600 | 0 | 0.543 | 0.400 | 0.400 |
| | $CH_4$ | 0.223 | 0 | 0.201 | 0.148 | 0.148 |
| | NMHC | 1.141 | 0 | 1.032 | 0.760 | 0.760 |
| | TOG | 0.667 | 0 | 0.603 | 0.444 | 0.444 |
| | $CO_2$ | 0.005 | 0 | 0.004 | 0.003 | 0.003 |
| | CO | 0.711 | 0 | 0.644 | 0.474 | 0.474 |
| | $NO_x$ | 0.003 | 0 | 0.002 | 0.002 | 0.002 |
| | PM | 0.043 | 0 | 0.039 | 0.029 | 0.029 |
| Starts | THC | 0 | 0 | 0 | 0 | 0 |
| | $CH_4$ | 0 | 0 | 0 | 0 | 0 |
| | NMHC | 0 | 0 | 0 | 0 | 0 |
| | TOG | 0 | 0 | 0 | 0 | 0 |
| | $CO_2$ | 0 | 0 | 0 | 0 | 0 |
| | CO | 0 | 0 | 0 | 0 | 0 |
| | $NO_x$ | 0 | 0 | 0 | 0 | 0 |
| | PM | 0 | 0 | 0 | 0 | 0 |
| Extended Idle | THC | 0.207 | 0 | 0.187 | 0.138 | 0.138 |
| | $CH_4$ | 0.077 | 0 | 0.070 | 0.051 | 0.051 |
| | NMHC | 0.394 | 0 | 0.356 | 0.262 | 0.262 |
| | TOG | 0.230 | 0 | 0.208 | 0.153 | 0.153 |
| | $CO_2$ | 0.054 | 0 | 0.049 | 0.036 | 0.036 |
| | CO | 0.208 | 0 | 0.188 | 0.138 | 0.138 |
| | $NO_x$ | 0.008 | 0 | 0.007 | 0.005 | 0.005 |
| | PM | 0.436 | 0 | 0.394 | 0.290 | 0.290 |

[A] $CO_2$ is not included in the MOVES crankcaseEmissionRatio table, in part due to its small fraction compared to running exhaust $CO_2$. However, it is included here for comparison with other pollutants.

For $PM_{2.5}$ emissions, MOVES applies crankcase ratios to each of the intermediate $PM_{2.5}$ species (EC, nonECnonSO4PM, SO4, and H2O). The MOVES $PM_{2.5}$ speciation profile developed from the ACES Phase 1 study combined the crankcase and tailpipe emissions. As such, we model crankcase emissions as having the same speciation as tailpipe emissions, and the crankcase fractions for the intermediate $PM_{2.5}$ species in Table 6-9 are the same as derived for total $PM_{2.5}$ in Table 6-8. In MOVES4, we set the tailpipe ratios for model year 2007-2009 equal to one because we now assume that the tailpipe emission factors only include tailpipe exhaust. This approach was taken because the 2007-2009 model year running $PM_{2.5}$ emission rates are based on assumed reductions from MY 1998-2006 vehicles based on certification data (See Section 2.1.2.1.7). Assuming the resulting running PM emission rates in 2007-2008 only include tailpipe exhaust was deemed equally valid as our previous assumption, and simplifies the calculation of crankcase emissions by keeping all tailpipe ratios in the crankcase calculator equal to one. The extended idle emissions for model year 2007-2009 are based on tailpipe measurements only, and using a extended idle ratio equal to one is consistent with the measured data. The peer-reviewers comments from the MOVES3 crankcase review agreed with this update.[162]

The crankcase emission ratios for MHD regulatory class for the intermediate PM species are the same as total $PM_{2.5}$ (0.039 for running and 0.394 for extended idle) as shown in Table 6-8.

**Table 6-9. MOVES Exhaust and Crankcase Ratios for Model Year 2007-2009 HHD Diesel by Pollutant and Process for $PM_{2.5}$ Species**

| Process | Model Year Group | Pollutant | Start | Running | Extended Idle |
|---|---|---|---|---|---|
| Tailpipe Exhaust | 2007-2009 | EC | 1 | 1 | 1 |
| | | nonECnon$SO_4$PM | 1 | 1 | 1 |
| | | $SO_4$ | 1 | 1 | 1 |
| | | $H_2O$ | 1 | 1 | 1 |
| Crankcase | 2007-2009 | EC | 0 | 0.0290 | 0.2929 |
| | | nonECnon $SO_4$PM | 0 | 0.0290 | 0.2929 |
| | | $SO_4$ | 0 | 0.0290 | 0.2929 |
| | | $H_2O$ | 0 | 0.0290 | 0.2929 |

#### *6.2.2.3 2010-2026 Model Years*

The HDIUT program (see Section 2.1.1.1) is used as the source of baseline exhaust emission rates for model year 2010-2026 diesel vehicles. As the HDIUT program measures tailpipe exhaust emissions from trucks in-use, the crankcase is not routed to the tailpipe and therefore not accounted for in the data. To account for crankcase emissions for 2010 and later diesel vehicles, we used direct crankcase measurements of $NO_x$, THC, CH4, and CO emissions from the US EPA's National Vehicle and Fuel Emissions Laboratory (NVFEL) testing of two heavy duty trucks (MY 2015 and MY 2019). Each of the trucks had less than 10,000 miles and represent properly functioning low-mileage heavy-duty vehicles. Testing was conducted on a chassis dynamometer over a drive cycle that consists of a hot or cold start followed by an ARB transient cycle (Phase 1), followed by four repetitions of the same ARB transient (Phase 2), 10 minutes of idling (Phase 3), and steady-state highway activity at 55 mph and 60 mph (Phase 4). The speed trace and a graphical indication of the testing phases are shown in Figure 6-1.

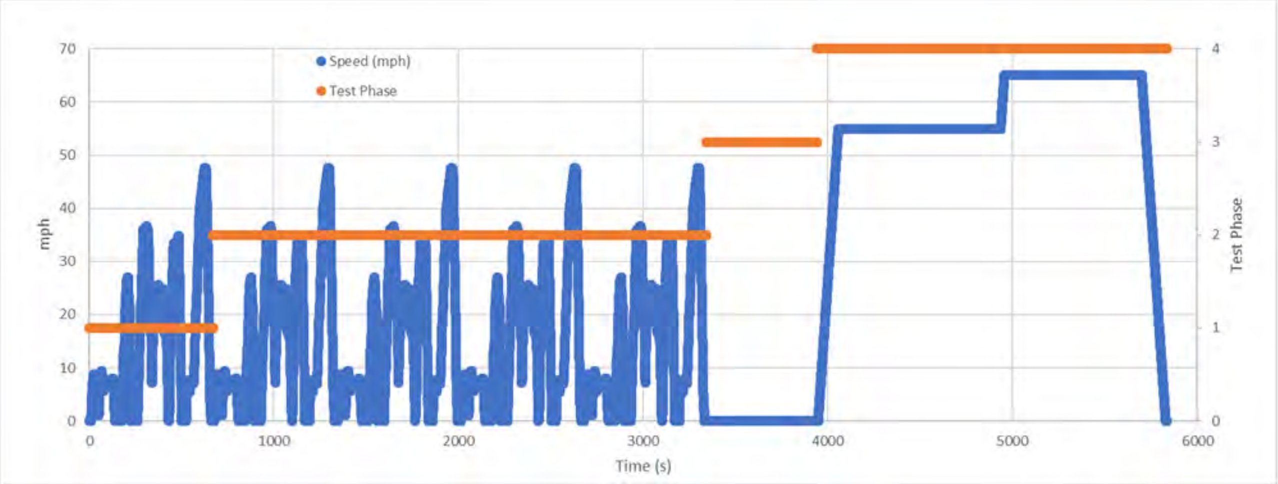


**Figure 6-1 Speed trace of the NVFEL testing program along with each phase**

There were a total of thirteen repetitions between the two trucks, with soak times between repetitions of either between one and three hours (hot start) or greater than twelve hours (cold start) as shown in Table 6-10.

**Table 6-10: Testing information for the NVFEL test program**

| Truck ID | Number of Tests | Dates of Testing | Soak Times |
|---|---|---|---|
| 1 | 6 (3 Hot Start, 3 Cold Start) | May 30, 2017 – June 1, 2017 | Hot Starts 1-3 hrs<br>Cold Starts 12+ hours |
| 2 | 7 (3 Hot Start, 4 Cold Start) | August 20, 2019 – August 13, 2019 | Hot Starts 1-3 hrs<br>Cold Starts 12+ hours |

Table 6-11 reports the average emission rates across the repetitions by truck and phase, and by phase only (weighting the two trucks equally).

**Table 6-11 NVFEL Vehicle average emission rates by testing phase and truck**

| | Crankcase CO (g/hr) | Crankcase $NO_x$ (g/hr) | Crankcase THC (g/hr) | Crankcase $CH_4$ (g/hr) |
|---|---|---|---|---|
| Phase 1 Average | 1.0900 | 0.4427 | 0.3463 | 0.0324 |
| Truck 1 average | 0.5057 | 0.5527 | 0.2373 | 0.0053 |
| Truck 2 average | 1.6742 | 0.3327 | 0.4552 | 0.0595 |
| Phase 2 Average | 0.6224 | 0.9086 | 0.4537 | 0.0155 |
| Truck 1 average | 0.1916 | 1.0316 | 0.2835 | 0.0001 |
| Truck 2 average | 1.0532 | 0.7855 | 0.6238 | 0.0309 |
| Phase 3 Average | 0.2461 | 0.7097 | 0.4529 | 0.0058 |
| Truck 1 average | 0.1670 | 0.7633 | 0.2634 | 0.0000 |
| Truck 2 average | 0.3252 | 0.6560 | 0.6424 | 0.0115 |
| Phase 4 Average | 0.2679 | 1.8447 | 0.5915 | 0.0053 |
| Truck 1 average | 0.1521 | 1.7766 | 0.3711 | 0.0000 |
| Truck 2 average | 0.3836 | 1.9127 | 0.8118 | 0.0106 |
| Average of all phase averages | 0.5677 | 0.9764 | 0.4611 | 0.0148 |

The average running rate was calculated by calculating a weighted average between Phase 2 (36.7%) and Phase 4 (63.3%). The phase-weighting was calculated to match the national running operating mode distribution for MY2015, HHD diesel vehicles in short- and long-haul single-unit and combination trucks (source type 52,53,61,62) as estimated in a MOVES national run using a draft version of MOVES3 for calendar year 2015.[72] Phase 2 had transient operation below 50 mph and was mapped to operating modes 0-30 (36.7% of total activity) and Phase 4 had constant high speed data and was mapped to operating-modes 33-40 (63.3% of total activity) as shown in Table 6-12. HHD diesel vehicles in short- and long-haul single-unit and combination trucks vehicles were chosen as to match the NVFEL testing vehicles.

**Table 6-12. Assignment of MOVES Operating Modes to Test Phase from the NVFEL data, and Phase weighting determined from the Operating Mode activity from a National draft MOVES run for MY 2015 HHD Vehicles in the Short- and Long-haul Single-unit and Combination Trucks Source Types**

| OpModeID | Operating Mode Description | Scaled Tractive Power ($STP_t$, skW) | Vehicle Speed ($v_t$, mph) | % of Total Activity from MOVES run | NVEL Test Phase |
|---|---|---|---|---|---|
| 0 | Deceleration/Braking | | | 2.69 | Phase 2 |
| 1 | Idle | | $v_t < 1.0$ | 5.40 | |
| 11 | Coast | $STP_t < 0$ | $1 \leq v_t < 25$ | 4.55 | |
| 12 | Cruise/Acceleration | $0 \leq STP_t < 3$ | $1 \leq v_t < 25$ | 6.62 | |
| 13 | Cruise/Acceleration | $3 \leq STP_t < 6$ | $1 \leq v_t < 25$ | 1.64 | |
| 14 | Cruise/Acceleration | $6 \leq STP_t < 9$ | $1 \leq v_t < 25$ | 1.00 | |
| 15 | Cruise/Acceleration | $9 \leq STP_t < 12$ | $1 \leq v_t < 25$ | 0.77 | |
| 16 | Cruise/Acceleration | $12 \leq STP_t$ | $1 \leq v_t < 25$ | 1.36 | |
| 21 | Coast | $STP_t < 0$ | $25 \leq v_t < 50$ | 3.37 | |
| 22 | Cruise/Acceleration | $0 \leq STP_t < 3$ | $25 \leq v_t < 50$ | 1.34 | |
| 23 | Cruise/Acceleration | $3 \leq STP_t < 6$ | $25 \leq v_t < 50$ | 1.54 | |
| 24 | Cruise/Acceleration | $6 \leq STP_t < 9$ | $25 \leq v_t < 50$ | 1.52 | |
| 25 | Cruise/Acceleration | $9 \leq STP_t < 12$ | $25 \leq v_t < 50$ | 1.04 | |
| 27 | Cruise/Acceleration | $12 \leq STP_t < 18$ | $25 \leq v_t < 50$ | 1.86 | |
| 28 | Cruise/Acceleration | $18 \leq STP_t < 24$ | $25 \leq v_t < 50$ | 0.98 | |
| 29 | Cruise/Acceleration | $24 \leq STP_t < 30$ | $25 \leq v_t < 50$ | 0.53 | |
| 30 | Cruise/Acceleration | $30 \leq STP_t$ | $25 \leq v_t < 50$ | 0.49 | |
| 33 | Cruise/Acceleration | $STP_t < 6$ | $50 \leq v_t$ | 16.26 | Phase 4 |
| 35 | Cruise/Acceleration | $6 \leq STP_t < 12$ | $50 \leq v_t$ | 14.90 | |
| 37 | Cruise/Acceleration | $12 \leq STP_t < 18$ | $50 \leq v_t$ | 13.61 | |
| 38 | Cruise/Acceleration | $18 \leq STP_t < 24$ | $50 \leq v_t$ | 8.60 | |
| 39 | Cruise/Acceleration | $24 \leq STP_t < 30$ | $50 \leq v_t$ | 5.05 | |
| 40 | Cruise/Acceleration | $30 \leq STP_t$ | $50 \leq v_t$ | 4.89 | |

The average start rate was calculated by taking the difference between time-based emission rates (g/hr) of Phase 1 and Phase 2 of each test and averaging the differences together as shown in Equation 6-7 and multiplying by the length of Phase 1.

$$\mathrm{CC_{start}} = \frac{\sum_{\mathrm{j=1}}^{\mathrm{n}} \left(\mathrm{CC_{phase\ 1,j}} - \mathrm{CC_{phase\ 2,j}}\right)}{\mathrm{n}} \times 11\ minutes\ \times \left(\frac{1\ hour}{60\ minutes}\right)$$

**Equation 6-7**

Where

$\mathrm{CC_{start}}$= average crankcase (g/start) emission from all the test runs
$\mathrm{CC_{phase\ 1,j}}$ = crankcase (g/hr) emission rate from test run j and Phase 1
n= the number of tests (13)

In the case of THC and $NO_x$, Equation 6-7 yielded negative start emission rates, because the average Phase 2 (g/hr) emission rates for these pollutants are higher than the Phase 1 (g/hr) emission rates. There are physical explanations that can lead to an observed increase in crankcase emission rates in Phase 2. Lubricating oil and diesel fuel in the crankcase can evaporate as the engine block heats during operation, which is measured as THC and $PM_{2.5}$ if the vapors condense upon dilution. For $NO_x$ emissions, the engine-out emissions during the start period can be lower than running period, due to lower air-fuel ratios and lower in-cylinder temperatures. In fact, MOVES models zero $NO_x$ tailpipe starts for pre-2010 heavy-duty diesel trucks based on observations of negative start emission rates as discussed in Section 2.2.1.2. Thus, we set the start crankcase emission rate to zero for THC and $NO_x$. The average $CH_4$ start emission rate was positive, but because methane is estimated in MOVES as a fraction of THC, we also set it equal to zero as shown in Table 6-13.

For the crankcase extended idling rate we used the average of emissions in the idling phase (Phase 3).

These rates also informed the base crankcase rates for NMHC and TOG. We used Equation 6-3 to calculate TOG crankcase emissions, with the MOVES NMOG/NMHC ratio for 2010+ diesel running exhaust (1.085) from the hcspeciation table in MOVES.[1]

The crankcase rates are ratioed to the tailpipe emissions from the HDIUT vehicles from the model year 2010-2013 and 2014+ $NO_x$ FEL 0.2 groups (See Table 2-7) for each pollutant. These vehicles were chosen as they comprise the majority of the fleet in most model years (See Figure 2-12). The HDIUT data are used instead of the tailpipe values from the NVFEL test trucks because 1) they are the basis of the MOVES tailpipe emission rates, 2) we have much more confidence in the mean HDIUT tailpipe emission rates than the mean tailpipe emission rates from the two NVEL test-trucks to represent fleet-average rates, and 3) the variability of the tailpipe measurements from the NVFEL vehicles is generally much greater than the variability of the crankcase measurements, including for THC emissions.[163] Thus, by using tailpipe emissions from MOVES, we yield more stable crankcase ratios.

The ratios for NMHC, TOG, and $NO_x$ are applied to the pollutants chained to them as well (Table 6-1).

**Table 6-13 Average Crankcase Emission Rates for MOVES Processes from NVFEL data**

| Process | CO | $NO_x$ | THC | $CH_4$ | NMHC | TOG |
|---|---|---|---|---|---|---|
| Crankcase Running Exhaust (g/hr) | 0.398 | 1.501 | 0.541 | 0.009 | 0.5318 | 0.5861 |
| Crankcase Start Exhaust (g/start) | 0.049 | 0 | 0 | 0 | 0 | 0 |
| Crankcase Extended Idling Exhaust (g/hr) | 0.246 | 0.710 | 0.453 | 0.006 | 0.4471 | 0.4909 |

No $PM_{2.5}$ crankcase emission measurements were made in the NVFEL study, so the 2010 and later model year calculations use the crankcase $PM_{2.5}$ rates from ACES Phase 1 report as described for model years 2007-2009 in Section 0. More information on the PM calculations for model year 2010 and later vehicles is provided later in this section.

We used the base exhaust emission rates from the $NO_x$ FEL 0.2 group for HHD engines in short and long-haul single-unit and combination trucks (source types 52,53,61,62). These vehicles were chosen from the full HDIUT data set to match the NVFEL testing vehicles.

**Table 6-14 The $NO_x$ FEL 0.2 MOVES Exhaust Base Rates for Running (Weighted by Operating Mode Activity) and Extended Idling (g/hr)**

| | Model Year Group | CO | $NO_x$ | THC | $CH_4$ | NMHC | TOG | Total $PM_{2.5}$ |
|---|---|---|---|---|---|---|---|---|
| Running Exhaust | 2010-2013 | 125.42 | 62.51 | 1.50 | 0.57 | 0.93 | 1.58 | 0.15 |
| | 2014+ | 60.06 | 61.87 | 1.47 | 0.56 | 0.91 | 1.55 | 0.12 |
| Extended Idle Exhaust | 2010-2013 | 39.26 | 42.60 | 2.75 | 1.04 | 1.70 | 2.89 | 0.03 |
| | 2014+ | 39.26 | 42.60 | 1.64 | 0.62 | 1.01 | 1.72 | 0.02 |

The HHD tailpipe rates have two model year groups 2010-2013 and 2014+, so the ratios differ for these model year groups as shown in Table 6-15.

As was done for the development of the 2007-2009 crankcase emission ratios documented in Section 6.2.2.2 we assume that the crankcase ratios derived for MY2010-2026 heavy heavy-duty diesel (HHD) engines apply to the other heavy-duty regulatory classes (LHD45, MHD and Urban Bus) and source types (other buses, transit buses, school buses, refuse trucks, and motorhomes), and that crankcase emissions are proportional to the exhaust emissions across regulatory classes and source use types. Additionally, we use Equation 6-6 to account for the fraction of open crankcase systems within each regulatory class shown in Table 6-7.

**Table 6-15 Crankcase/Tailpipe Ratios for Model Year 2010-2026 Heavy-Duty Diesel Regulatory Classes**

| Process | Pollutant | Model Year Group | HD baseline | Crankcase/Tailpipe ratio by regulatory class | | | |
|---|---|---|---|---|---|---|---|
| | | | | LHD45 | MHD | HHD | Urban Bus |
| Running | THC | 2010-2013 | 0.36 | 0 | 0.33 | 0.24 | 0.24 |
| | | 2014-2026 | 0.37 | 0 | 0.33 | 0.24 | 0.24 |
| | $CH_4$ | 2010-2013 | 0.02 | 0 | 0.014 | 0.011 | 0.011 |
| | | 2014-2026 | 0.02 | 0 | 0.015 | 0.011 | 0.011 |
| | NMHC | 2010-2013 | 0.57 | 0 | 0.52 | 0.38 | 0.38 |
| | | 2014-2026 | 0.58 | 0 | 0.53 | 0.39 | 0.39 |
| | TOG | 2010-2013 | 0.37 | 0 | 0.34 | 0.25 | 0.25 |
| | | 2014-2026 | 0.38 | 0 | 0.34 | 0.25 | 0.25 |
| | $CO_2$ | 2010-2013 | 0 | 0 | 0.002 | 0.002 | 0.002 |
| | | 2014-2026 | 0 | 0 | 0.002 | 0.002 | 0.002 |
| | CO | 2010-2013 | 0 | 0 | 0.003 | 0.002 | 0.002 |
| | | 2014-2026 | 0.01 | 0 | 0.006 | 0.004 | 0.004 |
| | $NO_x$ | 2010-2013 | 0.02 | 0 | 0.022 | 0.016 | 0.016 |
| | | 2014-2026 | 0.02 | 0 | 0.022 | 0.016 | 0.016 |
| | $PM_{2.5}$ | 2010-2013 | 0.26 | 0 | 0.24 | 0.17 | 0.17 |
| | | 2014-2026 | 0.32 | 0 | 0.29 | 0.21 | 0.21 |
| Starts | THC | 2010-2013 | 0 | 0 | 0 | 0 | 0 |
| | | 2014-2026 | 0 | 0 | 0 | 0 | 0 |
| | $CH_4$ | 2010-2013 | 0 | 0 | 0 | 0 | 0 |
| | | 2014-2026 | 0 | 0 | 0 | 0 | 0 |
| | NMHC | 2010-2013 | 0 | 0 | 0 | 0 | 0 |
| | | 2014-2026 | 0 | 0 | 0 | 0 | 0 |
| | TOG | 2010-2013 | 0 | 0 | 0 | 0 | 0 |
| | | 2014-2026 | 0 | 0 | 0 | 0 | 0 |
| | $CO_2$ | 2010-2013 | 0.03 | 0 | 0.03 | 0.02 | 0.02 |
| | | 2014-2026 | 0.03 | 0 | 0.03 | 0.02 | 0.02 |
| | CO | 2010-2013 | 0.16 | 0 | 0.15 | 0.11 | 0.11 |
| | | 2014-2026 | 0.16 | 0 | 0.15 | 0.11 | 0.11 |
| | $NO_x$ | 2010-2013 | 0 | 0 | 0 | 0 | 0 |
| | | 2014-2026 | 0 | 0 | 0 | 0 | 0 |
| | $PM_{2.5}$ | 2010-2013 | 0 | 0 | 0 | 0 | 0 |
| | | 2014-2026 | 0 | 0 | 0 | 0 | 0 |

**Table 6-15 (Continued) Crankcase/Tailpipe Ratios for Model Year 2010-2060 Heavy-Duty Diesel Regulatory Classes**

| Process | Pollutant | Model Year Group | HD baseline | Crankcase/Tailpipe ratio by regulatory class | | | |
|---|---|---|---|---|---|---|---|
| | | | | LHD45 | MHD | HHD | Urban Bus |
| Extended Idle | THC | 2010-2013 | 0.16 | 0 | 0.15 | 0.11 | 0.11 |
| | | 2014-2026 | 0.28 | 0 | 0.25 | 0.18 | 0.18 |
| | $CH_4$ | 2010-2013 | 0.005 | 0 | 0.005 | 0.004 | 0.004 |
| | | 2014-2026 | 0.009 | 0 | 0.008 | 0.006 | 0.006 |
| | NMHC | 2010-2013 | 0.26 | 0 | 0.24 | 0.17 | 0.17 |
| | | 2014-2026 | 0.44 | 0 | 0.4 | 0.29 | 0.29 |
| | TOG | 2010-2013 | 0.17 | 0 | 0.15 | 0.11 | 0.11 |
| | | 2014-2026 | 0.28 | 0 | 0.26 | 0.19 | 0.19 |
| | $CO_2$ | 2010-2013 | 0.015 | 0 | 0.013 | 0.01 | 0.01 |
| | | 2014-2026 | 0.015 | 0 | 0.013 | 0.01 | 0.01 |
| | CO | 2010-2013 | 0.006 | 0 | 0.006 | 0.004 | 0.004 |
| | | 2014-2026 | 0.006 | 0 | 0.006 | 0.004 | 0.004 |
| | $NO_x$ | 2010-2013 | 0.017 | 0 | 0.015 | 0.011 | 0.011 |
| | | 2014-2026 | 0.017 | 0 | 0.015 | 0.011 | 0.011 |
| | $PM_{2.5}$ | 2010-2013 | 1.11 | 0 | 1.01 | 0.74 | 0.74 |
| | | 2014-2026 | 1.82 | 0 | 1.64 | 1.21 | 1.21 |

As noted above, the $PM_{2.5}$ crankcase emission ratios are calculated using the ACES Phase 1 crankcase emission rates (MY 2007) and the $PM_{2.5}$ exhaust rates from the 2010-2013 and 2014+ $NO_x$ FEL 0.2 groups. As the tailpipe $PM_{2.5}$ exhaust emission rates are based upon in-use tailpipe testing for 2010+, the tailpipe ratio for all processes is 1, and the crankcase $PM_{2.5}$ ratio is a simple fraction of the tailpipe emissions as shown in Table 6-16 for MHD and HHD diesel vehicles. The fraction for LHD is zero, consistent with Table 6-15. Since $PM_{2.5}$ uses ACES Phase 1 data, starts emissions are assumed to be included in the running and the crankcase starts are set to zero.

**Table 6-16. MOVES Exhaust and Crankcase Ratios for 2010-2026 MHD and HHD Diesel by Pollutant, Process, and Model Year Group for $PM_{2.5}$ Species**

| Process | Model Year Group | Pollutant | Start | Running | Extended Idle |
|---|---|---|---|---|---|
| Tailpipe Exhaust | 2010-2013 | EC | 1 | 1 | 1 |
| | | nonECnonSO$_4$PM | 1 | 1 | 1 |
| | | SO$_4$ | 1 | 1 | 1 |
| | | $H_2O$ | 1 | 1 | 1 |
| | 2014-2026 | EC | 1 | 1 | 1 |
| | | nonECnonSO$_4$PM | 1 | 1 | 1 |
| | | SO$_4$ | 1 | 1 | 1 |
| | | $H_2O$ | 1 | 1 | 1 |
| HHD Crankcase | 2010-2013 | EC | 0 | 0.17 | 0.74 |
| | | nonECnonSO$_4$PM | 0 | 0.17 | 0.74 |
| | | SO$_4$ | 0 | 0.17 | 0.74 |
| | | $H_2O$ | 0 | 0.17 | 0.74 |
| | 2014-2026 | EC | 0 | 0.21 | 1.21 |
| | | nonECnonSO$_4$PM | 0 | 0.21 | 1.21 |
| | | SO$_4$ | 0 | 0.21 | 1.21 |
| | | $H_2O$ | 0 | 0.21 | 1.21 |
| MHD Crankcase | 2010-2013 | EC | 0 | 0.24 | 1 |
| | | nonECnonSO$_4$PM | 0 | 0.24 | 1 |
| | | SO$_4$ | 0 | 0.24 | 1 |
| | | $H_2O$ | 0 | 0.24 | 1 |
| | 2014-2026 | EC | 0 | 0.29 | 1.64 |
| | | nonECnonSO$_4$PM | 0 | 0.29 | 1.64 |
| | | SO$_4$ | 0 | 0.29 | 1.64 |
| | | $H_2O$ | 0 | 0.29 | 1.64 |

#### *6.2.2.4 2027-2060 Model Years*

For MY2027 and later vehicles, the HD2027 standards require manufacturers to use one of two options for controlling crankcase emissions, either: 1) closing the crankcase, or 2) an updated version of the current requirements for an open crankcase that includes additional requirements for measuring and accounting for crankcase emissions.

In the emissions impact analysis of the HD2027 rule, we assumed that closing the crankcase would be the preferred option to meet the standards. We revised the crankcase emission rates in MOVES4 accordingly by setting the crankcase emission rates for MY2027+ HHD, MHD and LHD45 diesel vehicles to zero.

### *6.2.3 Glider Crankcase Emissions*

Glider vehicles in MOVES are modeled using emission rates from MY 2000 heavy-duty diesel engines (Section 2.5); the pre-2007 crankcase rates (Table 6-8 and Table 6-9) are applied to glider vehicles (regClassID 49) for all model years.

## *6.3 Heavy-Duty Gasoline and CNG Crankcase Emissions*

The data on heavy-duty gasoline and CNG crankcase emissions are limited. All 1969 and later spark ignition heavy-duty engines are required to control crankcase emissions. All gasoline engines are assumed to use positive crankcase ventilation (PCV) systems, which route the crankcase gases into the intake manifold. For heavy-duty gasoline engines we use the same values of crankcase emission ratios as light-duty gasoline as shown in Table 6-17; these are documented in the MOVES light-duty emission rates report.[9] The HD2027 standards do not affect heavy-duty gasoline and CNG fueled engines since the rule only affects the crankcase emissions from the compression-ignition (diesel) heavy-duty engines.

For the 1969 and later vehicles, we assume 4 percent of PCV systems fail, which would cause increased tailpipe emissions for reasons such as misfiring of the engine, lubricating oil in the intake manifold, and increased deterioration of the three-way catalyst. Although these processes will increase tailpipe emissions, in MOVES we model this increase of emissions due to a failed PCV as crankcase emissions. We assume that the elevated emissions due to a failed PCV system would be equivalent to the crankcase emissions of a pre-1969 vehicles using Equation 6-8. The resulting fleet-wide crankcase to exhaust emission ratios for 1969 and later vehicles are shown in Table 6-17.

$$\text{Crankcase Ratio}_{1969+} = \text{PCV failure rate } (4\%) \times \text{Crankcase Ratio}_{\text{pre1969}} \qquad \textbf{Equation 6-8}$$

**Table 6-17 Crankcase to Tailpipe Exhaust Emission Ratio for Heavy-Duty Gasoline and CNG Vehicles for THC, CO, $NO_x$, and $PM_{2.5}$**

| Pollutant | pre-1969 | 1969 and later |
|---|---|---|
| HC | 0.33 | 0.013 |
| CO | 0.013 | 0.00052 |
| $NO_x$ | 0.001 | 0.00004 |
| PM (all species) | 0.20 | 0.008 |

Due to limited information, we used the gasoline heavy-duty crankcase emission factors for heavy-duty CNG engines because the majority of these engines are spark-ignited. However, at least one study (Clark et al., 2017)[164] suggests that CNG vehicles have open crankcase systems so we may be underestimating crankcase emissions, especially those of methane. We hope to revisit CNG crankcase emissions in future versions of MOVES.

The crankcase and exhaust ratios used by the crankcase calculator for $PM_{2.5}$ emissions from heavy-duty gasoline and compressed natural gas vehicles are provided in Table 6-18. These values are applied to calculate crankcase emissions associated with start exhaust as well as to running exhaust. No information is available to estimate separate speciation between exhaust and crankcase, so the factors are the same for all PM subspecies.

**Table 6-18 MOVES Exhaust and Crankcase Ratios for Heavy-Duty Gasoline and CNG Vehicles by Pollutant, Process, Model Year Group, and Fuel Type, and Source Type for $PM_{2.5}$ Species**

| Pollutant | Process | 1960-1968 | 1969-2050 |
|---|---|---|---|
| EC | Exhaust | 1 | 1 |
| nonECnonSO$_4$PM | | 1 | 1 |
| $SO_4$ | | 1 | 1 |
| $H_2O$ | | 1 | 1 |
| EC | Crankcase | 0.2 | 0.008 |
| nonECnonSO$_4$PM | | 0.2 | 0.008 |
| $SO_4$ | | 0.2 | 0.008 |
| $H_2O$ | | 0.2 | 0.008 |

# 7 Nitrogen Oxide Composition

This section discusses the values used to estimate nitric oxide (NO), nitrogen dioxide ($NO_2$) and nitrous acid (HONO) from nitrogen oxide ($NO_x$) emissions from heavy-duty vehicles. A similar section on $NO_x$ composition from light-duty emissions is included in the light-duty emissions report. $NO_x$ emissions are reported in mass-equivalent space of $NO_2$. In other words, the molar mass of $NO_2$ (46 g/mole) is used to calculate grams of $NO_x$ from the molar concentration of $NO_x$.

Nitrogen oxides ($NO_x$) are defined as NO + $NO_2$.[165,166] $NO_x$ is considered a subset of reactive nitrogen species ($NO_y$) with a nitrogen oxidation state of +2 or greater which contain other nitrogen containing species ($NO_z$), thus $NO_y = NO_x + NO_z$.[165] $NO_z$ compounds are formed in the atmosphere as oxidation products of $NO_x$.[166]

Chemiluminescent analyzers used for exhaust $NO_x$ measurements directly measure NO, as NO is oxidized by ozone to form $NO_2$ and produces florescent light. Chemiluminescent analyzers measure $NO_x$ (NO + $NO_2$) by using a catalyst that reduces the $NO_2$ to NO in the sample air stream before measurement. $NO_2$ is calculated as the difference between $NO_x$ and NO measurements. The $NO_x$ converter within chemiluminescent analyzers can also reduce other reactive nitrogen species ($NO_z$), including HONO to NO. If the concentrations of $NO_z$-interfering species in the sample stream are significant relative to $NO_2$ concentrations, then they can bias the $NO_2$ measurements high.[167]

MOVES estimates NO and $NO_2$ by applying an NO/$NO_x$ or $NO_2$/$NO_x$ fraction to the $NO_x$ emission rates. The NO/$NO_2$ and $NO_2$/$NO_x$ fractions are stored in a MOVES table called nono2ratio. The nono2ratio enables the nitrogen oxide composition to vary according to source type, fuel type, model year, and pollutant process. However, the current $NO_x$ fractions in MOVES vary only according to fuel type, model year, and emission process.

MOVES also estimates one important $NO_z$ species, nitrous acid (HONO), from the $NO_x$ values. HONO emissions are estimated as a fraction (0.8 percent) of $NO_x$ emissions from all vehicle types in MOVES, based on HONO and $NO_x$ measurements made at a road tunnel in Europe.[168] HONO emissions are also estimated using the nono2ratio MOVES table. For each source type, fuel type, and emission process, the NO, $NO_2$, and HONO values in the nono2ratio sum to one. Future work could be conducted to update MOVES to model $NO_x$ and HONO fractions according to regulatory class.

MOVES users should be aware that the definition of $NO_x$ in MOVES (NO+$NO_2$+HONO) is different than the standard $NO_x$ definition of $NO_x$ (NO + $NO_2$). In MOVES, we include HONO in the $NO_x$ values, because the chemiluminescent analyzers are biased slightly high by HONO in the exhaust stream, and HONO is formed almost immediately upon dilution into the roadway environment from $NO_2$ emissions. To avoid overcounting reactive nitrogen formation, we include HONO in the sum of $NO_x$ in MOVES. MOVES users should consider which measure they would like to use depending on their use-case. For example, for comparing $NO_x$ results with a vehicle emission test program, MOVES users may want to simply use $NO_X$ (pollutantID 3), whereas MOVES users developing air quality inputs of $NO_x$, $NO_2$, and HONO, may estimate $NO_x$ as the sum of NO + $NO_2$ (pollutantIDs 32 and 33), rather than using the direct $NO_x$ output in MOVES (polluantID 3).

## 7.1 Heavy-Duty Diesel

The heavy-duty diesel NO/$NO_x$, $NO_2$/$NO_x$ , and HONO/$NO_x$ fractions were updated in MOVES4 using data reported from recent emission studies, as described below.

We summarized $NO_2$/$NO_x$ fractions from three recent studies by aftertreatment technology and model year range shown in Table 7-1.

Preble et al. (2019)[139] sampled individual heavy-duty vehicle exhaust plumes at the entrance to the Caldecott Tunnel near Oakland, California and at the Port of Oakland for multiple years. The data from Preble et al. (2019) are also used to update the $NH_3$ emission rates as discussed in Section 5.1, however $NH_3$ was only measured in 2018 at the Caldecott TunnelwhileNO and $NO_2$ were measured at both locations for multiple years. Thirugengadam et al. (2015)[51] conducted exhaust sampling of five heavy-duty diesel vehicles measured on four different driving cycles used to represent goods movement in Southern California. Quiros et al. (2016)[49] sampled six heavy-duty diesel tractors hauling a mobile emissions laboratory trailer. They sampled the vehicles along six routes intended to represent goods movement in Southern California. The Advanced Collaborative Emissions Study conducted by Khalek et al. (2009)[47] and (2013)[169], tested four model year 2007 and three model year 2010 heavy-duty diesel engines using an engine dynamometer.

The $NO_2$/$NO_x$ fraction measured by aftertreatment technology and model year ranges are quite consistent across the four different studies. This suggests that the $NO_2$/$NO_x$ obtained from the plume capture measurements in Preble et al. (2019)[139] are relevant for the wide range of operation conditions sampled in Thirugengadam et al. (2015)[51] and Quiros et al. (2016).[49]

Each of the studies showed that the $NO_2$/$NO_x$ increased with the introduction of diesel particulate filters (DPF) in model years 2007-2009. This is expected because DPF aftertreatment systems are designed to increase the fraction of $NO_2$ to facilitate passive regeneration of the DPF. A diesel oxidation catalyst upstream of the DPF oxides NO to $NO_2$ which then oxidize soot collected on the filter.[170] The DPF+SCR aftertreatment systems introduced with MY 2010 and later engines also have higher $NO_2$/$NO_x$ fractions than pre-DPF engines, but are consistently lower than the DPF only engines.

**Table 7-1. $NO_2/NO_x$ ratios (± 95% Confidence Intervals, if available) from heavy-duty diesel vehicles reported from recent studies**

| Study | Study Description | Sample Size | Aftertreatment | Engine Model Year | $NO_2/NO_x$ |
|---|---|---|---|---|---|
| Preble et al. (2019)[139] | Caldecott Tunnel near Oakland California, Plume-Capture, Sample Years: 2014, 2015, 2018 | 1,471 | DPF + SCR | 2010-2018 | 0.19 ± 0.03 |
| | | 780 | DPF | 2007-2009 | 0.24 ± 0.02 |
| | | 359 | DPF Retrofit | 1994-2006 | 0.11 ± 0.02 |
| | | 190 | No DPF | 2004-2006 | 0.06 ± 0.01 |
| | | 454 | No DPF | 1965-2003 | 0.03 ± 0.01 |
| Preble et al. (2019)[139] | Port of Oakland, California, Plume-Capture, Sample Years: 2011, 2013, 2015 | 403 | DPF + SCR | 2010-2016 | 0.20 ± 0.05 |
| | | 1,598 | DPF | 2007-2009 | 0.23 ± 0.02 |
| | | 399 | DPF Retrofit | 1994-2006 | 0.15 ± 0.02 |
| | | 199 | No DPF | 2004-2006 | 0.04 ± 0.02 |
| Thiruvengadam et al. (2015)[51] | Chassis dynamometer on four duty cycles representative of goods movement | 1 | DPF + SCR | 2010-2011 | ~0.15 |
| | | 1 | DPF | 2011 | ~0.30 |
| | | 1 | DPF | 2009 | ~.30 |
| Quiros et al. (2016)[49] | Six good movements routes in Southern California sampled using mobile laboratory | 4 | DPF + SCR | 2013-2014 | 0.19 ± 0.17 |
| | | 1 | DPF (Hybrid Diesel) | 2011 | 0.33 |
| | | 1 | DPF | 2007 | 0.30 |
| Khalek et al. (2013)[169] | ACES engine dynamometer study, 16-hour cycle | 3 | DPF + SCR | 2011 | 0.52 ± 0.45 |
| Khalek et al. (2009)[47] | | 4 | DPF | 2007 | 0.54 ± 0.20 |

In MOVES4, we used the $NO/NO_x$ and $NO_2/NO_x$ fractions from the Caldecott Tunnel (Preble et al., 2019).[139] For model years 2004-2010, the updated values are similar to the values used in previous versions of MOVES. For model years earlier and later, the MOVES4 $NO_2/NO_x$ values are lower. We did not use the DPF retrofit values because these are representative of California drayage vehicles starting in 2010, but not the nation-wide fleet of heavy-duty pre-2007 vehicles.

MOVES3 and earlier versions use a HONO fraction of 0.8% obtained from Kurtenbach et al. (2001).[168] Table 7-2 summarizes $HONO/NO_x$ ratios from an updated literature review. Studies that measure HONO often don't measure individual vehicle exhaust, thus isolating the diesel specific HONO ratio is difficult. MOVES $HONO/NO_x$ ratios was not updated using this data as the MOVES3 value of 0.8% is well-within the range of the diesel-only $HONO/NO_x$ measurements.

**Table 7-2. Fleet-average and diesel specific HONO/NO$_x$ Ratios**

| Source | Study Type | HONO/NO$_x$ (%) | Diesel fleet (%) |
|---|---|---|---|
| Kramer et al. (2020)[171] | Road tunnel in the United Kingdom | 1.04 | Isolated diesel vehicle ratio |
| | | 0.85 | 66 |
| Liang et al. (2017)[172] | Road tunnel in Hong Kong | 1.24 | 33 |
| Xu et al. (2015)[173] | Ambient measurements in Hong Kong | 1.20 | 33 |
| Trinh et al. (2017)[174] | Chassis dynamometer across four drive cycles | 0.16 to 1 | Diesel vehicle equipped with DPF tested |
| Rappenglück et al. (2013)[175] | Road-side measurements in Houston, Texas | 1.17 | 5-10 |
| Kurtenbach et al. (2001)[168] | Tunnel Study in Germany | 0.80 | 6% heavy-duty vehicles, 6% commercial vans, 12.3% diesel passenger vehicles |
| | Single-vehicle Tunnel Study | 0.53 | Diesel truck |
| | Single-vehicle Tunnel Study | 0.66 | Diesel passenger car |

Table 7-3 shows the NO$_x$ and HONO fractions for heavy-duty diesel vehicles used in MOVES4. Vehicle model years subject to the HD2027 rule use the same fractions as model years 2010-2026, and APU exhaust fractions are the same for all model years 2024 and later. The NO/NO$_x$ and NO$_2$/NO$_x$ fractions reported in Preble et al. (2019) were renormalized to account for the 0.8 percent HONO emissions. The NO$_x$ fractions are the same across all diesel source types and across all emission processes (running, start, extended idle), except for auxiliary power units, which use the conventional NO$_x$ fractions (1960-2003) for all 1960-2023 model years because it is assumed that the these APUs are not fitted with diesel particulate filters. APU exhaust rates for the model year range 2024-2060 use the same NO$_x$ fractions as model year 2007-2009 running exhaust, because we assume they will be equipped with DPF systems but not SCR systems. Because the nono2ratio table is classified by source type, and not regulatory class, gliders use the same NO/NO$_2$ fractions as the other regulatory classes by model year, even though the 1960-2003 NO$_x$ fractions are more relevant for this regulatory class. We hope to address this design limitation in future versions of MOVES.

Finally, while the HD2027 rule as updated in MOVES4 will reduce NO$_x$ emissions from MY 2027+ HD gasoline vehicles, we modelled no change in the NO/NO$_2$ fractions.

**Table 7-3 $NO_x$ and HONO Fractions for Heavy-Duty Diesel Vehicles**

| Process | Model Year | NO | $NO_2$ | HONO |
|---|---|---|---|---|
| Running exhaust, start exhaust, extended idle exhaust | 1960-2003 [a] | 0.9622 | 0.0298 | 0.008 |
| | 2004-2006 | 0.9325 | 0.0595 | 0.008 |
| | 2007-2009 | 0.7539 | 0.2381 | 0.008 |
| | 2010-2060 | 0.8035 | 0.1885 | 0.008 |
| Auxiliary power unit exhaust | 1960-2023 | 0.9325 | 0.0595 | 0.008 |
| | 2024-2060 | 0.7539 | 0.2381 | 0.008 |

## 7.2 Heavy-Duty Gasoline

The $NO_x$ fractions for heavy-duty gasoline are based on the MOVES values used for light-duty gasoline estimates. Separate values are used for running and start emission processes. As stated in the MOVES2010 report,[176] the light-duty values are shifted to later model year groups to be consistent with heavy-duty emission standards and emission control technologies. These values are shown in Table 7-4 for both light-duty and heavy-duty gasoline vehicles. The $NO_2$ fractions originally developed for MOVES2010 were reduced by 0.008 to account for the HONO emissions.[176] While the HD2027 rule will reduce $NO_x$ emissions from HD gasoline vehicles, we modelled no change in the $NO_x$ fractions for MY 2027+.

**Table 7-4 $NO_x$ and HONO Fractions for Light-Duty (Source Type 21, 31, 32) and Heavy-Duty Gasoline Vehicles (Source Type 41, 42, 43, 51, 52, 53, 54, 61)**

| Light-Duty gasoline model year groups | Heavy-Duty gasoline model year groups | Running | | | Start | | |
|---|---|---|---|---|---|---|---|
| | | NO | $NO_2$ | HONO | NO | $NO_2$ | HONO |
| 1960-1980 | 1960-1987 | 0.975 | 0.017 | 0.008 | 0.975 | 0.017 | 0.008 |
| 1981-1990 | 1988-2004 | 0.932 | 0.06 | 0.008 | 0.932 | 0.031 | 0.008 |
| 1991-1995 | 2005-2007 | 0.954 | 0.038 | 0.008 | 0.987 | 0.005 | 0.008 |
| 1996-2060 | 2008-2060 | 0.836 | 0.156 | 0.008 | 0.951 | 0.041 | 0.008 |

## 7.3 Heavy-Duty Compressed Natural Gas

We used the average $NO_2$/ $NO_x$ fractions reported from three CNG transit buses with DDC Series 50 G engines by Lanni et al. (2003)[126] with the 0.008 HONO fraction assumed for other fuel types, to estimate the $NO_x$ fractions of NO, $NO_2$, and HONO. These assumptions yield the values in Table 7-5, which are used for CNG heavy-duty vehicles of all model years. In the future, we hope to update these values with data from more recent three-way catalyst CNG vehicles.[49]

**Table 7-5 $NO_x$ and HONO Fractions CNG Heavy-Duty Vehicles**

| Model Year | NO | $NO_2$ | HONO |
|---|---|---|---|
| 1960-2060 | 0.865 | 0.127 | 0.008 |

# 8 Appendices

# Appendix A Calculation of Accessory Power Requirements

### Table A-1. Accessory Load Estimates for HHD Trucks

| VSP | Cooling Fan | Air cond | Air comp | Alternator | Engine Accessories | Total Accessory Load (kW) |
|---|---|---|---|---|---|---|
| Low | | | Off = 0.5 kW | | | |
| Power (kw) | 19.0 | 2.3 | 3.0 | 1.5 | 1.5 | |
| % time on | 10% | 50% | 60% | 100% | 100% | |
| Total (kW) | 1.9 | 1.2 | 2.0 | 1.5 | 1.5 | 8.1 |
| Mid | | | Off = 0.5 kW | | | |
| Power (kw) | 19.0 | 2.3 | 2.3 | 1.5 | 1.5 | |
| % time on | 20% | 50% | 20% | 100% | 100% | |
| Total (kW) | 3.8 | 1.2 | 0.9 | 1.5 | 1.5 | 8.8 |
| High | | | Off = 0.5 kW | | | |
| Power (kw) | 19.0 | 2.3 | 2.3 | 1.5 | 1.5 | |
| % time on | 30% | 50% | 10% | 100% | 100% | |
| Total (kW) | 5.7 | 1.2 | 0.7 | 1.5 | 1.5 | 10.5 |

### Table A-2. Accessory Load Estimates for MHD Trucks

| VSP | Cooling Fan | Air cond | Air comp | Alternator | Engine Accessories | Total Accessory Load (kW) |
|---|---|---|---|---|---|---|
| Low | | | Off = 0.5 kW | | | |
| Power (kw) | 10.0 | 2.3 | 2.0 | 1.5 | 1.5 | |
| % time on | 10% | 50% | 60% | 100% | 100% | |
| Total (kW) | 1.0 | 1.2 | 1.4 | 1.5 | 1.5 | 6.6 |
| Mid | | | Off = 0.5 kW | | | |
| Power (kw) | 10.0 | 2.3 | 2.0 | 1.5 | 1.5 | |
| % time on | 20% | 50% | 20% | 100% | 100% | |
| Total (kW) | 2.0 | 1.2 | 0.8 | 1.5 | 1.5 | 7.0 |
| High | | | Off = 0.5 kW | | | |
| Power (kw) | 10.0 | 2.3 | 2.0 | 1.5 | 1.5 | |
| % time on | 30% | 50% | 10% | 100% | 100% | |
| Total (kW) | 3.0 | 1.2 | 0.7 | 1.5 | 1.5 | 7.8 |

### Table A-3. Accessory Load Estimates for Buses

| VSP | Cooling Fan | Air cond | Air comp | Alternator | Engine Accessories | Total Accessory Load (kW) |
|---|---|---|---|---|---|---|
| Low | | | Off = 0.5 kW | | | |
| Power (kw) | 19.0 | 18.0 | 4.0 | 1.5 | 1.5 | |
| % time on | 10% | 80% | 60% | 100% | 100% | |
| Total (kW) | 1.9 | 14.4 | 2.6 | 1.5 | 1.5 | 21.9 |
| Mid | | | Off = 0.5 kW | | | |
| Power (kw) | 19.0 | 18.0 | 4.0 | 1.5 | 1.5 | |
| % time on | 20% | 80% | 20% | 100% | 100% | |
| Total (kW) | 3.8 | 14.4 | 1.2 | 1.5 | 1.5 | 22.4 |
| High | | | Off = 0.5 kW | | | |
| Power (kw) | 19.0 | 18.0 | 4.0 | 1.5 | 1.5 | |
| % time on | 30% | 80% | 10% | 100% | 100% | |
| Total (kW) | 5.7 | 14.4 | 0.9 | 1.5 | 1.5 | 24.0 |

# Appendix B Tampering and Mal-maintenance for Diesel Running Exhaust

Tampering and mal-maintenance (T&M) effects represent the fleet-wide average increase in emissions as the fleet ages. In laboratory testing, properly maintained engines often yield very small rates of emissions deterioration through time. We assume that in real-world use, tampering and mal-maintenance dominate emissions deterioration over time for heavy-duty diesel vehicles. As a result, MOVES specifically models the deterioration due to tampering and mal-maintenance, which we assume also includes any other emission increases due to vehicle aging and deterioration.

The tampering and mal-maintenance methodology was first incorporated into MOVES2010[177] from studies conducted between 1988 and 2007 (See Section B.2.) The T&M methodology used in MOVES3 is unchanged from MOVES2010 along with much of the original T&M assumptions on T&M frequency and T&M adjustment factors. Slight updates to $NO_x$ and $PM_{2.5}$ T&M adjustment factors were made for MOVES2014.[35] No changes were made to the T&M assumptions or data between MOVES2014 and MOVES3. Minor corrections to the warranty and useful life of LHD vehicles were made in MOVES4. In MOVES4, we also updated the warranty and useful life of the MY2027+ heavy-duty vehicles based on the HD2027 standards and we calculated new T&M percentage effects for these vehicles that assume aftertreatment failure in a MY2027 vehicle would bring $NO_x$ tailpipe emissions to the same level as a MY 2010 vehicle with the same failure.

In the future, T&M adjustment factors in MOVES should be re-evaluated and updated, particularly to incorporate data on the durability and emissions performance of advanced aftertreatment systems on modern heavy-duty diesel vehicles and to account for recent work surveying intentional tampering in diesel pickup trucks.[178]

This section describes the derivation of T&M emission rates applied to diesel running exhaust. The estimation of heavy-duty gasoline deterioration is discussed in the derivation of the heavy-duty gasoline rates (Section 3). The derivation of the T&M effects for diesel extended idle emissions are described in Section 2.3.

## B.1 Modeling Tampering and Mal-maintenance

As T&M affects emissions through age, we developed a simple function of emission deterioration with age. New vehicles and 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. 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 & mal-maintenance (T&M) adjustment factor. Figure B-1 shows this relationship. The actual emission levels were determined through data analysis detailed below.

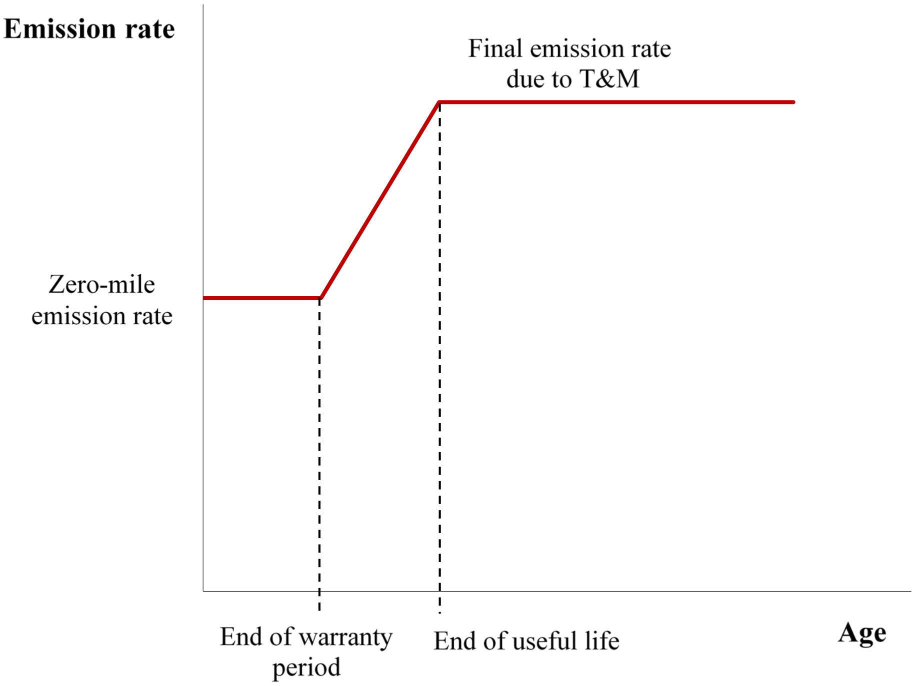


**Figure B-1. Qualitative Depiction of the Implementation of Age Effects**

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 8-1.

$$f_{T\&M,p} = \sum_{i} \left( \text{T\&M frequency}_{i} \times \text{T\&M emission effect}_{p,i} \right) \qquad \textbf{Equation 8-1}$$

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 emission $\text{effect}_i$= 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 8-2.

$$ER_{\text{End of useful life},p,r,o} = ER_{\text{zero mile},p,r,o} \times \left(1 + f_{T\&M,p}\right) \qquad \textbf{Equation 8-2}$$

Where:

$ER_{\text{End of useful life},p,r,o}$ = 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 8-1)

The useful life refers to the length of time that engines are required to meet emissions standards. We incorporated this age relationship by averaging emissions rates across the ages in each age group. Mileage was converted to age with VIUS[179] (Vehicle Inventory and Use Survey) data, which contains data on how quickly trucks of different regulatory classes accumulate mileage. Table B-1 shows the emissions warranty period and approximate useful life requirement period for each of the regulatory classes for pre-MY2027 vehicles. This table and the resulting values in MOVES have been corrected in MOVES4 to reflect the 50,000 miles warranty requirement for LHD vehicles, and the 150,000 useful life mileage for Tier 3 LHD2b3 vehicles.

**Table B-1. Warranty and Useful Life Requirements by Regulatory Class For Pre-MY2027 Vehicles**

| Regulatory class | Warranty requirement mileage/age requirement [b] | Calculated warranty age[a] | Useful life mileage/age requirement | Calculated useful life age[a] | Assumed mileage per year |
|---|---|---|---|---|---|
| LHD2b3 (Tier 2 and earlier) | 50,000/5 | 2 | 120,000/11 [c] | 5 | 26,000 |
| LHD2b3 (Tier 3) | 50,000/5 | 2 | 150,000/10 [d] | 6 | 26,000 |
| LHD45 | 50,000/5 | 2 | 110,000/10 [e] | 4 | 26,000 |
| MHD | 100,000/5 | 2 | 185,000/10 [e] | 5 | 41,000 |
| HHD | 100,000/5 | 1 | 435,000/10 [e] | 4 | 105,000 |
| BUS | 100,000/5 | 2 | 435,000/10 [f] | 10 | 44,000 |

Notes:

[a] The calculated warranty age and useful life age here are based on typical miles driven by vehicles in the regulatory class. For example, HHD vehicles typically accumulate a large number of miles per year (100,000+/year). Thus, HHD vehicles complete their warranty and useful life requirements based on mileage while the vehicle age is still much below the requirement.

[b] 40 CFR 1037.120

[c] 40 CFR 86.096-2, 40 CFR 86.1805-12

[d] 40 CFR 86.1805-17

[e] 40 CFR 86.001-2 (4). The useful life mileage is the same for each regulatory class for all exhaust pollutants ($NO_x$, HC, CO, and PM). The useful life age requirement is generally 10 years for $NO_x$, while it is 8 years for the other pollutants (and for $NO_x$ in 1996-1997). However, we calculated that the mileage requirement is the forcing requirement for all the heavy-duty regulatory classes.

[f] 40 CFR 86.098-2. The usefule life standard is 10 years for urban buses for both $NO_x$ and PM.

Starting from MY2027, the HD2027 standards require manufacturers to comply with new warranty and useful life provisions as shown in Table B-2.

**Table B-2 Warranty and Useful Life Requirements by Regulatory Class For MY2027+ Vehicles**

| Regulatory class | Warranty requirement mileage/age requirement | Calculated warranty age | Useful life mileage/age requirement | Calculated useful life age | Assumed mileage per year |
|---|---|---|---|---|---|
| LHD2b3 | Same as Pre-MY2027+ Vehicles | | | | |
| LHD45 | 210,000/10 | 8 | 270,000/15 | 10 | 26,000 |
| MHD | 280,000/10 | 7 | 350,000/12 | 9 | 41,000 |
| HHD | 450,000/10[a] | 4 | 650,000/11 | 6 | 105,000 |
| BUS | 450,000/10[a] | 10 | 650,000/11 | 15 | 44,000 |

[a] The HHD diesel and Urban Bus warranty year values in the tables were updated to 10 years in MOVES4 to be consistent with HD2027 final rule.

While both age and mileage metrics are given for these periods, whichever comes first determines the applicability of the warranty. As a result, since the mileage limit is usually reached before the age limit, but MOVES deals with age and not mileage, we needed to convert all the mileage values to age equivalents. The data show that on average, heavy heavy-duty trucks accumulate mileage much more quickly than other regulatory classes and reach the end of their warranty period more quickly. Therefore, deterioration in heavy heavy-duty truck emissions will presumably happen at younger ages than for other regulatory classes. Buses, on average, do not accumulate mileage as quickly. Therefore, their useful life period is governed by the age requirement, not the mileage requirement.

We use a "scaled age effect" to calculate the age-adjusted emission rates for each age. 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 B-2. When the vehicle age is between the end of the warranty and the useful life, $s_a$ is interpolated between 0 and 1 as summarized in Table B-3 below, and illustrated in Figure B-1 above.

**Table B-3. Calculation of $s_a$**

| Where: | $\mathbf{s_a}$ |
|---|---|
| $age \leq end\ of\ warranty\ age$ | $0$ |
| $end\ of\ warranty\ age < age < useful\ life$ | $\frac{(age - end\ of\ warranty\ age)}{(Useful\ life\ age - \ end\ of\ warranty\ age)}$ |
| $age\ \geq useful\ life$ | $1$ |

Since MOVES deals with age groups and not individual ages (Table 1-6), the increase in emissions by age must be calculated by age group. For simplicity, we modeled an even age distribution within each age group (e.g. ages 0, 1, 2, and 3 are equally represented in the 0-3 age group). We then calculated average scaled age effects for each age group. This is important since, for example, HHD trucks reach their useful life at four years, which means they will increase emissions through the 0-3 age group. As a result, the 0-3 age group emission rate will be higher than the zero-mile emission rate for HHD trucks. Table B-4 and Table B-5 show the average scaled age effect by age group for pre-2027 and 2027+ MY vehicles, respectively. In these tables, a value of 0 indicates no deterioration, (i.e., the zero-mile emissions level (ZML)), and a value of 1 indicates a fully deteriorated engine, or maximum emissions level, at or beyond the useful life (UL).

**Table B-4. Average Scaled Age Effect, $\bar{s}_a$ For Pre-MY2027 Vehicles**

| Age Group | LHD2b3 (Tier 2 and earlier) | LHD2b3 (Tier 3) | LHD45 | MHD | HHD | Bus |
|---|---|---|---|---|---|---|
| 0-3 | 0.0833 | 0.0625 | 0.125 | 0.083 | 0.25 | 0.0313 |
| 4-5 | 0.8333 | 0.6250 | 1 | 0.833 | 1 | 0.3125 |
| 6-7 | 1 | 1 | 1 | 1 | 1 | 0.5625 |
| 8-9 | 1 | 1 | 1 | 1 | 1 | 0.8125 |
| 10-14 | 1 | 1 | 1 | 1 | 1 | 1 |
| 15-19 | 1 | 1 | 1 | 1 | 1 | 1 |
| 20+ | 1 | 1 | 1 | 1 | 1 | 1 |

**Table B-5 Average Scaled Age Effect, $\bar{s}_a$ For MY2027+ Vehicles**

| Age Group | LHD2b3 (Tier 2 and earlier) | LHD2b3 (Tier 3) | LHD45 | MHD | HHD | Bus |
|---|---|---|---|---|---|---|
| 0-3 | Not subject to HD2027 rule. | Same as Pre-MY2027 Vehicles | 0 | 0 | 0.00 | 0 |
| 4-5 | | | 0 | 0 | 0.25 | 0 |
| 6-7 | | | 0 | 0 | 1.00 | 0 |
| 8-9 | | | 0.25 | 0.75 | 1.00 | 0 |
| 10-14 | | | 1 | 1 | 1.00 | 0.75 |
| 15-19 | | | 1 | 1 | 1.00 | 1 |
| 20+ | | | 1 | 1 | 1.00 | 1 |

Then, for each pollutant and age, we multiplied the zero-mile emission rate by one plus the product of the average scaled age effect and the T&M adjustment factor.

$$\mathrm{ER}_{\mathrm{p,r,a,o}} = \mathrm{ER}_{\mathrm{zero\ mile,p,r,o}} \times (1 + \bar{s}_a \times \mathrm{f}_{\mathrm{T\&M}})$$ **Equation 8-3**

Where:

$\mathrm{ER}_{\mathrm{p,r,o,a}}$ = the heavy-duty diesel emission rate for each pollutant p, regulatory class r, age a, operating mode, o,

$\mathrm{ER}_{\mathrm{zero\ mile}}$= the zero-mile heavy-duty diesel emission rate for each pollutant p, regulatory class r, operating mode, o

$\bar{s}_{\mathrm{a}}$= average scaled age effect at age group, a

$\mathrm{f}_{\mathrm{T\&M}}$= the tampering and mal-maintenance adjustment factor (Equation 8-1)

Sections B.2 through B.9 discuss the data sources and assumptions used to determine the T&M failure frequencies and T&M emission effects used to derive the T&M adjustment factor in Equation 8-1 for each pollutant and model year range of vehicle.

## *B.2 Data Sources*

EPA used the following information to develop the tampering and mal-maintenance occurrence rates used in MOVES:

- California's ARB EMFAC2007 Modeling Change Technical Memo[180] (2006). The basic EMFAC occurrence rates for tampering and mal-maintenance were developed from Radian and EFEE reports and CARB engineering judgment.
- Radian Study (1988). The report estimated the malfunction rates based on survey and observation. The data may be questionable for current heavy-duty trucks due to advancements such as electronic controls, injection systems, and exhaust aftertreatment.
- EFEE report (1998) on PM emission deterioration rates for in-use vehicles. Their work included heavy-duty diesel vehicle chassis dynamometer testing at Southwest Research Institute.
- EMFAC2000 (2000) Tampering and Mal-maintenance Rates
- EMA's comments on ARB's Tampering, Malfunction, and Mal-maintenance Assumptions for EMFAC 2007
- University of California –Riverside (UCR) "Incidence of Malfunctions and Tampering in Heavy-Duty Vehicles"
- Air Improvement Resources, Inc.'s Comments on Heavy-Duty Tampering and Mal-maintenance Symposium

## *B.3 T&M Failure Modes*

EPA generally adopted the T&M failure modes developed by CARB, with a few exceptions. The high fuel pressure category was removed. We added a failure mode for mis-fueling to represent the use of nonroad diesel in cases when ULSD onroad diesel is required. We combined the injector failure modes into a single group. We reorganized the EGR failure modes into "*Stuck Open*" and "*Disabled/Low Flow*." We included the PM regeneration system, including the igniter, injector, and combustion air system in the PM filter leak failure mode.

For model years 1994-2007, the EPA developed failure mode frequencies for model year groups that apply to all heavy-duty diesel vehicles, including earlier model years. For model year 2007-2012, we developed separate failure mode frequencies for heavy-duty diesel vehicles that are equipped with Lean $NO_x$ Traps (LNT) and Selective Catalyst Reduction (SCR) systems, respectively. Beyond model year 2012, we assume all heavy-duty vehicles are using SCR systems. Better understanding tampering and mal-maintenance effects in contemporary vehicles is an area where additional research would be beneficial.

## *B.4 T&M Model Year Groups*

EPA developed the model year groups based on regulation and technology changes.

- Pre-1994 represents non-electronic fuel control.
- 1998-2002 represents the time period with consent decree issues.
- 2003 represents early use of EGR.
- 2007 and 2010 contain significant PM and $NO_x$ regulation changes.
- 2010-and later represent heavy-duty trucks with required OBD. This rule began in MY 2010 with complete phase-in by MY 2013. The OBD impacts are discussed in Section B.10.
- 2027 and later represent the heavy-duty vehicles subject to the HD2027 standards including further technology improvements of heavy-duty engines and after-treatment system.[181]

## *B.5 T&M Failure Frequency Rates and Differences*

EPA adopted the CARB EMFAC2007 occurrence rates, except as noted below.

**Clogged Air Filter**: EPA reduced the frequency rate from EMFAC's 15 percent to 8 percent. EPA reduced this value based on the UCR results, the Radian study, and EMA's comments that air filters are a maintenance item. Many trucks contain indicators to notify the driver of dirty air filters and the drivers have incentive to replace the filters for other performance reasons.
**Other Air Problems**: EPA reduced the frequency rate from 8 percent to 6 percent based on the UCR results.
**Electronics Failed**: EPA continued to use the 3 percent frequency rate for all model years beyond 2010. We projected that the engine hardware would evolve through 2010, rather than be replaced with completely new engine systems that would justify a higher rate of failure. For 2010 and later vehicles, the occurrence of T&M on electronics associated with SCR and DPF aftertreatment systems is counted with the aftertreatment specific failure modes (including "$NO_x$ aftertreatment malfunction" and "PM Filter Disable"), rather than in the "Electronics Failed" mode.
**EGR Stuck Open:** EPA believes the failure frequency of this item is rare and therefore set the level at 0.2 percent. This failure will lead to drivability issues that will be noticeable to the driver and serve as an incentive to repair.
**EGR Disabled/Low Flow:** EPA estimates the ERG failure rate at 10 percent. All but one major engine manufacturer had EGR previous to the 2007 model year and all have it after 2007, so a large increase in rates seem unwarranted. However, the Illinois EPA stated that "EGR flow insufficient" is the top OBD issue found in their LDV I/M program[182] so it cannot be ignored.
**$NO_x$ Aftertreatment malfunction:** EPA developed a $NO_x$ aftertreatment malfunction rate that is dependent on the type of system used. We assumed that HHDD will use primarily SCR systems and LHDD will primarily use LNT systems. We estimated the failure rates of the various components within each system to develop a composite malfunction rate (Table B-6).
The individual failure rates were developed considering the experience in agriculture and stationary industries of $NO_x$ aftertreatment systems and similar component applications. Details are included in the chart below. We assumed that tank heaters had a five percent failure rate but were only required in one third of the country during one fifth of the year. The injector failure rate is lower than fuel injectors, even though they have similar technology, because there is only one required in

each system and it is operating in less severe environment of pressure and temperature. We believe the compressed air delivery system is very mature based on a similar use in air brakes. We also believe that manufacturers will initiate engine power de-rate as incentive to keep the urea supply sufficient.

**Table B-6. $NO_x$ Aftertreatment Failure Rates**

| | Occurrence Rate |
|---|---|
| **SCR** | |
| Urea tank | 0.5% |
| Tank heaters | 1% |
| In-exhaust injectors | 2% |
| Compressed air delivery to injector | 1% |
| Urea supply pump | 1% |
| Control system | 5% |
| Exhaust temperature sensor | 1% |
| Urea supply | 1% |
| **Overall** | **13%** |
| | |
| **LNT** | |
| Adsorber | 7% |
| In-exhaust injectors | 2% |
| Control system | 5% |
| Exhaust temperature sensor | 1% |
| **Overall** | **16%** |

**$NO_x$ aftertreatment sensor:** EPA will assume a 10 percent failure mode for the aftertreatment sensor. We developed the occurrence rate based on the following assumptions:

- Population: HHDD: vast majority of heavy-duty applications will use selective catalytic reduction (SCR) technology with a maximum of one $NO_x$ sensor. $NO_x$ sensors are not required for SCR – manufacturers can use models or run open loop. Several engine manufacturers representing 30 percent of the market plan to delay the use of $NO_x$ aftertreatment devices through the use of improved engine-out emissions and emission credits.
- Durability expectations: SwRI completed 6000 hours of the European Stationary Cycle (ESC) cycling with $NO_x$ sensor. Internal testing supports longer life durability. Discussions with OEMs in 2007 indicate longer life expected by 2010.
- Forward looking assumptions: Manufacturers have a strong incentive to improve the reliability and durability of the sensors because of the high cost associated with frequent replacements.

**PM Filter Leak:** EPA will use 5 percent PM filter leak and system failure rate. They discounted high failure rates currently seen in the field.
**PM Filter Disable:** EPA agrees with CARB's 2 percent tamper rate of the PM filter. The filter causes a fuel economy penalty so the drivers have an incentive to remove it.
**Oxidation Catalyst Malfunction/Remove:** EPA believes most manufacturers will install oxidation catalysts initially in the 2007 model year and agrees with CARB's assessment of 5 percent failure rate. This rate consists of an approximate 2 percent tampering rate and 3 percent

malfunction rate. The catalysts are more robust than PM filters, but have the potential to experience degradation when exposed to high temperatures.
**Misfuel:** EPA estimated that operators will use the wrong type of fuel, such as agricultural diesel fuel with higher sulfur levels, approximately 0.1 percent of the time.

In the future, we hope to collect updated real-world failure frequencies for newer technologies.

## *B.6 Tampering & Mal-maintenance Failure Frequency Rate Summary*

**Table B-7. T&M Failure Frequency Rate by Model Year Group**

| **Model Year** | **1994-1997** | **1998-2002** | **2003-2006** | **2007-2009** | **2007-2012** | **2010+** |
|---|---|---|---|---|---|---|
| **$NO_x$ Afterteatment Technology:** | **None** | **None** | **None** | **None** | **LNT** | **SCR** |
| | | | | | | |
| Timing Advanced | 5% | 2% | 2.0% | 2.0% | 2.0% | 2.0% |
| Timing Retarded | 3% | 2% | 2.0% | 2.0% | 2.0% | 2.0% |
| Injector Problem (all) | 28% | 28% | 13.0% | 13.0% | 13.0% | 13.0% |
| Puff Limiter Mis-set | 4% | 0% | 0.0% | 0.0% | 0.0% | 0.0% |
| Puff Limited Disabled | 4% | 0% | 0.0% | 0.0% | 0.0% | 0.0% |
| Max Fuel High | 3% | 0% | 0.0% | 0.0% | 0.0% | 0.0% |
| Clogged Air Filter - EPA | 8% | 8% | 8.0% | 8.0% | 8.0% | 8.0% |
| Wrong/Worn Turbo | 5% | 5% | 5.0% | 5.0% | 5.0% | 5.0% |
| Intercooler Clogged | 5% | 5% | 5.0% | 5.0% | 5.0% | 5.0% |
| Other Air Problem - EPA | 6% | 6% | 6.0% | 6.0% | 6.0% | 6.0% |
| Engine Mechanical Failure | 2% | 2% | 2.0% | 2.0% | 2.0% | 2.0% |
| Excessive Oil Consumption | 5% | 3% | 3.0% | 3.0% | 3.0% | 3.0% |
| Electronics Failed - EPA | 3% | 3% | 3.0% | 3.0% | 3.0% | 3.0% |
| Electronics Tampered | 10% | 15% | 5.0% | 5.0% | 5.0% | 5.0% |
| EGR Stuck Open | 0% | 0% | 0.2% | 0.2% | 0.2% | 0.2% |
| EGR Disabled/Low-Flow - EPA | 0% | 0% | 10.0% | 10.0% | 10.0% | 10.0% |
| $NO_x$ Aftertreatment Sensor | 0% | 0% | 0.0% | 0.0% | 10.0% | 10.0% |
| Replacement $NO_x$ Aftertreatment Sensor | 0% | 0% | 0.0% | 0.0% | 1.0% | 1.0% |
| $NO_x$ Aftertreatment Malfunction - EPA | 0% | 0% | 0.0% | 0.0% | 16.0% | 13.0% |
| PM Filter Leak | 0% | 0% | 0.0% | 5.0% | 5.0% | 5.0% |
| PM Filter Disabled | 0% | 0% | 0.0% | 2.0% | 2.0% | 2.0% |
| Oxidation Catalyst Malfunction/Remove - EPA | 0% | 0% | 0.0% | 5.0% | 5.0% | 5.0% |
| Mis-fuel - EPA | 0.1% | 0.1% | 0.1% | 0.1% | 0.1% | 0.1% |

## *B.7 $NO_X$ T&M Emission Effects*

### *B.7.1 Model Years 1994 through 2026*

For model years 1994 through 2026, EPA developed the emission effect from each tampering and mal-maintenance incident from CARB's EMFAC, Radian's dynamometer testing with and without the malfunction present, Engine, Fuel, and Emissions Engineering Inc. (EFEE) results, and EPA staff testing experience.

EPA estimated that the lean $NO_x$ traps (LNT) in LHD are 80 percent efficient and the selective catalyst reduction (SCR) systems in HHD are 90 percent efficient at reducing $NO_x$.
EPA developed the $NO_x$ emission factors of the $NO_x$ sensors based on SCR systems' ability to run in open-loop mode and still achieve $NO_x$ reductions. The Manufacturers of Emission Controls Association (MECA) has stated that a 75-90 percent $NO_x$ reduction should occur with open loop control and >95 percent reduction should occur with closed loop control.[183] Visteon reports a 60-80 percent $NO_x$ reduction with open loop control.[184]

In testing, the failure of the $NO_x$ aftertreatment system had a different impact on the $NO_x$ emissions depending on the type of aftertreatment. The HHD vehicles with SCR systems experienced a 1000 percent increase in $NO_x$ during a complete failure, therefore we estimated a 500 percent increase as a midpoint between normal operation and a complete failure. The LHD vehicles with LNT systems experienced a 500 percent increase in $NO_x$ during a complete failure. We estimated a 300 percent increase as a value between a complete failure and normal system operation. The values with 0 percent effect in shaded cells represent areas which have no occurrence rate.

As discussed in Section 2.1.1.4.6, we estimate that 25 percent of LHD MY 2007-2009 vehicles were equipped with LNT aftertreatment systems. For LHD2b3 MY 2010-2012 vehicles, we modeled that 25 percent of vehicles had LNT aftertreatment systems, and 75 percent had SCR systems. For LHD2b3 MY 2013+, we assume that all are equipped with SCR aftertreatment systems. For LHD45, MHD, HHD, and Urban buses, we modeled the model year 2010 and later T&M effects assuming all engines are equipped with SCR aftertreatment systems. We recognize this is a simplification as manufacturers produced non-SCR equipped engines in the initial implementation years of the 2010 standard due to average, banking, and trading, and the EPA allowance of nonconformance penalty (NCP) engines in 2012.[90]

### *B.7.2 Model Years 2027 and Later*

For MY2027+ vehicles, we further adjusted the MY2010 $NO_x$ T&M emission effect to reflect the HD2027 standards in MOVES4. As $NO_x$ emissions become more tightly controlled with the application of advanced technologies to meet the standards, we anticipate the $NO_x$ T&M emission effects will increase (i.e., there will be a relatively larger impact of T&M because the emission control system is reducing a greater percentage of the $NO_x$ produced by the engine).

To estimate the $NO_x$ T&M *emission effects* for the HD2027 standards, we first calculated the average zero-mile $NO_x$ emission rate $\overline{ER}_{zero\ mile,NOx}$ prior to the standard based on the weighted average of the different operating modes $o$, and regulatory class $r$, using Equation 8-4.

$$\overline{\mathrm{ER}}_{\text{zero mile,NOX}} = \frac{\sum_{r,o}\left(ER_{zero\ mile,NOx,r,o} \times t_{r,o}\right)}{\sum_{r,o} t_{r,o}}$$ **Equation 8-4**

Where:
$\overline{ER}_{zero\ mile,NOx}$ = 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 MOVES3.

Next, we estimated the $NO_x$ emission rate of MY 2010 vehicles with a tampering and mal-maintenance failure i, using Equation 8-5, which was derived from Equation 8-2 using the fleet average emission rate from Equation 8-4 assuming the T&M frequency is 100 percent.

$$\overline{\mathrm{ER}}_{\text{T\&M i},NO_X} = \overline{\mathrm{ER}}_{\text{zero mile},NO_X} \times \left(1 + \text{T\&M emission effect}_{\text{i},NO_X}\right)$$ **Equation 8-5**

We then derived Equation 8-6, assuming that a $NO_x$ aftertreatment equipment failure $i$, in the control scenario, would cause the average of the MY 2027+ failed emission rates, $\overline{ER}_{T\&M\ i,NO_X}$, to be the same as a $NO_x$ aftertreatment failure in the baseline MY 2010 case, Baseline $\overline{\mathrm{ER}}_{\text{T\&M i},NO_X}$

$$\text{MY2010 } \overline{\mathrm{ER}}_{\text{T\&M i},NO_X} = \text{MY2027 } \overline{\mathrm{ER}}_{\text{T\&M i},NO_X}$$
$$\text{MY2010 } \overline{\mathrm{ER}}_{\text{zero mile},NO_X} \times \left(1 + \text{MY2010 T\&M emission effect}_{\text{i},NO_X}\right) = \text{MY2027 } \overline{\mathrm{ER}}_{\text{zero mile},NO_X} \times \left(1 + \text{MY2027 T\&M emission effect}_{\text{i},NO_X}\right)$$ **Equation 8-6**

By rearranging Equation 8-6, we derived Equation 8-7 to estimate the control scenario $NO_x$ T&M emissions effects.

$$\text{MY2027 T\&M emission effect}_{\text{i},NO_X} = \left[\frac{\text{MY2010 } \overline{\mathrm{ER}}_{\text{zero mile},NO_X} \times \left(1 + \text{MY2010 T\&M emission effect}_{\text{i},NO_X}\right)}{\text{MY2027 } \overline{\mathrm{ER}}_{\text{zero mile},NO_X}}\right] - 1$$ **Equation 8-7**

The MY2027 T&M $NO_x$ emission effects for the $NO_x$ aftertreatment failures are much larger than the MY2010 values, because the zero-mile $NO_x$ emission rate for MY2027 vehicles are lower than the MY2010 zero-mile $NO_x$ emission rates.

**Table B-8. $NO_x$ T&M Emission Effect by Model Year Group**

| **Model Year** | **1994-1997** | **1998-2002** | **2003-2006** | **2007-2009** | **2007-2012** | **2010-2026** | **2027-2028** | **2029-2060** |
|---|---|---|---|---|---|---|---|---|
| **$NO_x$ Afterteatment Technology:** | **None** | **None** | **None** | **None** | **LNT** | **SCR** | **SCR** | **SCR** |
| **Federal $NO_x$ Emission Standard (g/bhp-hr)** | **5.0** | **5.0** | **4.0** | **2.0** | **0.2** | **0.2** | **0.05** | **0.05** |
| Timing Advanced | 60% | 60% | 60.0% | 60.0% | 12.0% | 6.0% | 6.0% | 6.0% |
| Timing Retarded | -20% | -20% | -20.0% | -20.0% | -20.0% | -20.0% | -20.0% | -20.0% |
| Injector Problem (all) | -5% | -1% | -1.0% | -1.0% | -1.0% | -1.0% | -1.0% | -1.0% |
| Puff Limiter Mis-set | 0% | 0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| Puff Limited Disabled | 0% | 0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| Max Fuel High | 10% | 0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| Clogged Air Filter - EPA | 0% | 0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| Wrong/Worn Turbo | 0% | 0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| Intercooler Clogged | 25% | 25% | 25.0% | 25.0% | 5.0% | 3.0% | 3.0% | 3.0% |
| Other Air Problem - EPA | 0% | 0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| Engine Mechanical Failure | -10% | -10% | -10.0% | -10.0% | -10.0% | -10.0% | -10.0% | -10.0% |
| Excessive Oil Consumption | 0% | 0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| Electronics Failed - EPA | 0% | 0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| Electronics Tampered | 80% | 80% | 80.0% | 80.0% | 16.0% | 8.0% | 8.0% | 8.0% |
| EGR Stuck Open | 0% | 0% | -20.0% | -20.0% | -20.0% | -20.0% | -20.0% | -20.0% |
| EGR Disabled/Low-Flow - EPA | 0% | 0% | 30.0% | 50.0% | 10.0% | 5.0% | 5.0% | 5.0% |
| $NO_x$ Aftertreatment Sensor[A] | 0% | 0% | 0.0% | 0.0% | 200.0% | 200.0% | 1294%;<br>1271%;<br>1620%;<br>1713% [B] | 1301%;<br>1277%;<br>1643%;<br>1741% [B] |
| Replacement $NO_x$ Aftertreatment Sensor[A] | 0% | 0% | 0.0% | 0.0% | 200.0% | 200.0% | 1294%;<br>1271%;<br>1620%;<br>1713% [B] | 1301%;<br>1277%;<br>1643%;<br>1741%[B] |
| $NO_x$ Aftertreatment Malfunction - EPA[A] | 0% | 0% | 0.0% | 0.0% | 300.0% | 500.0% | 2688%;<br>2641%;<br>3339%;<br>3527% [B] | 2703%;<br>2655%;<br>3386%;<br>3582% [B] |
| PM Filter Leak | 0% | 0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| PM Filter Disabled | 0% | 0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| Oxidation Catalyst Malfunction/Remove - EPA | 0% | 0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| Mis-fuel - EPA | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |

[A] $NO_x$ aftertreatment failure modes

[B] The values in the cells are for LHD45, MHD, HHD, Bus categories, respectively

### B.7.3 $NO_x$ Adjustment Factor Calculations

Combining the $NO_x$ emission effects with the frequency rates results in the initial T&M adjustment factors shown in the Table B-9 below. This methodology estimated a small (9-14%) T&M $NO_x$ adjustment factor for 2009 and earlier models due to $NO_x$ effects of the following failure modes: electronics tampered, timing advances, intercooler clogged, and ERG disabled/Low Flow. However, MOVES does not use the estimated $NO_x$ T&M emission effects initially estimated for 2009 and earlier model years, and assumes no $NO_x$ increase (with the exception of the LNT effect for LHD explained below). This is indicated in the 3rd column of Table B-9 labeled "(Removed 2009 and earlier)." Instead, MOVES assumes $NO_x$ increases only in the vehicles with advanced $NO_x$ exhaust aftertreatment technologies for a few reasons:

- The Consent Decree Testing conducted by West Virginia University did not show an increase in $NO_x$ emissions with odometer (and consequently, age) during or following the regulatory useful life.[185] Since the trucks in this program were collected from in-use fleets, we do not believe that these trucks were necessarily biased toward cleaner engines.
- Heavy-duty diesel manufacturers often certify zero or low deterioration factors for these engines.
- Starting with MY 2010 (2007 for vehicles with LNT), we expect T&M effects to become much more significant, because a failure in the $NO_x$ aftertreatment system will substantially increase emissions. We decided to initiate modeling of the $NO_x$ T&M adjustment factor with the implementation of the 2010 standards.

The assumption of no T&M $NO_x$ increases for pre-2010 heavy-duty vehicles (except LHD with LNT), extends to glider vehicles for all model years (regClassID 49).

**Table B-9. Tampering & Mal-Maintenance $NO_x$ Adjustment Factors ($f_{T\&M,NOx}$) (Percent) for Heavy-Duty Diesel Vehicles without Onboard Diagnostics (OBD)**

| Model years | $NO_x$ Aftertreatment Technology | $f_{T\&M,NOx,nonOBD}$ (Initial) | $f_{T\&M,NOx,nonOBD}$ (Removed 2009 and earlier for non-LNT engines) |
|---|---|---|---|
| 1994-1997 | None | 10 | 0 |
| 1998-2002 | None | 14 | 0 |
| 2003-2006 | None | 8.7 | 0 |
| 2007-2009 | None | 10.7 | 0 |
| 2007-2012 | LNT | 71.5 | 71.5 |
| 2010-2026 | SCR | 87.4 | 87.4 |
| 2027-2028 | SCR | 492.2 (LHD45);<br>483.5 (MHD);<br>612.7 (HHD);<br>647.3 (Bus) | 492.2 (LHD45);<br>483.5 (MHD);<br>612.7 (HHD);<br>647.3 (Bus) |
| 2029+ | SCR | 494.9 (LHD45);<br>486.0 (MHD);<br>621.3 (HHD);<br>657.6 (Bus) | 494.9 (LHD45);<br>486.0 (MHD);<br>621.3 (HHD);<br>657.6 (Bus) |

The T&M NO$_x$ emission rates for LHD2b3 vehicles equipped with LNT aftertreatment in 2007-2009 are calculated by first adjusting Equation 2-11 to account for T&M of LNT aftertreatment, as shown in Equation 8-8. The derivation of Equation 2-11 including the definition of normal operation frequency and DPF regeneration frequency are discussed in Section 2.1.1.4.6

$$\frac{2007-2009\ LNT\ NOx\ emissions\ (T\&M)}{Baseline\ Emissions}$$

$$= (normal\ op.frequency) \times \left(\frac{LNT\ normal\ emissions}{Baseline\ emissions}\right) \times (1+2007-2009\ LHD\ LNT\ T\&M\ effect) + (DPF\ reg.frequency) \times \left(\frac{Baseline\ emissions}{Baseline\ emission}\right)$$ **Equation 8-8**

$$= (0.90) \times (0.10) \times (1.715) + (0.10) \times (1) \times (1) = 0.2544$$

*Where Baseline Emissions = MOVES2010 MY 2003-2006 NO$_x$ emission rates for LHD2b3*

Because MOVES does not model LNT vehicles separately, we then calculated an average ratio for all 2007-2009 LHD2b3 NO$_x$ rates (both non-LNT and LNT with T&M) over the baseline 2003-2006 NO$_x$ rates by adjusting Equation 2-12 to account for the T&M effects of LNT, as shown in Equation 8-9.

$$\frac{2007-2009\ LHD2b3\ NOx\ emissions\ (T\&M)}{Baseline\ emissions}$$

$$= (LNT\ market\ share)\left(\frac{2007-2009\ LNT\ NOx\ emissions\ (T\&M)}{Baseline\ emissions}\right) + (non-LNT\ market\ share)\left(\frac{2007-2009\ emission\ standards}{Baseline\ emissions}\right)$$ **Equation 8-9**

$$= (0.25) \times (0.2544) + (0.75) \times (0.5) = 0.4386$$

*Where Baseline Emissions = MOVES2010 MY 2003-2006 NO$_x$ emission rates for LHD2b3*

Then, the T&M effect for 2007-2009 LHD2b3 is calculated in Equation 8-10 by dividing Equation 8-9 by Equation 2-12 and subtracting 1.

$$f_{T\&M,NOx,LHD2b3,2007-2009} = \frac{2007-2009\ LHD2b3\ NOx\ emissions\ (T\&M)}{2007-2009\ LHD2b3\ NOx\ emissions\ (zero\ mile)} - 1$$

**Equation 8-10**

$$= \left(\frac{2007-2009\ LHD2b3\ NOx\ (T\&M)}{Baseline\ emissions}\right) \Big/ \left(\frac{2007-2009\ LHD2b3\ NOx\ (zero\ mile)}{Baseline\ emissions}\right) - 1$$

$$= 0.4386/0.4225 - 1 = 1.038 - 1 = 3.8\%\ \text{increase due to T\&M}$$

*Where Baseline Emissions = MOVES2010 MY 2003-2006 NO$_x$ emission rates for LHD2b3*

For 2007-2009, LHD45 uses the same emission rates and T&M factors as LHD2b3.
As noted earlier, we assume no T&M NO$_x$ effects for pre-2010 MY vehicles in the other heavy-duty regulatory classes.

The T&M adjustment factors ($f_{T\&M,NOx}$) for model year 2010 and later model years incorporate the impact of onboard diagnostic (OBD) emission effect assumptions discussed in Section B.10, and calculated with Equation 8-15. As explained in that section, for LHD2b3 vehicles, we assume 100% OBD penetration starting in 2010. This reduces the T&M adjustment factor by 0.33 for these years.

For 2010-2012, LHD2b3, we assume that both LNT and SCR equipped vehicles will provide the same level of control with a 90 percent reduction from 2003-2006 levels (ignoring the PM regeneration NO$_x$ benefit for LNT aftertreatment considered for the 2007-2009 rates for simplicity). To calculate the T&M NO$_x$ effects for 2010-2012 $\left(f_{T\&M,NOx,LHD2b3,2010-2012}\right)$, we weighted the LNT-specific and SCR-specific T&M effects (from Table B-9) according to the market shares, and applied the 33% percent reduction for OBD as shown in Equation 8-11:

$$\begin{aligned} f_{T\&M,LHD2b3,2010-2012} &= (\text{LNT market share}) \times \left(f_{T\&M,NOx,LNT,nonOBD}\right) \times (f_{OBD}) \\ &+ (\text{SCR market share}) \times \left(f_{T\&M,NOx,SCR,nonOBD}\right) \times (f_{OBD}) \end{aligned}$$

**Equation 8-11**

$$= (25\%) \times (71.5\%) \times (67\%) + (75\%) \times (87.4\%) \times (67\%) = 55.9\%$$

For LHD45 and heavier regulatory classes, we assume a 33 percent OBD penetration in model year 2010-2012 as shown in Equation 8-12.

$$\begin{aligned} f_{T\&M,NOx,LHD45,2010-2012} &= \left(f_{T\&M,NOx,SCR,nonOBD}\right) \times (f_{OBD}) \times (\mathrm{p}_{OBD}) \\ &+ \left(f_{T\&M,NOx,SCR,nonOBD}\right) \times (1 - \mathrm{p}_{OBD}) \end{aligned}$$

**Equation 8-12**

$$= (87.4\%) \times (67\%) \times (33\%) + (87.4\%) \times (67\%) = 77.9\%$$

For 2013 and later model years, the T&M adjustment factors are calculated for heavy-duty vehicles assuming that all (with the exception of gliders) are using SCR technology and 100 percent OBD.

**Equation 8-13**

$$f_{T\&M,NOx,SCR,2013-2026} = \left(f_{T\&M,NOx,SCR,nonOBD}\right) \times \left(f_{OBD}\right) \times \left(\mathrm{p}_{OBD}\right)$$

$$= (87.4\%) \times (67\%) \times 100\% = 58.6\%$$

**Equation 8-14**

$$f_{T\&M,NOx,SCR,2027-2028,HHD} = \left(f_{T\&M,NOx,SCR,nonOBD}\right) \times \left(f_{OBD}\right) \times \left(\mathrm{p}_{OBD}\right)$$

$$= (612.7\%) \times (67\%) \times 100\% = 410.5\%$$

The $NO_X$ Tampering & Mal-maintenance adjustment factors by regulatory class and model year groups are summarized in Table B-10.

**Table B-10. $NO_X$ T&M Adjustment Factors ($f_{T\&M,NOx}$) by MOVES Regulatory Classes and Model Year Groups**

| Model Year Group | LH2b3 (RegClass 41) | LHD45 (RegClassID 42) | MHD, HHD, Bus (RegClassID 46,47,48) | Gliders (RegClassID 49) |
|---|---|---|---|---|
| 2007-2009 | 3.81% | 3.81% | 0% | 0% |
| 2010-2012 | 55.9% | 77.9% | 77.9% | 0% |
| 2013-2027 | 58.6% | 58.6% | 58.6% | 0% |
| 2027-2028 | Same as 2013-2027 | 329.7% | 324.0% (MHD); 410.5% (HHD); 433.7% (Bus) | 0% |
| 2029+ | Same as 2013-2027 | 331.6% | 325.6% (MHD); 416.3% (HHD); 440.6% (Bus) | 0% |

## *B.8 PM T&M Emission Effects*

EPA developed the PM emission effects for each tampering and mal-maintenance incident from CARB's EMFAC, Radian's dynamometer testing with and without the malfunction present, EFEE results, and internal testing experience.

EPA estimates that the diesel PM filter has 95 percent effectiveness. Many of the tampering and mal-maintenance items that impact PM also have a fuel efficiency and drivability impact. Therefore, operators will have an incentive to fix these issues.

EPA estimated that excessive oil consumption will have the same level of impact on PM as engine mechanical failure. The failure of the oxidation catalyst is expected to cause a PM increase of 30 percent; however, this value is reduced by 95 percent due to the PM filter effectiveness. We also considered a DOC failure will cause a secondary failure of PM filter regeneration. We accounted for this PM increase within the PM filter disabled and leak categories.

The values with 0 percent effect in shaded cells represent areas which have no occurrence rate.
In MOVES2014, we increased the PM emission effect for PM Filter Leaks and PM Filter Tampering for the 2007-2009 and 2010+ model year groups. The PM filter leak was increased from 600 percent to 935 percent and the PM Filter Disabled emission effect was increased from 1000 percent to 2670 percent. These in Table B-9 effects along with the OBD effects discussed in

Section B.10 results in a fleet average $PM_{2.5}$ Tampering & Mal-maintenance effect of 100 percent in 2007-2009 and 89 percent in 2010-2012 (Table 2-25).

**Table B-11. $PM_{2.5}$ T&M Emission Effect by Model Year Group**

| | 1994-1997 | 1998-2002 | 2003-2006 | 2007-2009 | 2010+ |
|---|---|---|---|---|---|
| Federal Emission Standard | 0.1 | 0.1 | 0.1 | 0.01 | 0.01 |
| | | | | | |
| Timing Advanced | -10% | -10% | -10% | 0% | 0% |
| Timing Retarded | 25% | 25% | 25% | 1% | 1% |
| Injector Problem | 100% | 100% | 100% | 5% | 5% |
| Puff Limiter Mis-set | 20% | 0% | 0% | 0% | 0% |
| Puff Limiter Dsabled | 50% | 0% | 0% | 0% | 0% |
| Max Fuel High | 20% | 0% | 0% | 0% | 0% |
| Clogged Air Filter | 50% | 50% | 30% | 2% | 2% |
| Wrong/Worn Turbo | 50% | 50% | 50% | 3% | 3% |
| Intercooler Clogged | 50% | 50% | 30% | 2% | 2% |
| Other Air Problem | 40% | 40% | 30% | 2% | 2% |
| Engine Mechanical Failure | 500% | 500% | 500% | 25% | 25% |
| Excessive Oil Consumption | 500% | 500% | 500% | 25% | 25% |
| Electronics Failed | 60% | 60% | 60% | 3% | 3% |
| Electronics Tampered | 50% | 50% | 50% | 3% | 3% |
| EGR Stuck Open | 0% | 0% | 100% | 5% | 5% |
| EGR Disabled/Low Flow | 0% | 0% | -30% | -30% | -30% |
| $NO_x$ Aftertreatment Sensor | 0% | 0% | 0% | 0% | 0% |
| Replacement $NO_x$ Aftertreatment Sensor | 0% | 0% | 0% | 0% | 0% |
| $NO_x$ Aftertreatment Malfunction | 0% | 0% | 0% | 0% | 0% |
| PM Filter Leak | 0% | 0% | 0% | 935% | 935% |
| PM Filter Disabled | 0% | 0% | 0% | 2670% | 2670% |
| Oxidation Catalyst Malfunction/Remove | 0% | 0% | 0% | 0% | 0% |
| Mis-fuel - EPA | 30% | 30% | 30% | 100% | 100% |

## *B.9 THC and CO T&M Emission Effects*

EPA estimated oxidation catalysts are 80 percent effective at reducing hydrocarbons. All manufacturers will utilize oxidation catalysts in 2007, but only a negligible number were installed prior to the PM regulation reduction in 2007. We assumed that with Tampering and Mal-maintenance, the THC zero level emissions will increase by 50 percent. This still represents a 70 percent reduction in THC emissions between zero-mile 2006 emissions and fully deteriorated 2007 vehicles.

We reduced CARB's THC emission effect for timing advancement because earlier timing should reduce THC, not increase them. The effect of injector problems was reduced to 1000 percent based on EPA's engineering staff experience. We increased the THC emission effect of high fuel pressure (labeled as Max Fuel High) to 10 percent in 1994-1997 years because the higher pressure will lead to extra fuel in early model years and therefore increased THC. Lastly, we used the THC emission effect of advanced timing for the electronics tampering (0 percent) for all model years. The values with 0 percent effect in shaded cells represent areas which have no occurrence rate.

**Table B-12. THC T&M Emission Effect by Model Year Group**

| **Model Year** | **1994-1997** | **1998-2002** | **2003-2006** | **2007-2009** | **2010+** |
|---|---|---|---|---|---|
| Federal HC Emission Standard (g/bhp-hr) | 1.3 | 1.3 | 1.3 | 0.2 | 0.14 |
| Timing Advanced | 0% | 0% | 0% | 0% | 0.0% |
| Timing Retarded | 50% | 50% | 50% | 50% | 10.0% |
| Injector Problem (all) | 1000% | 1000% | 1000% | 1000% | 200.0% |
| Puff Limiter Mis-set | 0% | 0% | 0% | 0% | 0.0% |
| Puff Limited Disabled | 0% | 0% | 0% | 0% | 0.0% |
| Max Fuel High | 10% | 0% | 0% | 0% | 0.0% |
| Clogged Air Filter - EPA | 0% | 0% | 0% | 0% | 0.0% |
| Wrong/Worn Turbo | 0% | 0% | 0% | 0% | 0.0% |
| Intercooler Clogged | 0% | 0% | 0% | 0% | 0.0% |
| Other Air Problem - EPA | 0% | 0% | 0% | 0% | 0.0% |
| Engine Mechanical Failure | 500% | 500% | 500% | 500% | 100.0% |
| Excessive Oil Consumption | 300% | 300% | 300% | 300% | 60.0% |
| Electronics Failed - EPA | 50% | 30% | 50% | 50% | 10.0% |
| Electronics Tampered | 0% | 0% | 0% | 0% | 0.0% |
| EGR Stuck Open | 0% | 0% | 100% | 100% | 20.0% |
| EGR Disabled/Low-Flow - EPA | 0% | 0% | 0% | 0% | 0.0% |
| $\text{NO}_x$ Aftertreatment Sensor | 0% | 0% | 0% | 0% | 0.0% |
| Replacement $\text{NO}_x$ Aftertreatment Sensor | 0% | 0% | 0% | 0% | 0.0% |
| $\text{NO}_x$ Aftertreatment Malfunction - EPA | 0% | 0% | 0% | 0% | 0.0% |
| PM Filter Leak | 0% | 0% | 0% | 0% | 0.0% |
| PM Filter Disabled | 0% | 0% | 0% | 0% | 0.0% |
| Oxidation Catalyst Malfunction/Remove - EPA | 0% | 0% | 0% | 50% | 50.0% |
| Mis-fuel - EPA | 0% | 0% | 0% | 0% | 0% |

A separate tampering analysis was not performed for CO; rather, the THC effects were assumed to apply for CO.

Combining all of the emissions effects and failure frequencies discussed in this section, and the OBD effects discussed in the next section, we summarized the aggregate emissions impacts over the useful life of the fleet in the main body of the document in Table 2-28 (THC and CO).

## *B.10 HD OBD impacts*

With the finalization of the heavy-duty onboard diagnostics (HD OBD) rule, we made adjustments to 2010 and later model years to reflect the rule's implementation.

Specifically, we reduced the emissions increases for all pollutants due to an OBD tampering and mal-maintenance factor, $f_{OBD}$, which reduced the T&M adjustment factors by 33 percent. Data on the impact of OBD were not available for heavy-duty trucks, and this number is probably a conservative estimate. This is in addition to the substantial $PM_{2.5}$ and $NO_x$ reductions for 2010 and later vehicles due to the implementation of other standards. We assumed, since the rule phased-in OBD implementation, that 33 percent of all LHD45, MHD, HHD and Urban Bus engines would have OBD in the 2010, 2011, and 2012 model years, and 100 percent would have OBD by 2013 model year and later. For LHD2b3 vehicles, we assumed they would have 100% OBD penetration starting in 2010.  Equation 8-15 describes the calculation of the percent increase in emission rate through useful life (T&M adjustment factors ($f_{T\&M}$)), where $p_{OBD}$ represents the fraction of the fleet equipped with OBD (Table B-11). ).

$$f_{T\&M,p} = f_{T\&M,nonOBD,p} \times (1 - p_{OBD}) + f_{T\&M,nonOBD,p} \times f_{OBD} \times (p_{OBD})$$

**Equation 8-15**

Where:

$f_{T\&M,p}$= the tampering and mal-maintenance adjustment factor for pollutant, p, that accounts for the phase-in of OBD

$f_{T\&M,nonOBD,p}$= the tampering and mal-maintenance adjustment factor for pollutant, p, for engines without OBD; calculated in Sections B.7 through B.9

$p_{OBD}$= penetration of the fleet equipped with OBD, as shown in Table B-11.

$f_{OBD}$= the effect of OBD on the T&M adjustment factor = 0.67= 33% reduction

**Table B-13. Onboard Diagnostic (OBD) Assumed Phase-in ($p_{OBD}$) by Model Year and Regulatory Class**

| Model years | Regulatory Class | $p_{OBD}$ (%) |
|---|---|---|
| Pre-2010 | LHD2b3, LHD45, MHD, HHD, Urban Bus | 0 |
| 2010-2012 | LHD2b3 | 100 |
| 2010-2012 | LHD45, MHD, HHD, Urban Bus | 33 |
| 2013+ | LHD2b3, LHD45, MHD, HHD, Urban Bus | 100 |

# Appendix C Tampering and Mal-maintenance for MY 2007 and Later Diesel Extended Idle

As discussed in Section 2.3.2.3 we assume the failure of diesel particulate filters (DPF) is the primary cause of T&M effects on emission deterioration in 2007+ extended idle emissions. We made assumptions about the failure rates of DPFs from in-use trucks based on consultation with several references and staff at the California Air Resources Board (CARB) as summarized in Table C-1. We adopted the assumption shared by CARB staff that 10 percent of 2007-2009 DPFs fail in the real-world, and 5 percent of 2010+ DPFs fail in the real-world.

**Table C-1. References Used to Support In-Use DPF Failure Rate Assumption for Extended Idling Emissions**

| Study | Relevant Information |
|---|---|
| US EPA (2015)[109] | 7% of 2007+ trucks in MOVES are assumed to either have a PM filter leak or have the PM filter disabled. Current assumption for running exhaust emissions in MOVES3. |
| Preble et al. (2015)[186] | 20% of trucks produce 80% of black carbon (BC) emissions from Port of Oakland 2013 truck fleet, where 99% of the trucks are equipped with DPFs |
| Bishop et al. (2014)[187] | 3% of 2007+ trucks at Port of LA have PM emissions 3× the standard. 9% of 2008+ trucks at Cottonwood site have PM emissions 3× the standard |
| CARB (2015)[188] | 35% to 4% of trucks submitted warranty claims related to the PM filter between 2007 and 2011 |
| CARB (2015)[188] | 8% of trucks were classified as high emitters (emitting over 5% opacity) from a sample of >1,800 trucks test in the snap-idle acceleration test by CARB, about ~1/2 equipped with DPFs |
| CARB correspondence (2016) | ~10% of 2007-2009 DPFs and ~5% of 2010+ DPFs to fail in real-world, based on their observations from warranty claims, snap-idle acceleration opacity tests, and their review of the Bishop et al. (2014)[187] and Preble et al. (2015)[186] studies. |

To account for the failure of DPF in the THC and $PM_{2.5}$ emission rates, we used the 2005-2006 average extended idle emission rates to represent the ‘failed’ DPF emission rates. We then calculated a ‘Deteriorated’ emission rate that represents a mix of failed and properly operating systems by assigning the ‘failed’ DPF emission rates a weight of 10 percent in the 2007-2009 model year group, and 5 percent weight in the 2010-2012, and 2013+ model year groups, as shown in Table C-2. The ‘Deteriorated’ emission rate represents the presumed emission rate of fully-aged heavy-duty diesel trucks. Unlike the start and running MOVES emission rates, extended idle emission rates in MOVES are not distinguished by age. Thus, these rates are constant with respect to age.

**Table C-2. Baseline and deteriorated THC and $PM_{2.5}$ emission rates to account for failure of diesel particulate filters (DPFs) by model year groups**

| Engine Model Year | Baseline | | | | Deteriorated | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | THC (g/hr) | $PM_{2.5}$ (g/hr) | EC (g/hr) | nonEC (g/hr) | Failure rate | THC (g/hr) | $PM_{2.5}$ (g/hr) | EC (g/hr) | nonEC (g/hr) |
| 2005-2006 | 8.49 | 0.251 | 0.065 | 0.187 | - | 8.49 | 0.251 | 0.065 | 0.187 |
| 2007-2009 | 8.49 | 0.075 | 0.007 | 0.067 | 10% | 8.49 | 0.092 | 0.013 | 0.079 |
| 2010-2012 | 2.53 | 0.026 | 0.004 | 0.022 | 5% | 2.83 | 0.037 | 0.007 | 0.030 |
| 2013+ | 1.38 | 0.012 | 0.002 | 0.010 | 5% | 1.74 | 0.024 | 0.005 | 0.019 |

We assume that trucks that are under warranty would have substantially fewer aftertreatment failures than older trucks. Because extended idle rates are modelled as constant with age, to estimate the fleet-average emission rates used in MOVES, we used the ‘Baseline’ emission rates to represent trucks that are within the specified 435,000 miles useful-life of the engine in the US EPA regulations. We use the deteriorated emission rate to represent the years between the regulated “useful life” and the 1,530,000 miles that MOVES models as the mean life-time miles for a long-haul combination trucks. Using the ‘deterioration fraction’ [(1-.435)/1.53 = 0.72] as the fraction of the vehicle miles traveled during the deterioration phase, we calculated fleet-average emission rates used for MOVES in Table C-3. As shown, the MOVES EC/PM emission rates for MY 2007+ trucks are slightly higher than the ‘Baseline’ EC/PM fractions in Table C-2, because the fleet emissions are assumed to include some contribution of emissions from trucks with failed DPFs, which have a higher EC/PM fraction.

**Table C-3. Emission Rates Calculated from Weighting the ‘Baseline’ and ‘Deteriorated’ Emission Rates from Table C-2 Using the Deteriorated Fraction**

| Engine Model Year | MOVES | | | | | |
|---|---|---|---|---|---|---|
| | Deteriorated Fraction | THC (g/hr) | $PM_{2.5}$ (g/hr) | EC (g/hr) | nonEC (g/hr) | EC/PM |
| 2005-2006 | - | 8.49 | 0.251 | 0.065 | 0.187 | 0.26 |
| 2007-2009 | 0.72 | 8.49 | 0.087 | 0.012 | 0.076 | 0.13 |
| 2010-2012 | 0.72 | 2.75 | 0.034 | 0.006 | 0.028 | 0.18 |
| 2013+ | 0.72 | 1.64 | 0.021 | 0.004 | 0.017 | 0.20 |

Although, 2005-2006 model year engine data was used in this analysis, the update itself is limited to the model year 2007 and later emission rates.

# Appendix D Pre-2007 Model Year Extended Idle Data Summary

These tables provides additional information on the data used to estimate extended idle emissions for pre-2007 MY vehicles as described in Section 2.3.1.

**Table D-1. Data for Pre-2007 Extended Idle NO$_x$ Emissions**

| **Idle NOx Rates (gram/hour) Summary** | | | |
|---|---|---|---|
| **Program** | **Condition** | **# Samples** | **Mean NOX Emiss Rate** |
| 1991-2006 Low Speed Idle, A/C Off | | | |
| McCormick, High Altitude, HDT | Low RPM, AC Off | 12 | 85 |
| Lim, EPA | Low RPM, No access | 12 | 109 |
| Irick, Clean Air Tech & IdleAire | | 49 | 87 |
| WVU - 1991-2004 | Low RPM, AC Off | 48 | 83 |
| WVU, NCHRP | | 2 | 47 |
| Tang, Metro NY 1984-1999 | | 33 | 81 |
| Calcagno | Low RPM, AC Off | 27 | 120 |
| Brodrick, UC Davis | Low RPM, AC Off | 1 | 104 |
| Storey | Low RPM, AC Off | 4 | 126 |
| | **Overall** | **188** | **91** |
| 1991-2006 High Speed Idle, A/C Off | | | |
| Lim, EPA CCD | High RPM, No access | 5 | 169 |
| Calcagno | High RPM, AC Off | 21 | 164 |
| | **Overall** | **26** | **165** |
| 1991-2006 High Speed Idle, A/C On | | | |
| Lim, EPA CCD | High RPM, AC On | 5 | 212 |
| Brodrick, UC Davis | High RPM, AC On | 1 | 240 |
| Calcagno | High RPM, AC On | 21 | 223 |
| Storey | High RPM, AC On | 4 | 262 |
| | **Overall** | **31** | **227** |
| 1975-1990 Low Speed Idle, A/C Off | | | |
| WVU - 1975-1990 | Low RPM, AC Off | 18 | 48 |
| Lim, EPA, CCD, 1985 MY | Low RPM, AC Off | 1 | 20 |
| | **Overall** | **19** | **47** |
| 1975-1990 High Speed Idle, A/C On (calculated) | | | |
| Ratio of 1991-2006 "High Idle, A/C On" to "Low Idle, A/C Off" | | | 2.5 |
| | **Overall (calculated)** | | **115.4** |
| **Calculated Extended Idle MYs 1975-1990:** | | | **69.3** |
| **Calculated Extended Idle MYs 1991-2006:** | | | **136.1** |

**Table D-2. Data for Pre-2007 Extended Idle HC Emissions**

| Idle HC Rates (gram/hour) Summary | | | |
|---|---|---|---|
| **Program** | **Condition** | **# Samples** | **Mean HC Emiss Rate** |
| 1991-2006 Low Speed Idle, A/C Off | | | |
| McCormick, High Altitude, HDT | Low Idle, AC Off | 12 | 10.2 |
| WVU - 1991-2004 | Low Idle, AC Off | 48 | 9.5 |
| Storey | Low Idle, AC Off | 4 | 28 |
| | **Overall** | **64** | **10.8** |
| | | | |
| 1991-2006 High Speed Idle, A/C On | | | |
| Brodrick, UC Davis | High Idle, AC On | 1 | 86 |
| Storey | High Idle, AC On | 4 | 48 |
| | **Overall** | **5** | **55.6** |
| | | | |
| 1975-1990 Low Speed Idle, A/C Off | | | |
| WVU - 1975-1990 | Low Idle, AC Off | 18 | 21 |
| | **Overall** | **18** | **21** |
| | | | |
| 1975-1990 High Speed Idle, A/C On (calculated) | | | |
| Ratio of 1991-2006 "High Idle, A/C On" to "Low Idle, A/C Off" | | | 5.2 |
| | **Overall (calculated)** | | **108.2** |
| | | | |
| **Calculated Extended Idle MYs 1975-1990:** | | | **49.8** |
| **Calculated Extended Idle MYs 1991-2006:** | | | **25.6** |

**Table D-3. Data for Pre-2007 Extended Idle CO Emissions**

| **Idle CO Rates (gram/hour) Summary** | | | |
|---|---|---|---|
| **Program** | **Condition** | **# Samples** | **Mean CO Emiss Rate** |
| 1991-2006 Low Speed Idle, A/C Off | | | |
| McCormick, High Altitude, HDT | Low Idle, AC Off | 12 | 71 |
| Calcagno | Low Idle, AC Off | 27 | 37 |
| WVU - 1991-2004 | Low Idle, AC Off | 48 | 23 |
| Storey | Low Idle, AC Off | 4 | 25 |
| | **Overall** | **91** | **33.6** |
| | | | |
| 1991-2006 High Speed Idle, A/C On | | | |
| Calcagno | High Idle, AC On | 21 | 99 |
| Brodrick, UC Davis | High Idle, AC On | 1 | 190 |
| Storey | High Idle, AC On | 4 | 73 |
| | **Overall** | **26** | **98.5** |
| | | | |
| 1975-1990 Low Speed Idle, A/C Off | | | |
| WVU - 1975-1990 | Low Idle, AC Off | 18 | 31 |
| | **Overall** | **18** | **31** |
| | | | |
| 1975-1990 High Speed Idle, A/C On (calculated) | | | |
| Ratio of 1991-2006 "High Idle, A/C On" to "Low Idle, A/C Off" | | | 2.9 |
| | **Overall (calculated)** | | **91.0** |
| | | | |
| **Calculated Extended Idle MYs 1975-1990:** | | | **50.8** |
| **Calculated Extended Idle MYs 1991-2006:** | | | **55.0** |

**Table D-4. Data for Pre-2007 Extended Idle PM Emissions**

| **Idle PM Rates (gram/hour) Summary** | | | |
|---|---|---|---|
| **Program** | **Condition** | **# Samples** | **Mean PM Emiss Rate** |
| 1991-2006 Low Speed Idle, A/C Off | | | |
| McCormick, High Altitude, HDT | Low Idle, AC Off | 12 | 1.8 |
| Calcagno | Low Idle, AC Off | 27 | 2.55 |
| WVU - 1991-2004 | Low Idle, AC Off | 48 | 1.4 |
| Storey | Low Idle, AC Off | 4 | 0.3 |
| | **Overall** | **91** | **1.7** |
| | | | |
| 1991-2006 High Speed Idle, A/C On | | | |
| Calcagno | High Idle, AC On | 21 | 4.11 |
| Storey | High Idle, AC On | 4 | 3.2 |
| | **Overall** | **25** | **4.0** |
| | | | |
| 1975-1990 Low Speed Idle, A/C Off | | | |
| WVU - 1975-1990 | Low Idle, AC Off | 18 | 3.8 |
| | **Overall** | **18** | **3.8** |
| | | | |
| 1975-1990 High Speed Idle, A/C On (calculated) | | | |
| Ratio of 1991-2006 "High Idle, A/C On" to "Low Idle, A/C Off" | | | 2.3 |
| | **Overall (calculated)** | | **8.6** |
| | | | |
| **Calculated Extended Idle MYs 1975-1990:** | | | **5.4** |
| **Calculated Extended Idle MYs 1991-2006:** | | | **2.5** |

# Appendix E Developing Pre-2007 Model Year HD Diesel $PM_{2.5}$ Emission Rates for Missing Operating Modes

As noted in Section 2.1.2.1 , in cases where an estimated operating mode $PM_{2.5}$ rate for pre-2007 MY HD diesel trucks could not be directly calculated from data, we imputed the missing value using a log-linear least-squares regression procedure. Regulatory class, model year group and speed class (0–25 mph, 25-50 mph and 50+ mph) were represented by dummy variables in the regression. The natural logarithm of emissions was regressed versus scaled tractive power (STP) to represent the operating mode bins. The regression assumed a constant slope versus STP for each regulatory class. Logarithmic transformation factors (mean square error of the regression squared / 2) were used to transform the regression results from a log based form to a linear form. Due to the huge number of individual second-by-second data points, all of the regression relationships were statistically significant at a high level (99 percent confident level). The table below shows the regression statistics, and the equation shows the form of the resulting regression equation.

**Table E-1. Regression Coefficients for HD Diesel Pre-2007 $PM_{2.5}$ Emission Factor Model**

| Model-year group | Speed Class (mph) | Type | Medium Heavy-Duty | Heavy Heavy-Duty |
|---|---|---|---|---|
| 1960-87 | 1-25 | Intercept ($\beta_0$) | -5.419 | -5.143 |
| | 25-50 | | -4.942 | -4.564 |
| | 50+ | | -4.765 | -4.678 |
| 1988-90 | 1-25 | | -5.366 | -5.847 |
| | 25-50 | | -4.929 | -5.287 |
| | 50+ | | -4.785 | -5.480 |
| 1991-93 | 1-25 | | -5.936 | -5.494 |
| | 25-50 | | -5.504 | -5.269 |
| | 50+ | | -5.574 | -5.133 |
| 1994-97 | 1-25 | | -5.927 | -6.242 |
| | 25-50 | | -5.708 | -5.923 |
| | 50+ | | -5.933 | -6.368 |
| 1998-2006 | 1-25 | | -6.608 | -6.067 |
| | 25-50 | | -6.369 | -5.754 |
| | 50+ | | -6.305 | -6.154 |
| | STP | Slope ($\beta_1$) | 0.02821 | 0.0968 |
| | | Transformation Coefficient ($0.5\sigma^2$) | 0.5864 | 0.84035 |

$$\ln(PM) = \beta_0 + \beta_1 STP + 0.5\sigma^2$$

Where :

$\beta_0$ = an intercept term for a speed class within a model year group, as shown in the table above,

$\beta_1$ = a slope term for STP, and

$\sigma^2$ = the mean-square error or residual error for the model fit,

STP = the midpoint value for each operating mode (kW/metric ton, see Table 1-4).

# Appendix F Heavy-Duty Gasoline Start Emissions Analysis Figures

The figures below show heavy-duty gasoline start emissions as mentioned in Section 3.2.1,

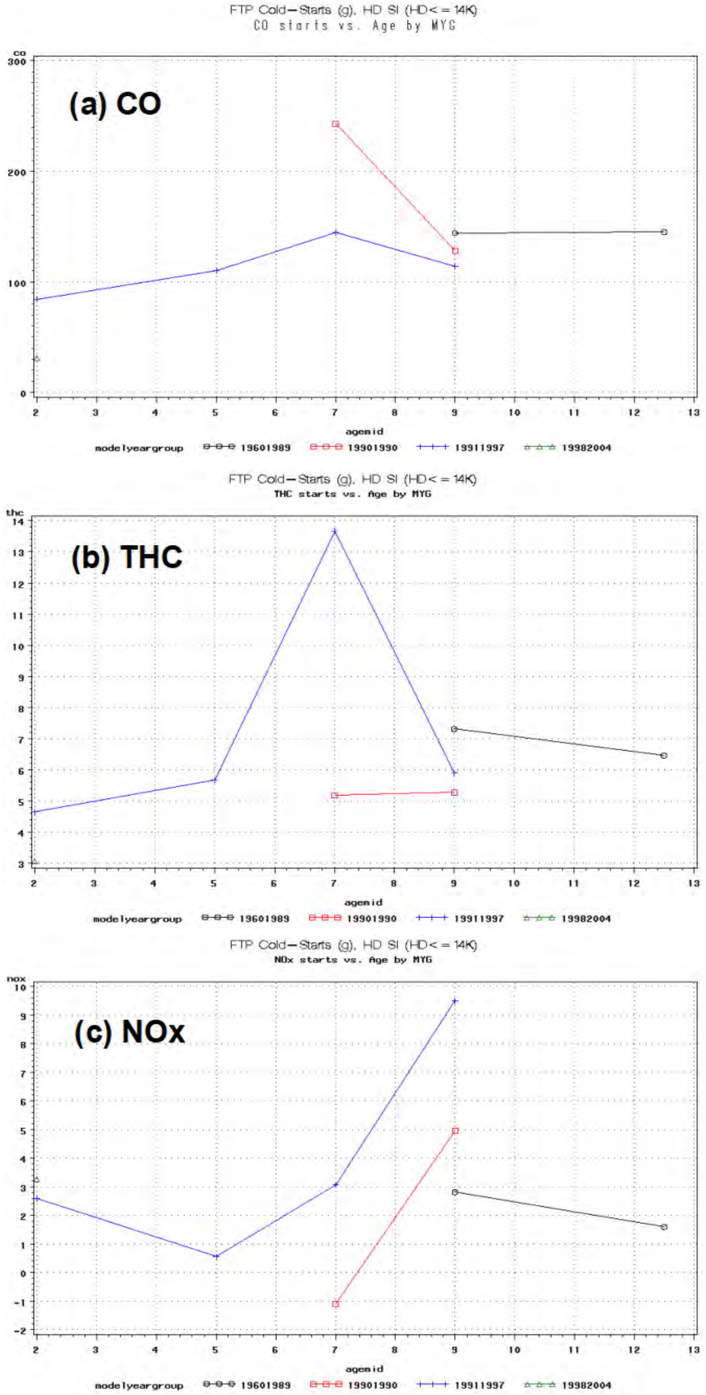


**Figure F-1 Cold-Start FTP Emissions for Heavy-Duty Gasoline Vehicles, Averaged by Model-year and Age Groups**

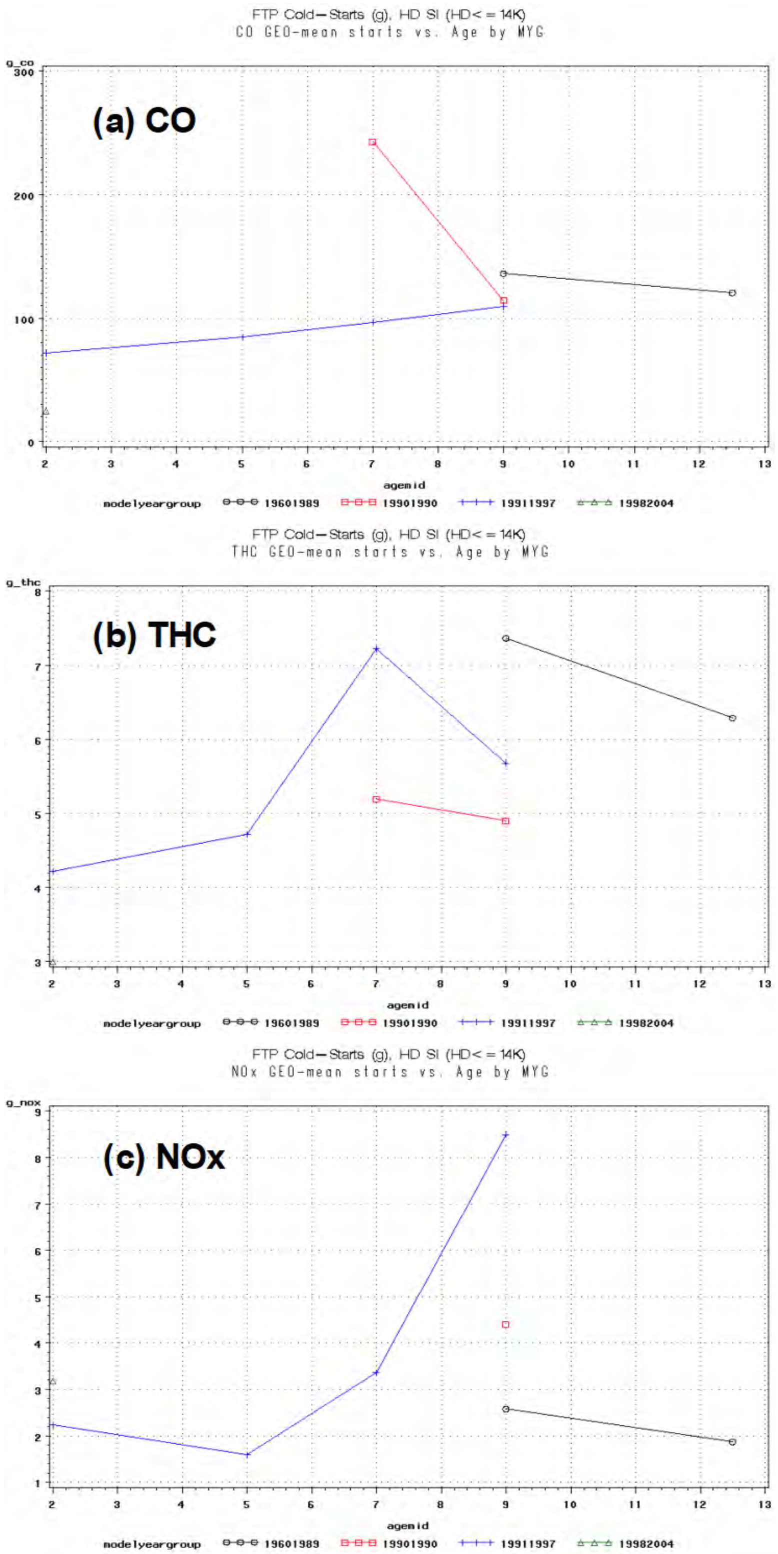
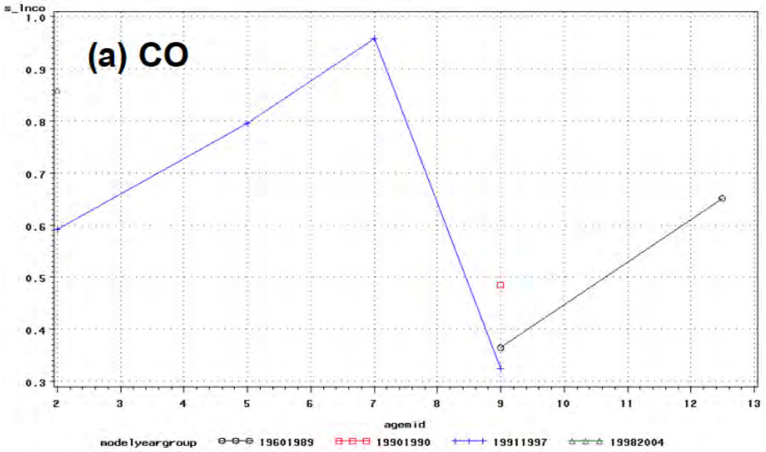
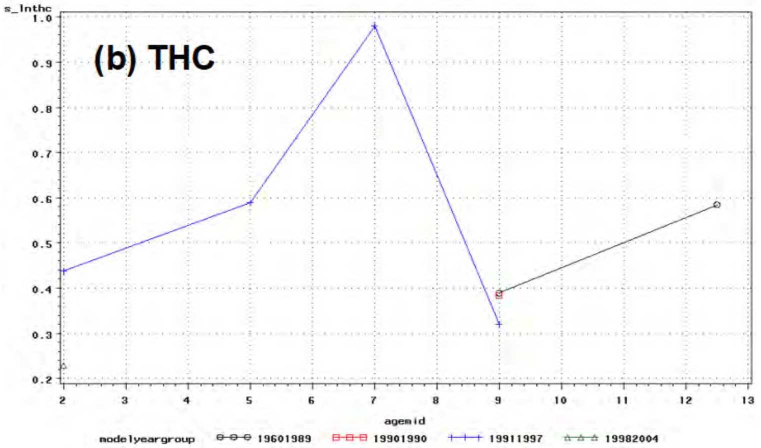


**Figure F-2 Cold-Start FTP Emissions for Heavy-Duty Gasoline Vehicles, GEOMETRIC MEANS by Model-year and Age Groups**

CO ln_SD vs. Age by MYG



FTP Cold−Starts (g), HD SI (HD< = 14K)
THC ln_SD vs. Age by MYG



FTP Cold−Starts (g), HD SI (HD< = 14K)
NOx ln_SD vs. Age by MYG

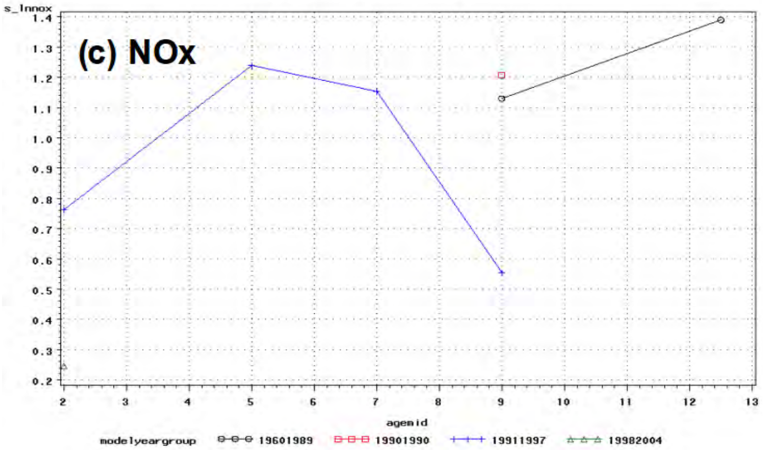


**Figure F-3 Cold-start FTP Emissions for Heavy-Duty Gasoline Trucks: LOGARITHMIC STANDARD DEVIATION by Model-year and Age Groups**

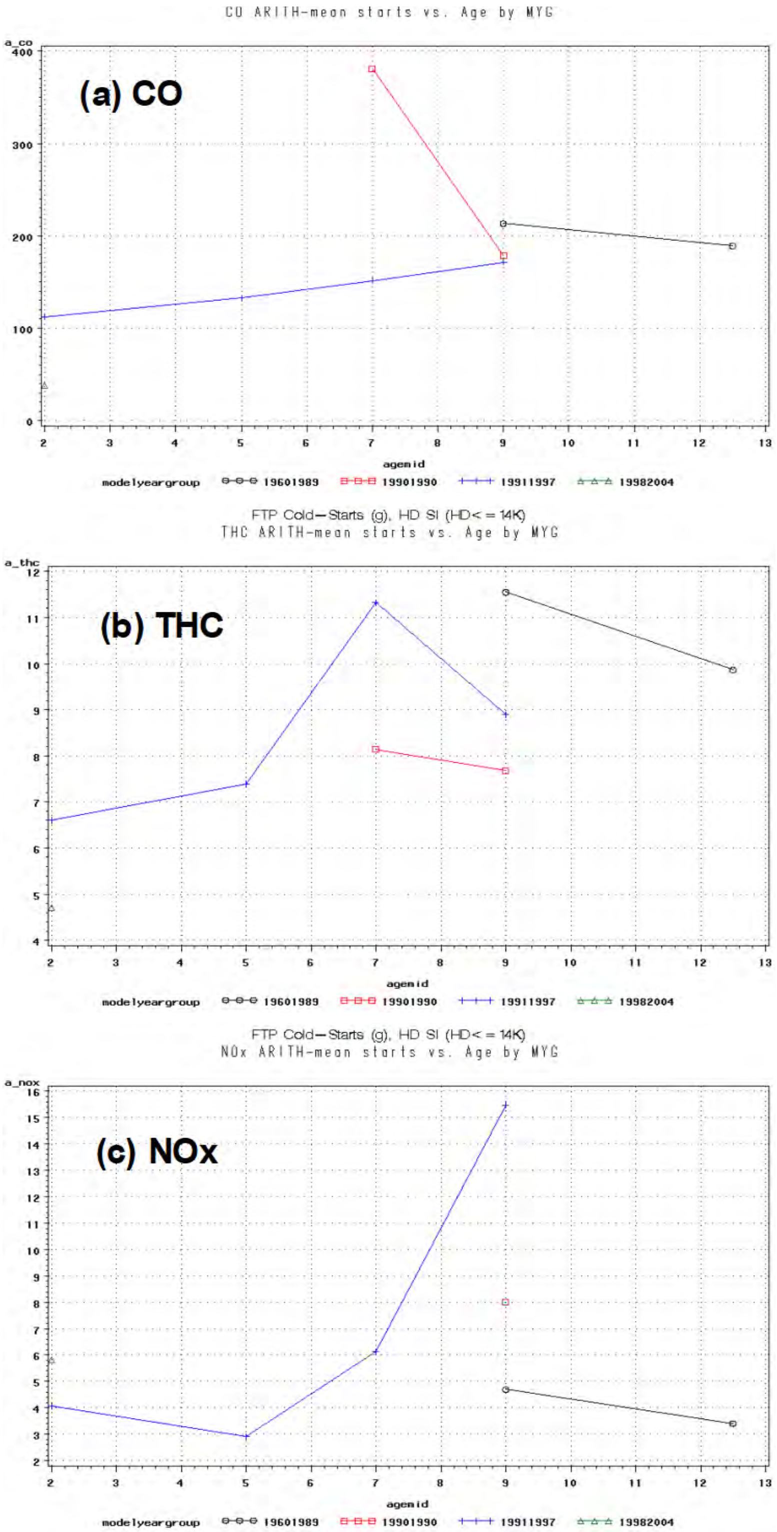


**Figure F-4 Cold-Start Emissions for Heavy-Duty Gasoline Trucks: RECALCULATED ARITHMETIC MEANS by Model-year and Age Groups**

**Table F-1 Emission Standards for Heavy-Duty Spark-Ignition Onroad Engines**

| Regulatory Class | Model Year | Emissions Standards (g/hp-hr) | | | | |
|---|---|---|---|---|---|---|
| | | CO | THC | NMHC | $NO_x$ | NMHC + $NO_x$ |
| LHD2b3 | 1990 | 14.4 | 1.1 | | 6.0 | |
| | 1991-1997 | 14.4 | 1.1 | | 5.0 | |
| | 1998-2004 | 14.4 | 1.1 | | 4.0 | |
| | 2005-2007 | 14.4 | | | | 1.0 |
| | 2008+ | 14.4 | | 0.14 | 0.20 | |
| LHD45, MHD | 1990 | 37.1 | 1.9 | | 6.0 | |
| | 1991-1997 | 37.1 | 1.9 | | 5.0 | |
| | 1998-2004 | 37.1 | 1.9 | | 4.0 | |
| | 2005-2007 | 37.1 | | | | 1.0 |
| | 2008+ | 14.4 | | 0.14 | 0.20 | |

# Appendix G Selection of Fixed Mass Factor ($f_{scale}$) values for MY 2010+ Heavy-Duty Vehicles

In MOVES3, for model year 2010 and newer heavy-duty diesel, gasoline, and CNG running-exhaust emissions operating mode based rates, we discarded the fixed mass factor ($f_{scale}$) value of 17.1 metric tons used in previous MOVES versions, and used the manufacturer-run HDIUT data to estimate new $f_{scale}$ values for LHD, MHD, and HHD weight classes. New $f_{scale}$ values were needed because the 17.1 value was too large, limiting emission rate data to low and medium power operating modes, and requiring gap-filling for high-power operating modes.

The new $f_{scale}$ values for MY 2010+ vehicles are 5.00, 7.00, and 10.00 metric tons for LHD (regClass 41 and 42), MHD (regClass 46), and HHD (regClass 47 and 48), respectively. These $f_{scale}$ values are used when analyzing the real-world emissions data that leads to the base emission rates in the MOVES database. The $f_{scale}$ values are also used by the MOVES model, at run time, to convert vehicle activity to operating mode-based time distributions. For consistency, operating mode-based emissions rates and time distributions, for a given regulatory class and model year, must be based on the same $f_{scale}$ value. Glider vehicles (regClass 49) continue to use emission rates from pre-2010 vehicles, and thus their $f_{scale}$ value is unchanged at 17.1. Note that it is not meaningful to compare operating mode based rates based on different $f_{scale}$ values. This appendix describes how we arrived at the $f_{scale}$ values.

The entire MY 2010+ HDIUT dataset (Section 2.1.1.1) was analyzed using a range of $f_{scale}$ values. For this exercise we analyzed LHD, MHD, and HHD separately, but within those regulatory classes, we did not divide the data set by $NO_x$ FEL or model years. We included the MOVES2014 value ($f_{scale} = 17.1$) to show how the operating mode distribution would look for a "business as usual" case. It is expected that the $f_{scale}$ for LHD should be lower than MHD, which in turn should be lower than HHD. Our goal was to find $f_{scale}$ values that allow the HDIUT data to cover all operating modes, thus reducing the need for gap-filling while also leaving the highest power operating modes (30 and 40) as not saturated because the HDIUT data is not expected to have very aggressive operation. If the $f_{scale}$ is too big, the high power operating modes are left vacant. On the other hand, if the $f_{scale}$ is too small, a lot of the data gets pushed to the high power operating modes, and the high operating modes no longer capture emissions at only the most extreme and aggressive operating conditions measured in the HDIUT data set. Both cases are sub-optimal because they reduce the model's capability to distinguish operating modes in a meaningful way.

When analyzing the HDIUT data for various $f_{scale}$ values, we estimated the number of vehicles, time, and mass/time emission rates for each operating mode. Vehicle count and time, per operating mode, were first cut criteria during the $f_{scale}$ selection process. We used the $CO_2$ mass/time rates as an additional check because these rates are known to have consistent and predictable monotonically rising trend within each speed-bin (since higher power demand requires burning more fuel which leads to more $CO_2$).Table G-1 through Table G-3 show how the choice of $f_{scale}$ values would affect the vehicle count and seconds in each operating mode, for LHD, MHD, and HHD, respectively. The number of seconds is based on the HDIUT-based operating mode time fractions applied to a cycle of one million seconds. Using a unique but representative $f_{scale}$ for each regClass, when combined with a cycle of the same number of total seconds, should result in similar number of seconds in high power operating modes. In other words, we expect LHD, MHD, and HHD vehicles in the HDIUT data set to have somewhat similar time distribution across power modes. Finally, we used the $CO_2$ mass/time rate trends as an additional metric to pick a final $f_{scale}$ between candidate values that look reasonably good for both vehicle count and time distribution.

Looking at Table G-1 for LHD vehicles, $f_{scale}$ = 2.06 results in every one of the 64 vehicles having operation in operating modes 30 and 40 and significantly more seconds of data than operating modes 29 and 39, respectively. On the other hand, a $f_{scale}$ value of 9.00 or 17.1 meant the high power operating modes had only a couple vehicles and seconds, which is a sign of under-representation in those operating modes. Thus, a suitable $f_{scale}$ value, for LHD, should be between 2.06 and 9.00. Based on further analysis, the final $f_{scale}$ candidates for LHD were 4.00, 5.00, and 6.00. A value of 4.00 seemed too small because we did not expect over 40 (out of 64) vehicles to have operation in operating modes 30 and 40. A value of 6.00 seemed too high because it led to only 40 seconds and 135 seconds of data (from a cycle with a million seconds) in operating modes 30 and 40, respectively. The small sample size was deemed insufficient to determine robuts emission rates for these operating mode bins. We picked 5.00 as the final $f_{scale}$ value for LHD because it resulted in a reasonable number of vehicles and seconds in the high power operating modes 29, 30, 39, and 40. For confirmation purpose, we also compared the $CO_2$ mass/time rates for all the $f_{scale}$ values considered during the analysis and Figure G-1 shows a comparison between the final candidates of 4.00, 5.00, and 6.00. As seen in the figure, all three values provide good monotonically increasing trend. $f_{scale}$ 5.00 yields much more aggressive driving behavior in operating modes 30 and 40 compared to $f_{scale}$ 4.00, with mean $CO_2$ emissions rates approximately 30% higher in these operating modes. As stated earlier, our objective is to select the $f_{scale}$ that yields the most aggressive operation in the highest operating modes while still providing sufficiently robust estimates of the emission rates. Because $f_{scale}$ 5.00 still provides mean $CO_2$ emissions rates that are robust for the high operating mode bins, $f_{scale}$ 5.00 is preferable to an $f_{scale}$ of 4.00. $f_{scale}$ 5.00 provides strong and expected increasing trends in $CO_2$ emission rates between operating modes 29 and 30, whereas $f_{scale}$ 6.00 does not. We believe this is due to insufficient data in the highest operating mode bins with $f_{scale}$ of 6.00 to determine robust estimates at the highest operating modes. Thus, we decided to use an $f_{scale}$ of 5.00 for LHD in MOVES.

For MHD and HHD, we went through similar reasoning and steps as for LHD. Our final $f_{scale}$ values for LHD, MHD, and HHD are 5.00, 7.00, and 10.00, respectively. From Table G-1 - Table G-3, these $f_{scale}$ values lead to comparable vehicle count (20-40 % of total vehicles in the regulatory class) and seconds of data (1000-3000 seconds out of one million) in OpModes 30 and 40.

We did not try to find a precise and even more suitable $f_{scale}$ value. Thus, for example, whether $f_{scale}$ of 4.80 or 5.20 is better than 5.00, for LHD, was not tested. There are diminishing returns for the extra time and effort required for that analysis because: (1) the HDIUT data set lacks certain things such as very aggressive operation or malfunctioning vehicles, so a very suitable value of $f_{scale}$ from this data set might not be as suitable with another data set; (2) comparing closely spaced $f_{scale}$ values does not necessarily provide a clear winner across the board because there’s more than one criteria (vehicle count, time, mass/time rates for various pollutants).

In the 2019 peer-review, one of peer-reviewers asked if we have evaluated the time distribution from real-world data using the proposed $f_{scale}$ value. In Figure G-4 through Figure G-6. we conducted a comparison of the operating mode distributions measured from the HDIUT dataset and real-world operating modes estimated from MOVES3 national scale runs for the three evaluated regulatory classes LHD, MHD, and HHD at the proposed proposed $f_{scale}$ values. As shown, the distributions are similar between the HDIUT dataset and national MOVES runs, with most of the data occurring at idle and the operating modes above 50 mph (opModeID 33-40). One notable difference is for a national scale run MOVES estimates a higher percentage of activity in the highest power, high speed operating mode bins. This is expected, given that the HDIUT dataset is expected to under-represent high power operation due to steep grades, high speeds, and heavy-pay loads (e.g. multiple trailers, over-weight trailers) compared to the in-use fleet. This comparison supports our logic to select the $f_{scale}$ that maps only the most aggressive operation from the HDIUT dataset into the highest MOVES operating mode bins.

The peer-reviewer suggested that we compare the operating mode distribution obtained from the proposed $f_{scale}$ values from other in-use datasets. We agree that this would be useful to better understand the representativeness of the HDIUT dataset, as well as further evaluate the MOVES default activity assumptions, including the MOVES heavy-duty driving cycles. In the population and activity report, we listed this as a project for consideration for future MOVES work.

**Table G-1 Effect of $f_{scale}$ Value on Vehicle Count and Time for Light Heavy-Duty Vehicles**

| OpMode | Number of vehicles[1] | | | | | | Number of seconds based on a cycle with one million seconds[1,2] | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | fs 2.06 | fs 4.0 | fs 5.0 | fs 6.0 | fs 9.0 | fs 17.1 | fs 2.06 | fs 4.0 | fs 5.0 | fs 6.0 | fs 9.0 | fs 17.1 |
| 0 | 64 | 64 | 64 | 64 | 64 | 64 | 41131 | 41131 | 41131 | 41131 | 41131 | 41131 |
| 1 | 64 | 64 | 64 | 64 | 64 | 64 | 358957 | 358957 | 358957 | 358957 | 358957 | 358957 |
| 11 | 64 | 64 | 64 | 64 | 64 | 64 | 46235 | 46235 | 46235 | 46235 | 46235 | 46235 |
| 12 | 64 | 64 | 64 | 64 | 64 | 64 | 15112 | 24896 | 29023 | 32878 | 42842 | 61989 |
| 13 | 64 | 64 | 64 | 64 | 64 | 64 | 10311 | 14877 | 16658 | 18290 | 20756 | 16153 |
| 14 | 64 | 64 | 64 | 64 | 64 | 43 | 8109 | 11394 | 12304 | 12431 | 10835 | 2387 |
| 15 | 64 | 64 | 64 | 64 | 63 | 18 | 6995 | 8784 | 8680 | 8092 | 4190 | 200 |
| 16 | 64 | 64 | 64 | 64 | 41 | 1 | 40203 | 20778 | 14065 | 9039 | 2107 | 1 |
| 21 | 64 | 64 | 64 | 64 | 64 | 64 | 45157 | 45157 | 45157 | 45157 | 45157 | 45157 |
| 22 | 59 | 64 | 64 | 64 | 64 | 64 | 7153 | 16366 | 22038 | 28166 | 47554 | 92823 |
| 23 | 64 | 64 | 64 | 64 | 64 | 64 | 9877 | 24704 | 31884 | 38195 | 49094 | 41467 |
| 24 | 64 | 64 | 64 | 64 | 64 | 48 | 12315 | 25290 | 28989 | 30288 | 26962 | 6425 |
| 25 | 64 | 64 | 64 | 64 | 64 | 22 | 13307 | 21400 | 21274 | 19931 | 11739 | 850 |
| 27 | 64 | 64 | 64 | 64 | 44 | 1 | 25844 | 28819 | 25061 | 18770 | 5671 | 1 |
| 28 | 64 | 64 | 64 | 44 | 22 | 2 | 21514 | 15281 | 8422 | 5020 | 544 | 5 |
| 29 | 64 | 64 | 42 | 23 | 0 | 0 | 16292 | 5808 | 2900 | 1161 | 0 | 0 |
| 30 | 64 | 43 | 22 | 13 | 2 | 1 | 35269 | 3903 | 1002 | 40 | 5 | 1 |
| 33 | 64 | 64 | 64 | 64 | 64 | 64 | 26999 | 42467 | 55797 | 73408 | 142294 | 267976 |
| 35 | 64 | 64 | 64 | 64 | 64 | 46 | 16820 | 75707 | 110862 | 131366 | 129751 | 18220 |
| 37 | 64 | 64 | 64 | 63 | 44 | 5 | 33332 | 86600 | 79892 | 67271 | 13177 | 7 |
| 38 | 64 | 63 | 62 | 44 | 22 | 1 | 46641 | 52178 | 31818 | 12100 | 978 | 2 |
| 39 | 64 | 62 | 41 | 23 | 1 | 1 | 49374 | 21416 | 6167 | 1940 | 1 | 2 |
| 40 | 64 | 41 | 23 | 14 | 1 | 1 | 113054 | 7852 | 1685 | 135 | 18 | 13 |

Notes:

[1] Values in bold are for final selected $f_{scale}$. Shaded cells show instances where using an excessively high $f_{scale}$ value causes data deficit in the higher power operating modes within a speed bin.

[2] Number of seconds = Average operating mode time fraction * cycle with one million seconds. The average operating mode time fraction is the average of the time fraction (for that operating mode) across all vehicles.

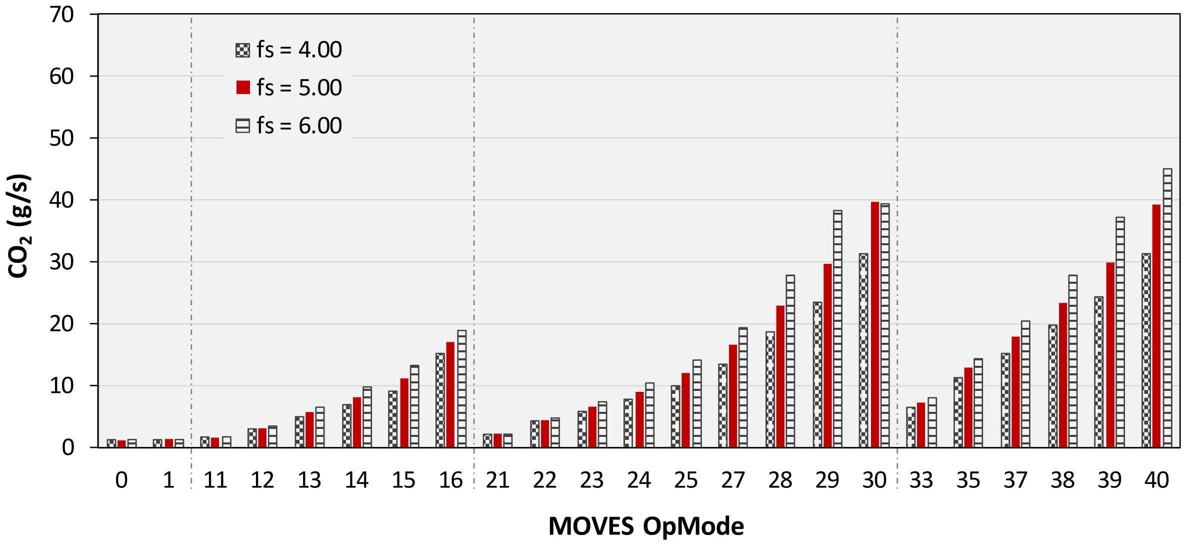


**Figure G-1 Effect of *$f_{scale}$* Value on Coverage and Trends of operating mode Based $CO_2$ for Light Heavy-Duty Vehicles**

Absolute values of operating mode based emissions rates cannot be compared between series with different $f_{scale}$ values.

**Table G-2 Effect of $f_{scale}$ Value on Vehicle Count and Time for Medium Heavy-Duty Vehicles**

| OpMode | Number of vehicles[1] | | | | | | Number of seconds based on a cycle with one million seconds[1,2] | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | fs 4.0 | fs 5.0 | fs 6.0 | fs 7.0 | fs 9.0 | fs 17.1 | fs 4.0 | fs 5.0 | fs 6.0 | fs 7.0 | fs 9.0 | fs 17.1 |
| 0 | 58 | 58 | 58 | 58 | 58 | 58 | 36170 | 36170 | 36170 | 36170 | 36170 | 36170 |
| 1 | 58 | 58 | 58 | 58 | 58 | 58 | 349622 | 349622 | 349622 | 349622 | 349622 | 349622 |
| 11 | 58 | 58 | 58 | 58 | 58 | 58 | 32693 | 32693 | 32693 | 32693 | 32693 | 32693 |
| 12 | 58 | 58 | 58 | 58 | 58 | 58 | 20755 | 23825 | 26630 | 29346 | 34264 | 48508 |
| 13 | 58 | 58 | 58 | 58 | 58 | 58 | 11234 | 12492 | 13612 | 14397 | 15495 | 16683 |
| 14 | 58 | 58 | 58 | 58 | 58 | 58 | 8252 | 9101 | 9517 | 9898 | 10003 | 7687 |
| 15 | 58 | 58 | 58 | 58 | 58 | 30 | 6688 | 7014 | 7142 | 7000 | 6576 | 1914 |
| 16 | 58 | 58 | 58 | 58 | 58 | 16 | 28357 | 22855 | 18385 | 14645 | 8948 | 496 |
| 21 | 58 | 58 | 58 | 58 | 58 | 58 | 44291 | 44291 | 44291 | 44291 | 44291 | 44291 |
| 22 | 58 | 58 | 58 | 58 | 58 | 58 | 10132 | 14200 | 18827 | 23955 | 34436 | 78404 |
| 23 | 58 | 58 | 58 | 58 | 58 | 58 | 19195 | 25479 | 31609 | 37379 | 48401 | 49534 |
| 24 | 58 | 58 | 58 | 58 | 58 | 58 | 21109 | 27513 | 32401 | 34297 | 30771 | 19215 |
| 25 | 58 | 58 | 58 | 58 | 58 | 37 | 22136 | 24498 | 22647 | 20428 | 17498 | 5111 |
| 27 | 58 | 58 | 58 | 58 | 58 | 16 | 32912 | 28713 | 25621 | 22502 | 17220 | 1306 |
| 28 | 58 | 58 | 58 | 58 | 25 | 0 | 18677 | 15863 | 13842 | 10424 | 4619 | 0 |
| 29 | 58 | 58 | 46 | 25 | 10 | 0 | 12105 | 10075 | 5243 | 3550 | 625 | 0 |
| 30 | 58 | 39 | 25 | 14 | 0 | 0 | 17304 | 7229 | 3379 | 1034 | 0 | 0 |
| 33 | 58 | 58 | 58 | 58 | 58 | 58 | 37996 | 45307 | 54057 | 64727 | 92859 | 212774 |
| 35 | 58 | 58 | 58 | 58 | 58 | 58 | 40077 | 63649 | 87949 | 107234 | 130599 | 92395 |
| 37 | 58 | 58 | 58 | 58 | 57 | 15 | 63932 | 76693 | 81453 | 80818 | 72135 | 3197 |
| 38 | 58 | 58 | 57 | 49 | 30 | 1 | 56697 | 58308 | 51520 | 44843 | 11144 | 1 |
| 39 | 58 | 53 | 43 | 25 | 10 | 1 | 45255 | 39067 | 25466 | 8307 | 1628 | 1 |
| 40 | 53 | 39 | 26 | 14 | 1 | 0 | 64411 | 25344 | 7923 | 2440 | 2 | 0 |

Notes:

[1] Values in bold are for final selected $f_{scale}$. Shaded cells show instances where using an excessively high $f_{scale}$ value causes data deficit in the higher power operating modes within a speed bin.

[2] Number of seconds = Average operating mode time fraction * cycle with one million seconds. The average operating mode time fraction is the average of the time fraction (for that operating mode) across all vehicles.

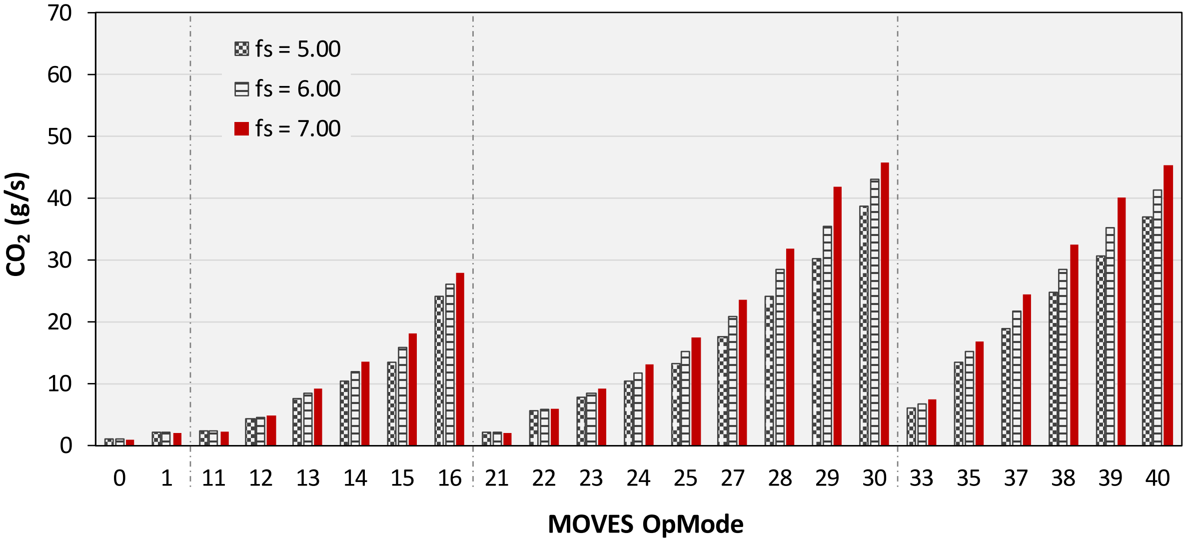


**Figure G-2 Effect of $f_{scale}$ Value on Coverage and Trends of operating mode Based $CO_2$ for Medium Heavy-Duty Vehicles**

**Table G-3 Effect of $f_{scale}$ Value on Vehicle Count and Time for Heavy Heavy-Duty Vehicles**

| OpMode | Number of vehicles[1] | | | | | | Number of seconds based on a cycle with one million seconds[1,2] | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | fs 9.0 | fs 10.0 | fs 11.0 | fs 12.0 | fs 14.0 | fs 17.1 | fs 9.0 | fs 10.0 | fs 11.0 | fs 12.0 | fs 14.0 | fs 17.1 |
| 0 | 159 | 159 | 159 | 159 | 158 | 159 | 18010 | 18010 | 18010 | 18010 | 18010 | 18010 |
| 1 | 159 | 159 | 159 | 159 | 159 | 159 | 297662 | 297662 | 297662 | 297662 | 297662 | 297662 |
| 11 | 159 | 159 | 159 | 159 | 158 | 159 | 37453 | 37453 | 37453 | 37453 | 37453 | 37453 |
| 12 | 159 | 159 | 159 | 159 | 158 | 159 | 24580 | 25976 | 27238 | 28427 | 30556 | 33336 |
| 13 | 159 | 159 | 159 | 159 | 158 | 159 | 9472 | 9547 | 9576 | 9576 | 9551 | 9524 |
| 14 | 159 | 159 | 159 | 159 | 158 | 159 | 5545 | 5557 | 5579 | 5533 | 5446 | 5159 |
| 15 | 159 | 159 | 159 | 159 | 158 | 159 | 3938 | 3840 | 3762 | 3704 | 3456 | 2892 |
| 16 | 159 | 159 | 159 | 159 | 153 | 152 | 10041 | 8657 | 7422 | 6337 | 4568 | 2666 |
| 21 | 159 | 159 | 159 | 159 | 158 | 159 | 32325 | 32325 | 32325 | 32325 | 32325 | 32325 |
| 22 | 159 | 159 | 159 | 159 | 158 | 159 | 12785 | 14388 | 15951 | 17580 | 20814 | 25721 |
| 23 | 159 | 159 | 159 | 159 | 158 | 159 | 14276 | 15457 | 16513 | 17395 | 18748 | 20117 |
| 24 | 159 | 159 | 159 | 159 | 158 | 159 | 11401 | 11865 | 12272 | 12453 | 12761 | 12587 |
| 25 | 159 | 159 | 159 | 159 | 158 | 159 | 8967 | 9058 | 9085 | 9044 | 8501 | 8402 |
| 27 | 159 | 159 | 159 | 159 | 153 | 154 | 12410 | 11927 | 11767 | 12026 | 13569 | 15804 |
| 28 | 154 | 154 | 154 | 153 | 134 | 27 | 8660 | 9619 | 10875 | 12433 | 8684 | 632 |
| 29 | 153 | 142 | 122 | 75 | 8 | 0 | 8905 | 9822 | 6562 | 2329 | 185 | 0 |
| 30 | 114 | 59 | 10 | 1 | 0 | 0 | 5861 | 1127 | 239 | 4 | 0 | 0 |
| 33 | 159 | 159 | 159 | 159 | 158 | 159 | 114214 | 126216 | 139731 | 154101 | 186094 | 237960 |
| 35 | 159 | 159 | 159 | 159 | 158 | 159 | 139109 | 160667 | 176144 | 186131 | 189813 | 176111 |
| 37 | 159 | 159 | 159 | 159 | 153 | 153 | 115050 | 102440 | 91446 | 83420 | 74122 | 61219 |
| 38 | 154 | 154 | 153 | 152 | 131 | 26 | 55279 | 52010 | 50633 | 47483 | 27291 | 2421 |
| 39 | 152 | 138 | 122 | 83 | 9 | 0 | 37885 | 33033 | 19207 | 6576 | 391 | 0 |
| 40 | 114 | 65 | 11 | 1 | 0 | 0 | 16174 | 3344 | 550 | 0 | 0 | 0 |

Notes:

[1] Values in bold are for final selected $f_{scale}$. Shaded cells show instances where using an excessively high $f_{scale}$ value causes data deficit in the higher power operating modes within a speed bin.

[2] Number of seconds = Average operating mode time fraction * cycle with one million seconds. The average operating mode time fraction is the average of the time fraction (for that operating mode) across all vehicles.

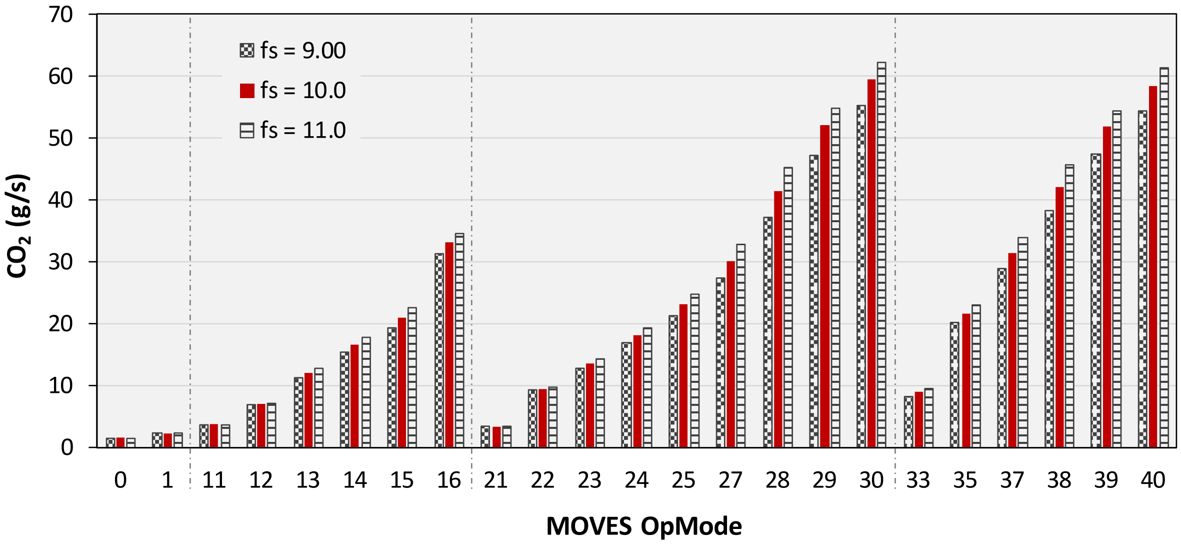


**Figure G-3 Effect of $f_{scale}$ Value on Coverage and Trends of operating mode Based $CO_2$ for Heavy Heavy-Duty Vehicles**

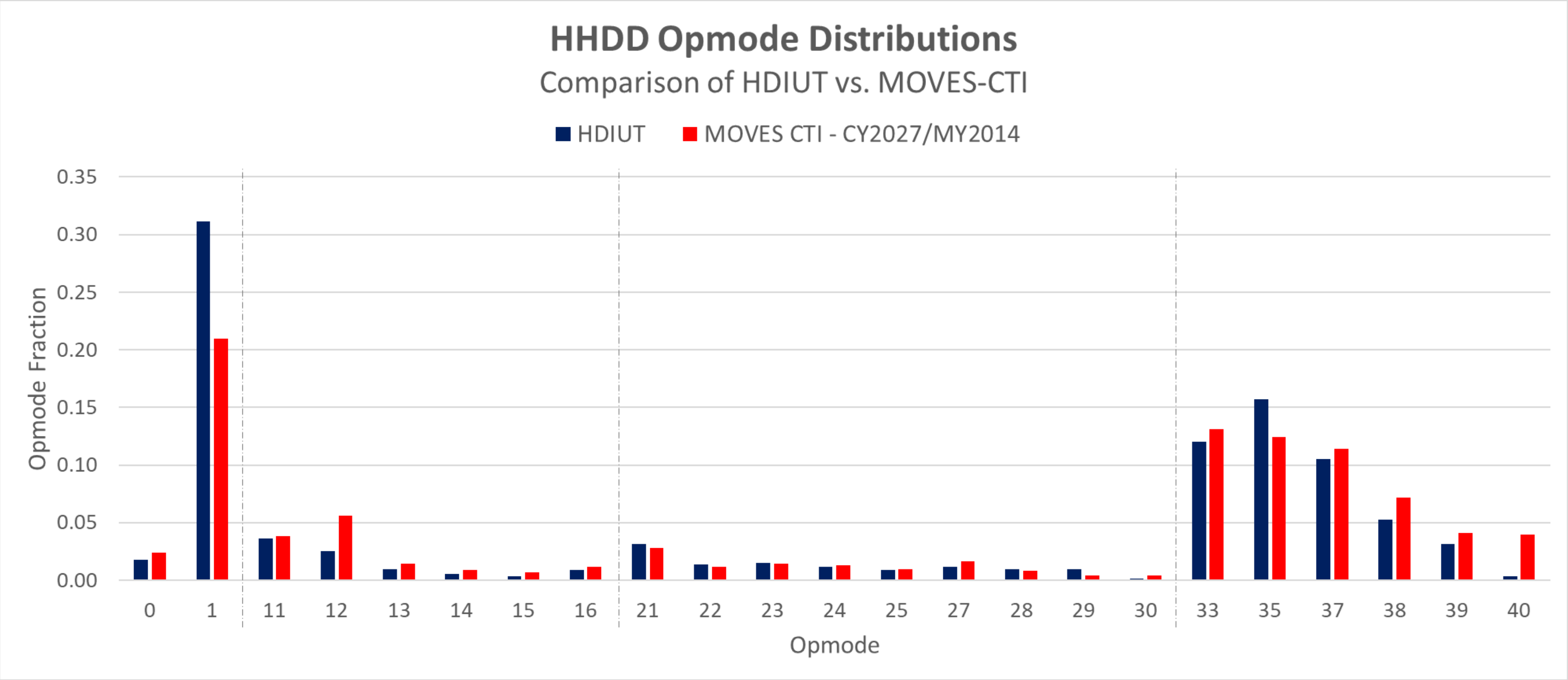


**Figure G-4. Heavy Heavy-Duty Diesel Operating Mode Distribution compared between the Heavy-Duty In-Use Testing (HDIUT) Program and from MOVES3 for a MY 2014 vehicle with an $f_{scale}$ of 10 metric tons**

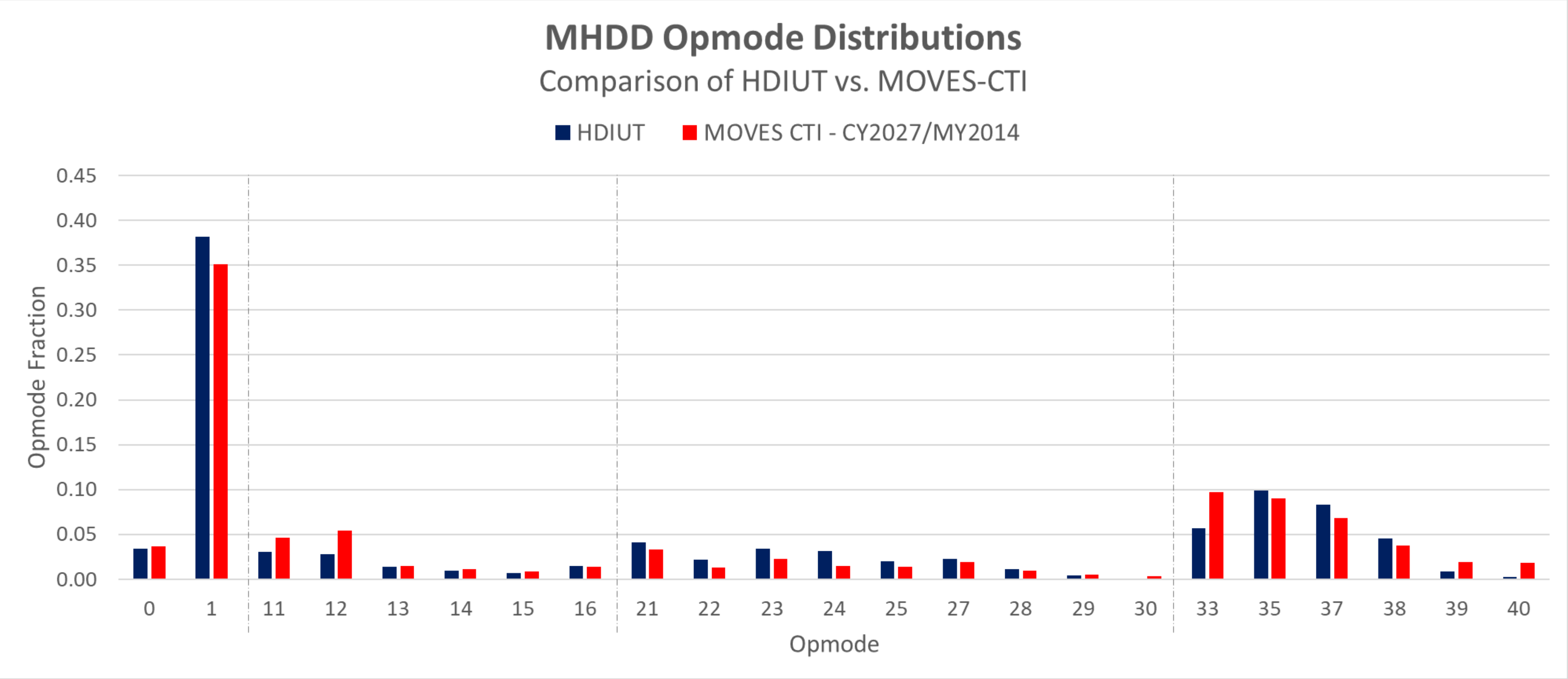


**Figure G-5. Medium Heavy-Duty Diesel Operating Mode Distribution compared between the Heavy-Duty In-Use Testing (HDIUT) Program and from MOVES3 for a MY 2014 vehicle with an $f_{scale}$ of 7 metric tons**

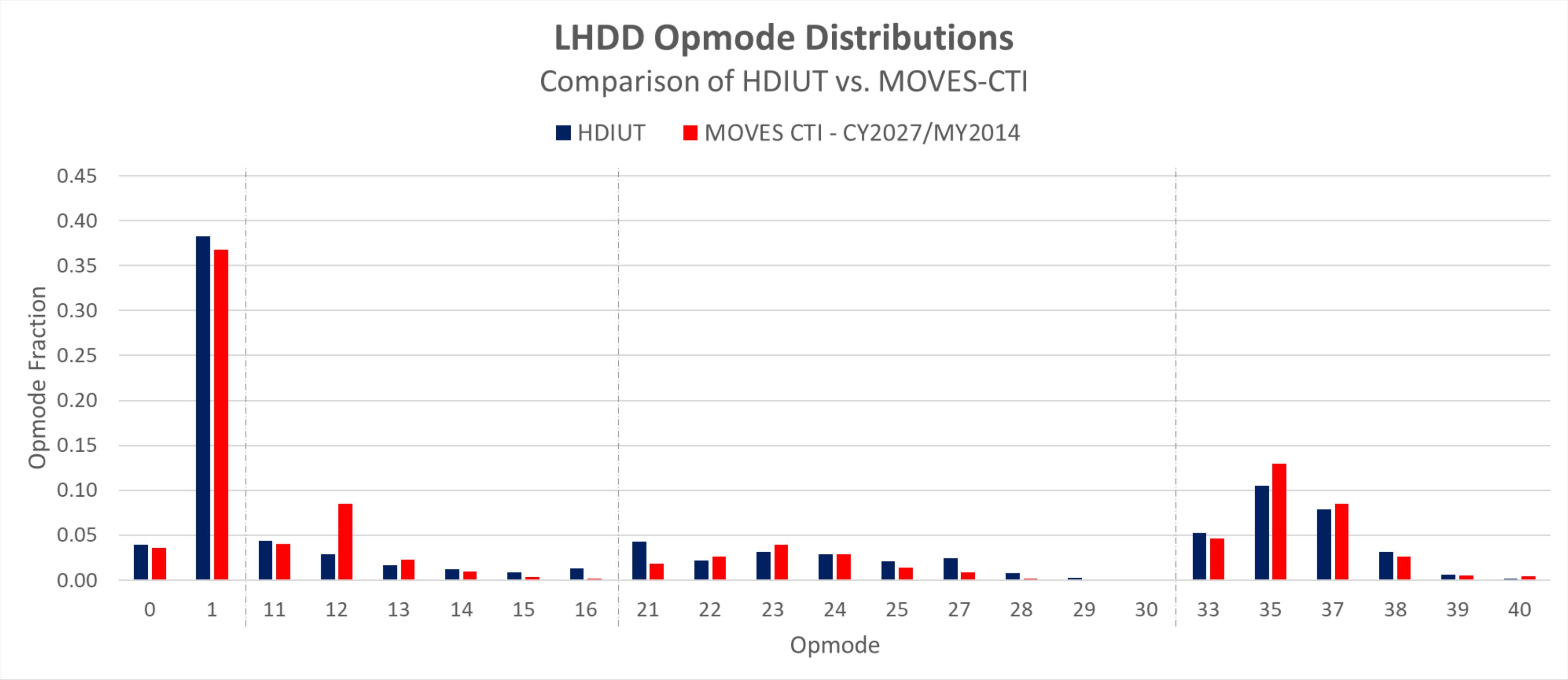


**Figure G-6. Light Heavy-Duty Diesel Operating Mode Distribution compared between the Heavy-Duty In-Use Testing (HDIUT) Program and from MOVES3[uu] for a MY 2014 vehicle with an $f_{scale}$ of 5 metric tons.**

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[uu] The MOVES operating mode distribution excludes class 2b light-heavy-duty vehicles in the passenger truck and light-commercial truck source types The vehicles included in the HDIU are all engine-certified vehicles and are class 3 or heavier.

# Appendix H THC and CO Emisssion rates from 2010 and Later Model Year Heavy-duty Vehicles from the HDIUT

## *H.1 Comparison of THC and CO Emission Rates by NO$_x$ FEL Groups for MY 2010-2013 Vehicles in LHD and MHD*

As noted in 2.1.3.2, this appendix section contains figures of the mean THC and CO emission rates by NO$_x$ FEL Group for LHD and MHD. The figures for HHD are included in the main report.

### *H.1.1 LHD*

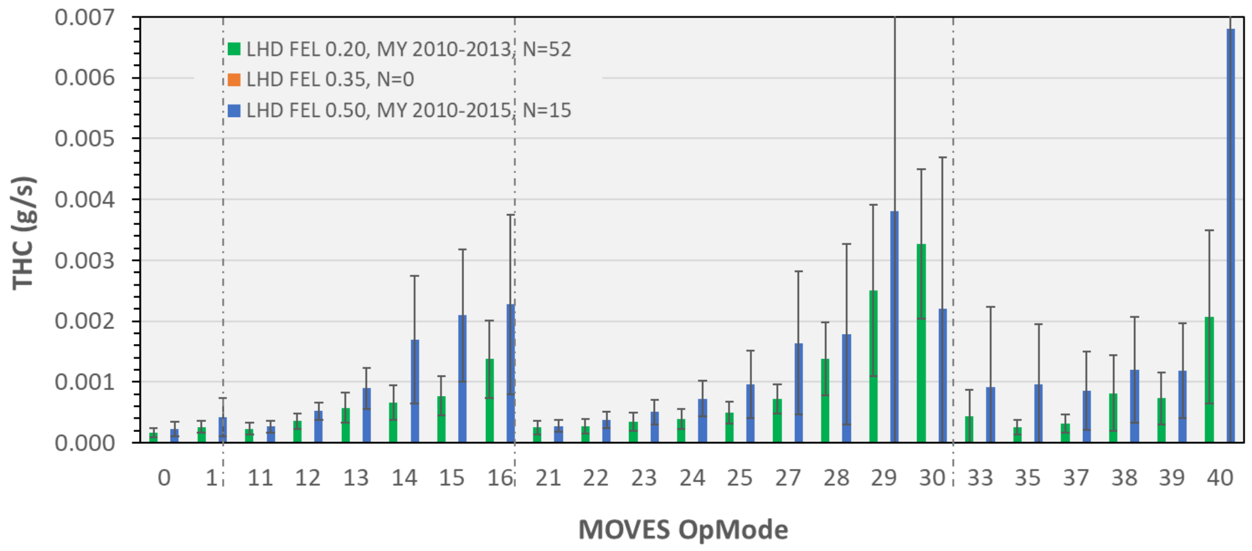

**Figure H-1. Average LHD THC Emission Rates by Operating Mode for the 0.2 NO$_x$ FEL for MY 2010-2013 and the 0.5 NO$_x$ FEL for MY 2010-2016. Error Bars are 95% Confidence Intervals of the Mean**

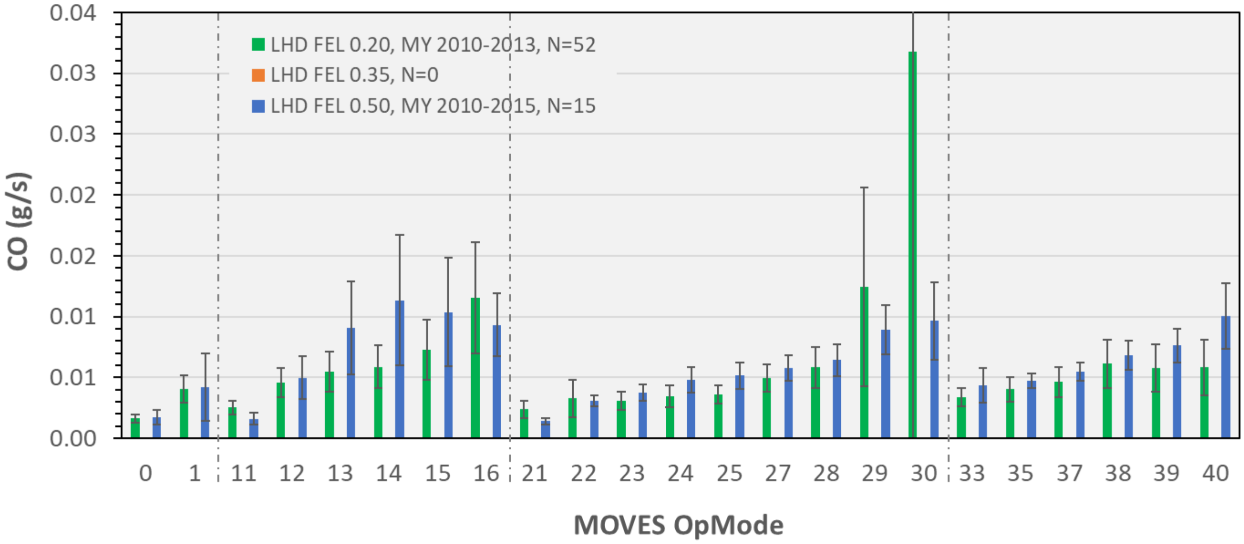

**Figure H-2.Average LHD THC Emission Rates by Operating Mode for the 0.2 NO$_x$ FEL for MY 2010-2013 and the 0.5 NO$_x$ FEL for MY 2010-2016. Error Bars are 95% Confidence Intervals of the Mean**

### *H.1.2 MHD*

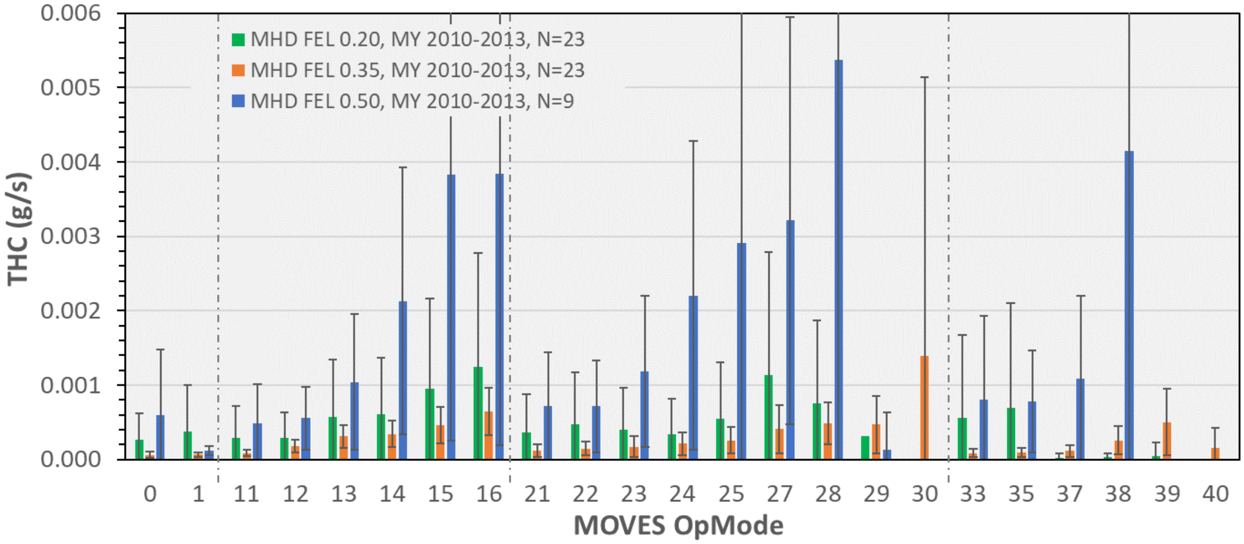

**Figure H-3.Average MHD THC Emission Rates by Operating Mode for the 0.2, 0.35 and 0.50 NO$_x$ FEL Groups for MY 2010-2013 Vehicles. Error Bars are 95% Confidence Intervals of the Mean**

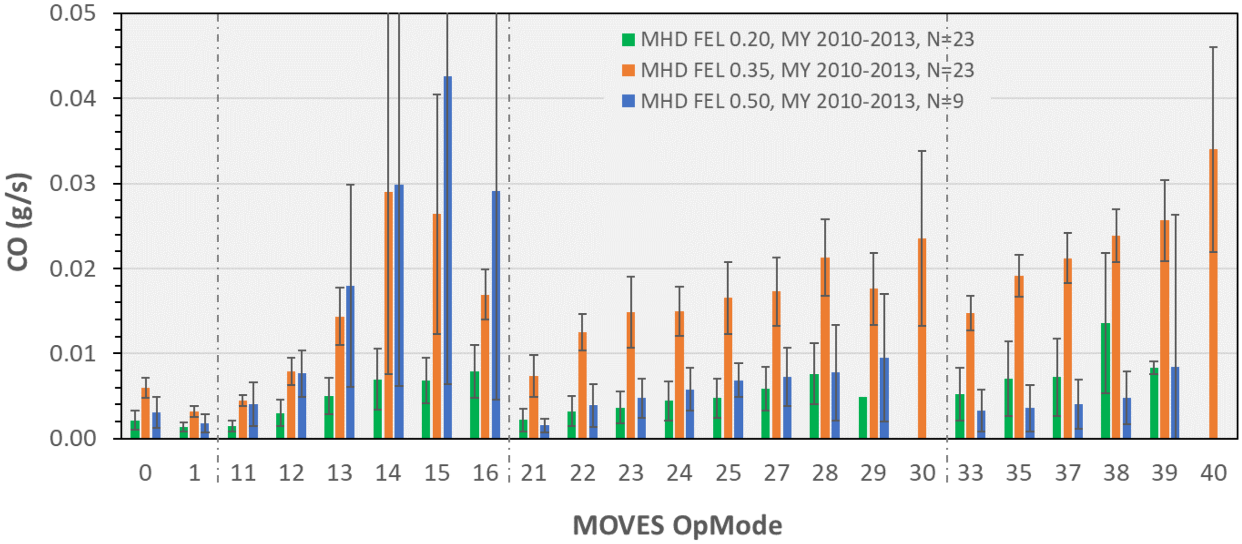

Figure H-4. Average MHD CO Emission Rates by Operating Mode for the 0.2, 0.35 and 0.50 $NO_x$ FEL Groups for MY 2010-2013 Vehicles. Error Bars are 95% Confidence Intervals of the Mean

## H.2 Comparison of THC and CO Emission Rates between MY 2010-2013 and MY 2014 in the 0.2 NO$_x$ FEL Group for LHD and MHD

The following figures show the comparison of the mean THC and CO emission rates between model year 2010-2013 and 2014 and later vehicles in the 0.2 NO$_x$ FEL Group for the LHD and MHD regulatory class by operating mode. The figures for HHD are located in the main report (Figure 2-42 and Figure 2-43).

### H.2.1 LHD

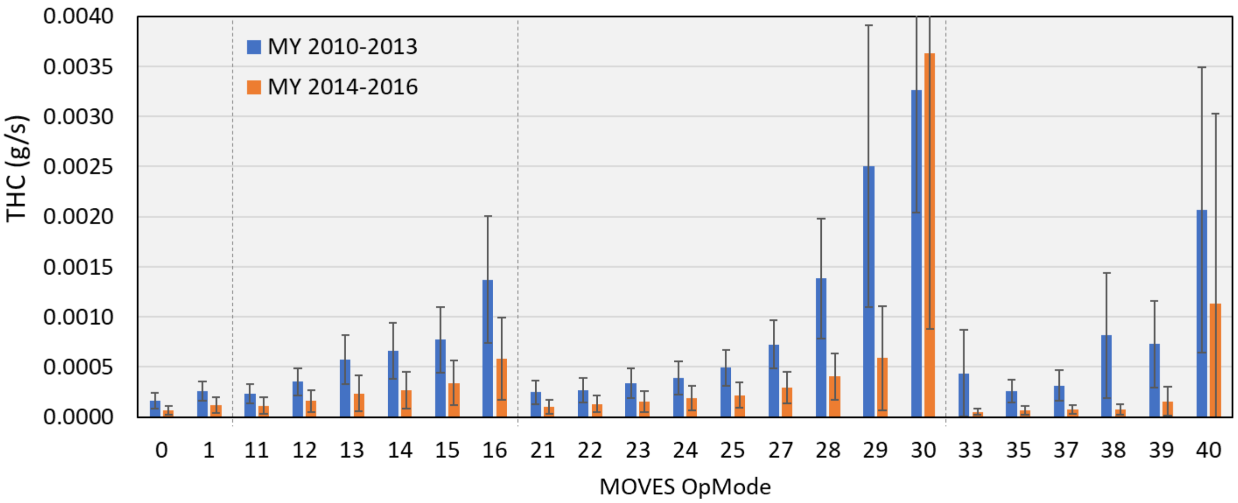

**Figure H-5. THC emission rates for the MY 2010-2013 and MY 2014-2016 vehicles in the LHD 0.20 NO$_x$ FEL Group**

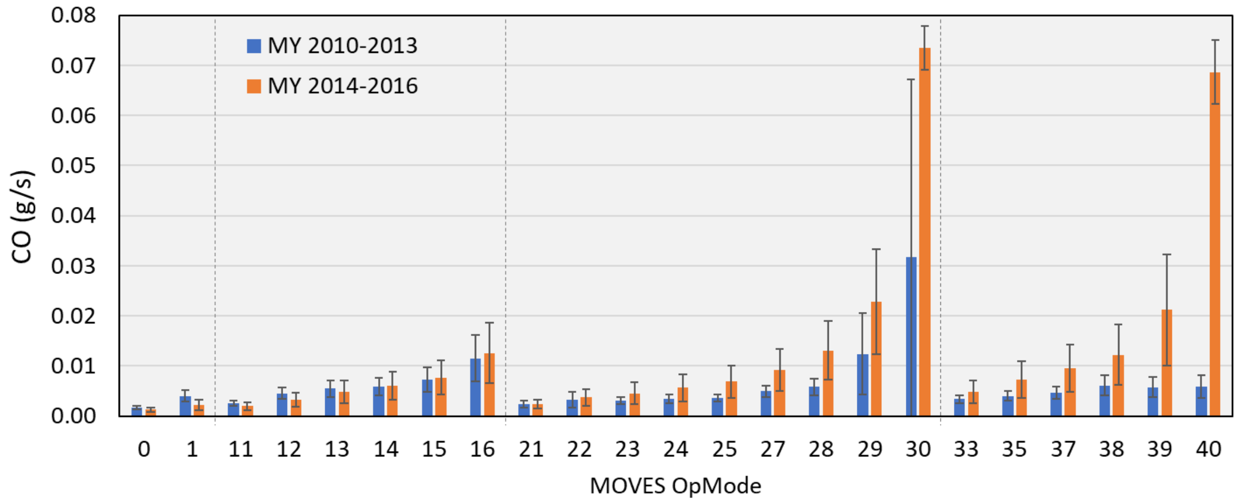

**Figure H-6. CO emission rates for the MY 2010-2013 and MY 2014-2016 vehicles in the LHD 0.20 NO$_x$ FEL Group**

### *H.2.2 MHD*

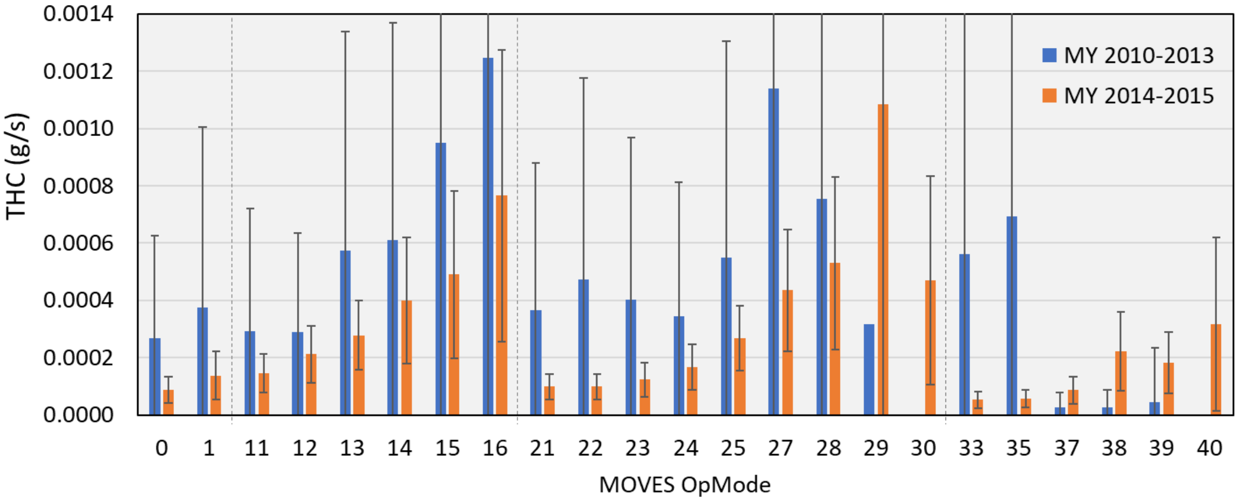

**Figure H-7. THC emission rates for the MY 2010-2013 and MY 2014-2015 vehicles in the MHD 0.20 $NO_x$ FEL Group**

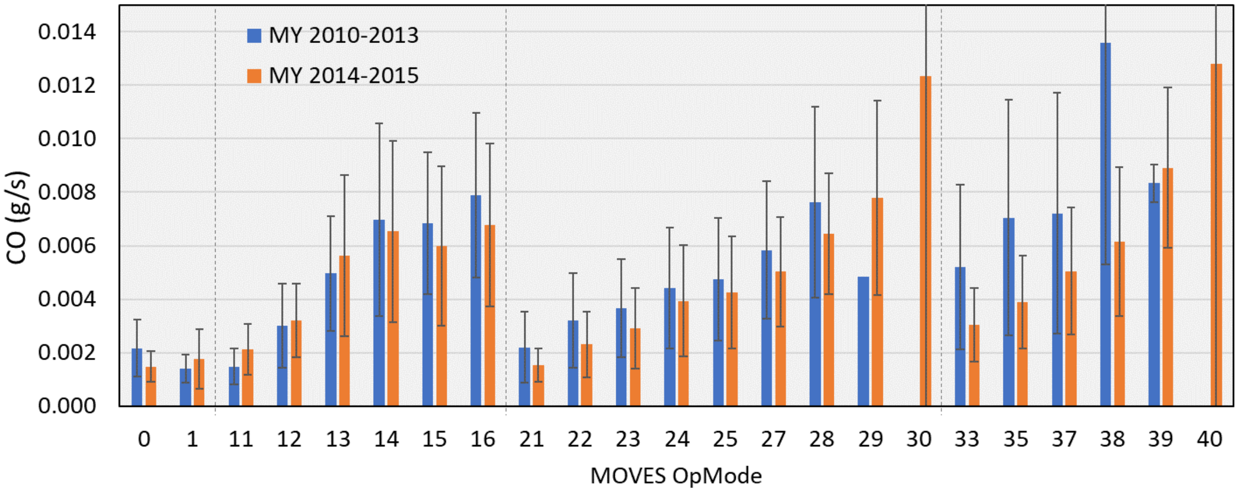

**Figure H-8. CO emission rates for the MY 2010-2013 and MY 2014-2015 vehicles in the MHD 0.20 $NO_x$ FEL Group**

# Appendix I Analysis of 2010 and Later Model Year Heavy-duty Gasoline Emission Rates

This appendix contains additional details of the analysis used to update the 2010 and later model year heavy-duty gasoline running emission rates documented in Section 3.1.1.2.1.

## *I.1 Removal of Start Emissions from Real-World PEMS Data in Developing Heavy-duty Gasoline Running Exhaust Emissions*

The running exhaust emissions rates update for 2010 model year and later heavy-duty gasoline vehicles is meant to include emissions from only the hot-running condition. Thus, ideally, emissions assigned to start effects should be removed before estimating operating mode-based average rates per test and per vehicle. This is less of a concern if each test is a full-day of operation since the incremental start emissions might then be a small fraction of total emissions. However, on-road tests of the three HD gasoline involved drive cycles that range from 10 to 90 minutes in duration. Also, the idle tests, of 15 or 30 minute duration, need to have start effects removed to ensure their contribution to OpMode 1 (idle mode) rate is unaffected by start emissions. Note that the effect of start emissions is modeled as a separate process in MOVES and by removing them from the running emissions, we are minimizing double-counting.

Start emissions in the Federal Test Procedure are calculated as Bag 1 minus Bag 3 of the FTP cycle, where Bag 1 is driving after a cold start and Bag 3 is the same cycle as Bag 1 but under hot-stabilized conditions. This method is not possible in real-world testing because it is not possible to replicate the exact drive cycle due to varying traffic conditions. Thus, we decided to define start emissions as the incremental emissions that occur before the TWC reaches the light-off condition where it achieves optimal emissions reduction efficacy. We define light-off condition as the point when the TWC first reaches 421 °C (790 °F). TWC light-off temperatures are based on design specifics but are generally in the range of 400 °C. The selection of 421 °C as the criteria is somewhat arbitrary at the very precise level – there is not a good reason why 421 °C is more appropriate than say 410 °C or 430 °C. We picked 421 °C based on visual comparison of a handful of the on-road tests for each of the three gasoline vehicles to find out at what point the TWC temperature starts to stabilize. The effect of soak time on time to reach 421 °C catalyst temperature and grams of emissions assigned to the start effect, thus removed from running exhaust emissions, are shown in Table I-1. The following figure shows the data for $NO_x$. Interestingly, the trend for $NO_x$ from on-road testing is comparable to the trends from previous lab-based testing, shown in Figure 3-23. For the on-road data, grams of $NO_x$ from starts emissions for 105-minute soak is 1.15 times the 720-minute soak. For the same conditions, the ratios in Figure 3-23 are approximately 1.17 and 1.37 for the data series labeled as “MOVES” and “New Data”, respectively. The trends for THC and CO are also similar between the two figures.

**Table I-1 Time and Pollutant Mass for Driving Assigned to Start Emissions**

| Soak Time (min) | Number of Tests | Avg. time[1] for TWC to reach 421 °C (sec) | Avg. grams of pollutant removed | | | |
|---|---|---|---|---|---|---|
| | | | $NO_x$ | $CO_2$ | CO | THC |
| 0 | 109 | 78 | 0.2 | 356 | 3 | 0.4 |
| 3 | 6 | 42 | 0.02 | 213 | 1 | 0.03 |
| 18 | 6 | 63 | 0.1 | 265 | 3 | 0.3 |
| 30 | 6 | 91 | 0.8 | 427 | 9 | 0.8 |
| 45 | 8 | 114 | 1.9 | 493 | 14 | 1.6 |
| 75 | 5 | 122 | 1.8 | 470 | 16 | 1.8 |
| 105 | 7 | 102 | 2.3 | 463 | 19 | 1.9 |
| 180 | 4 | 107 | 3.0 | 531 | 22 | 2.7 |
| 240 | 2 | 94 | 1.1 | 424 | 18 | 1.9 |
| 360 | 1 | 1 | 0.00 | 0 | 0 | 0.00 |
| 720 | 48 | 125 | 2.0 | 662 | 25 | 3.3 |

Note:

[1] Of the total 202 tests listed here, in three tests the catalyst never reached 421 °C, so they are not included in the average time calculation, however, the grams of pollutant removed columns include these three tests.

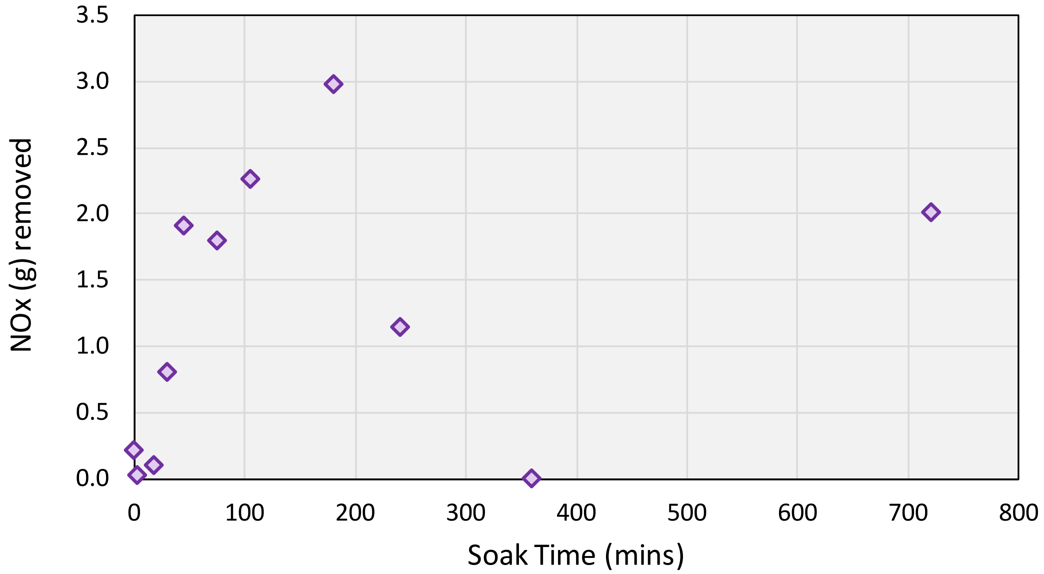

**Figure I-1. Grams of $NO_x$ from Start Emissions versus Soak Time**

## *I.2 Comparison of Heavy-duty Gasoline Emission Rates by Vehicle*

The figures in this subsection show the emission rates calculated from the PEMS testing data collected on three heavy-duty gasoline vehicle. The emission rates in these figures were analyzed using an $f_{scale}$ of 5 metric tons used for the LHD2b3 and LHD45 regulatory class emission rates. The error bars are the 95% confidence intervals of the mean calculated by treating the number of routes (R) as independent random variables.

The Isuzu NPR has the highest $NO_x$ emission rates across all operating modes. The Ford E459 and the Ram 3500 have more similar $NO_x$ emission rates, except for the high speed and power operating modes (opModeID 39 and 40).

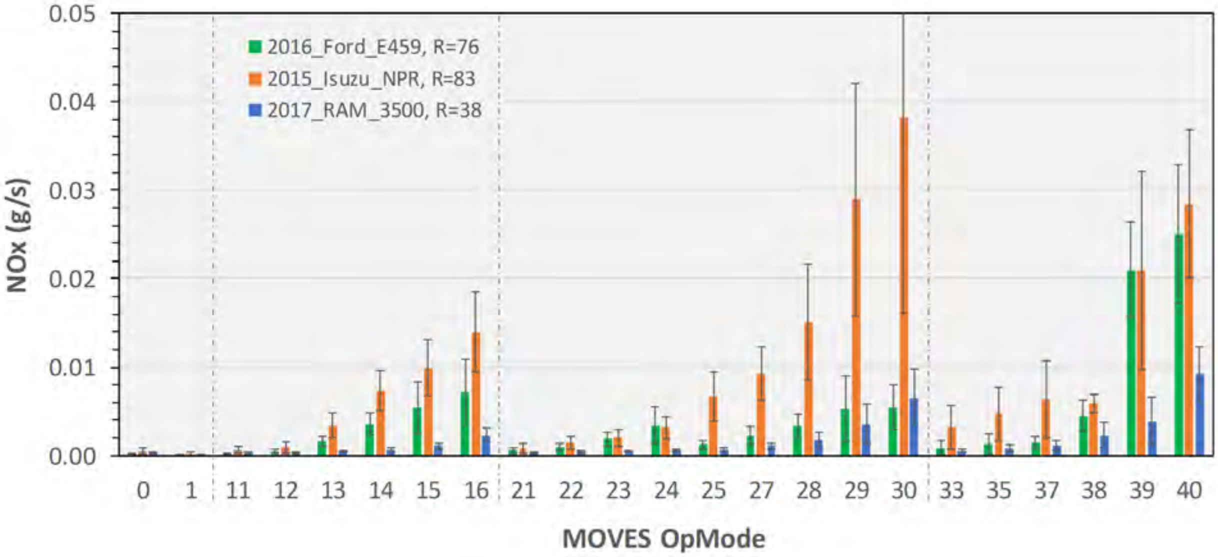

**Figure I-2. Mean Heavy-duty Gasoline $NO_x$ Emission Rates by Operating Mode and Vehicle Calculated using $f_{scale}$ of 5 metric tons.**

For THC and CO, the Isuzu NPR tends to have lower emission rates. The differences between the vehicles is more dependent on operating mode. The Ram 3500 has the highest emission rates for the high STP and high speed operating modes, but is more comparable to the other vehicles at the low STP and low speed operating mode bins.

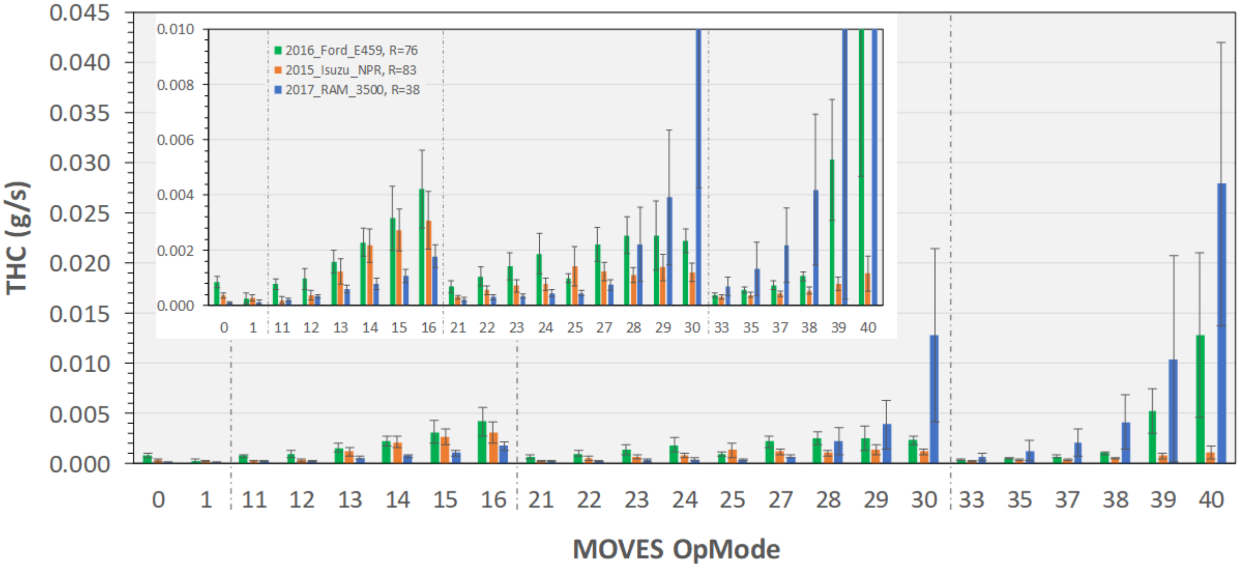

**Figure I-3. Mean Heavy-duty Gasoline THC Emission Rates by Operating Mode and Vehicle Calculated using $f_{scale}$ of 5 metric tons.**

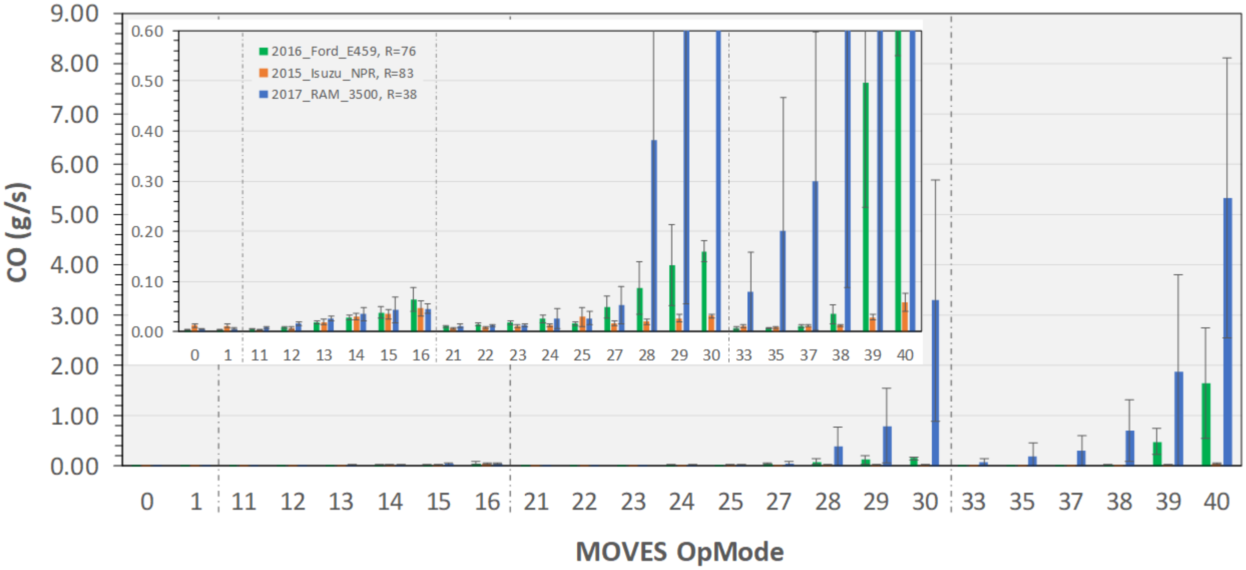

**Figure I-4. Mean Heavy-duty Gasoline CO Emission Rates by Operating Mode and Vehicle Calculated using $f_{scale}$ of 5 metric tons.**

## *I.3 Extrapolating High-Power Operating Modes*

When analyzing the heavy-duty gasoline data for the MHD and HHD regulatory classes (using an $f_{scale}$ of 7 and 10 metric tons respectively), there was limited or no data for high power operating mode bins. The figure below shows the mean $NO_x$ emission rates by vehicle and operating mode when using an using an $f_{scale}$ of 10 used for HHD vehicles. Operating modes 29, 30, 39, 40 are missing data from at least one of the tested vehicles. Operating mode 16 and 28 have limited data from the Ford and Isuzu vehicles (less than 10 routes had data measured in those operating mode bins). The small amount of data in these operating mode bins decreases our confidence in the mean operating modes, and can lead to inconsistent trends in emission rates with power. For example, operating mode 16 has lower mean $NO_x$ emission rates than operating mode 15.

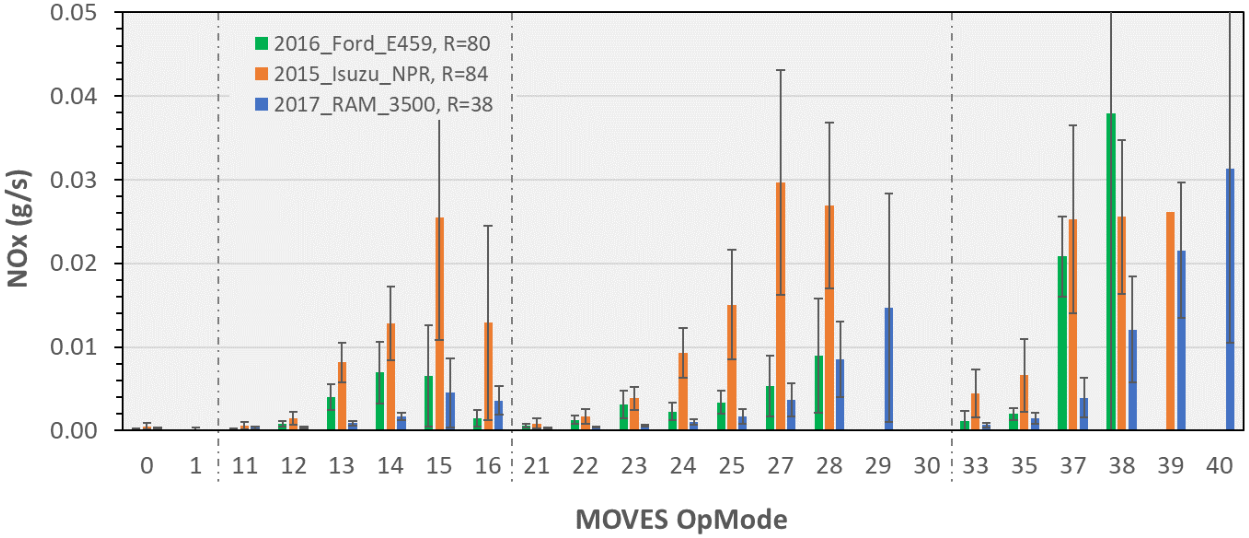

**Figure I-5. Mean Heavy-duty Gasoline $NO_x$ Emission Rates by Operating Mode and Vehicle Calculated for HHD using an $f_{scale}$ of 10 metric tons**

In the case of missing data, we used the emission rates of the nearest operating mode bin with data. In case where there were limited data, we aggregated the averages with data from the next closest bin into into single averages. The figure below displays the resulting emission rates by vehicles for $NO_x$ for HHD vehicles. For the Ford and Isuzu vehicles, the following operating modes were aggregated into single averages: 15-16, 27-30, 38-40. For the RAM vehicle, operating modes 29-30 were aggregated. The same aggregation was used to calculated the updated THC and CO emission rates.

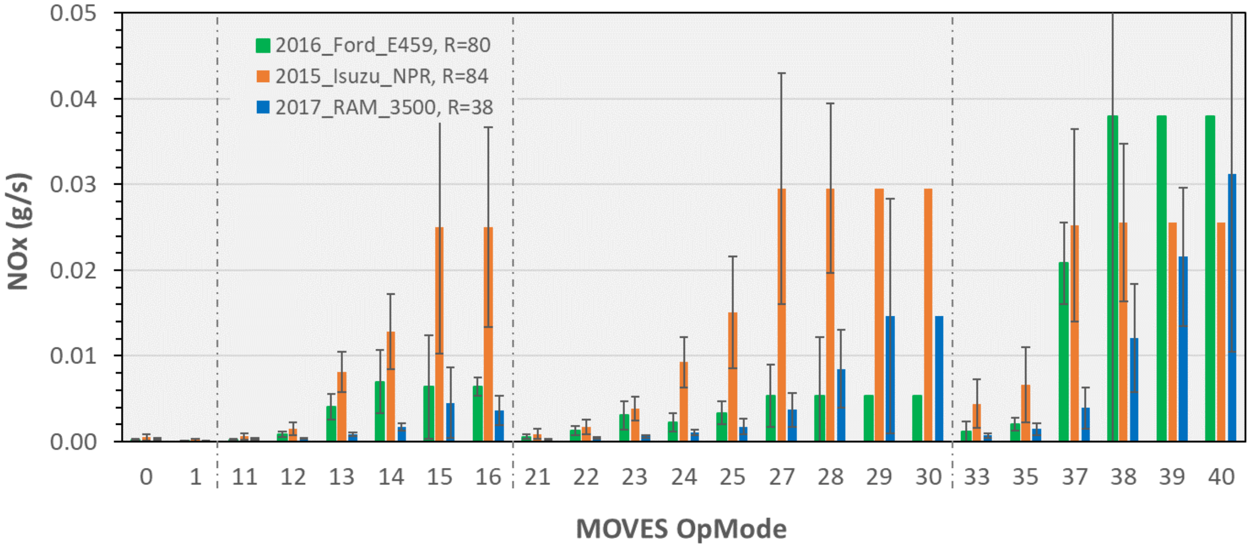

**Figure I-6. Mean Heavy-duty Gasoline $NO_x$ Emission Rates by Operating Mode and Vehicle Calculated for HHD using an $f_{scale}$ of 10 metric tons with Aggregated Means for High Power Bins with Limited Data**

The figure below shows the weighted average $NO_x$ emission rate calculated by averaging the three vehicles together according to their production volume sales.

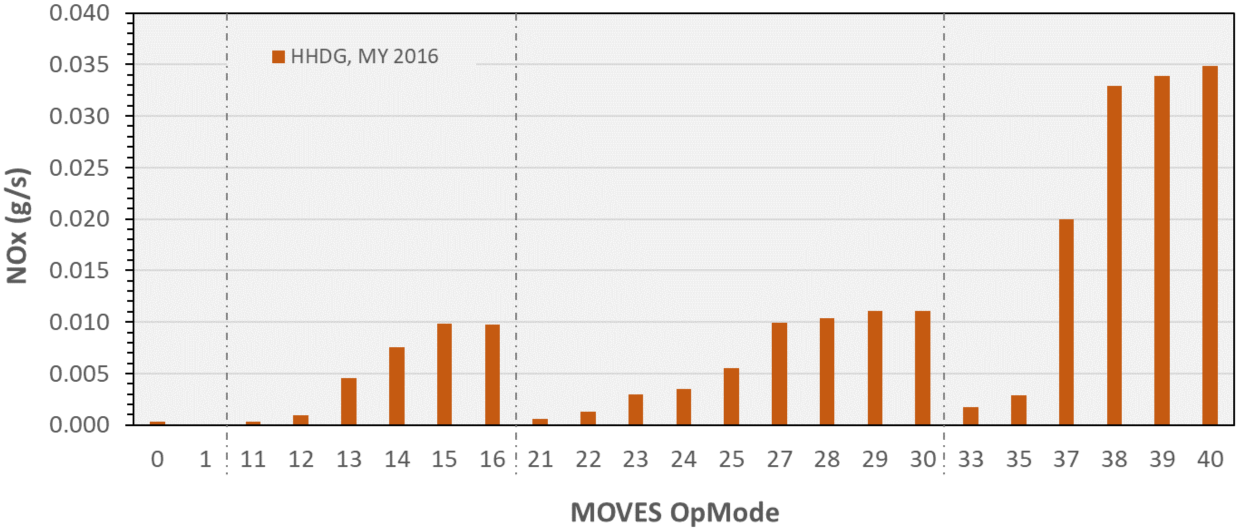

**Figure I-7. Weighted Average Heavy-duty Gasoline $NO_x$ Emission Rates by Operating Mode for HHD Using Production Volumes**

For $CO_2$ emission rates, we used a different method than for THC, CO, and $NO_x$. Rather than aggregate the emission rates with limited or no data, we extrapolated the higher operating modes (30, 39, and 40) using the STP values using Equation 2-5. The assumed mid-point STP for each operating mode bin is displayed in Table I-2.

**Table I-3 Assumed STP Midpoint for Each Operating Mode**

| OpModeID | STP_midpoint |
|---|---|
| 0 | - |
| 1 | - |
| 11 | - |
| 12 | 1.5 |
| 13 | 4.5 |
| 14 | 7.5 |
| 15 | 10.5 |
| 16 | 13.5 |
| 21 | - |
| 22 | 1.5 |
| 23 | 4.5 |
| 24 | 7.5 |
| 25 | 10.5 |
| 27 | 15 |
| 28 | 21 |
| 29 | 27 |
| 30 | 33 |
| 33 | 3 |
| 35 | 9 |
| 37 | 15 |
| 38 | 21 |
| 39 | 27 |
| 40 | 33 |

The figure below displays the initial mean $CO_2$ emission rates using an $f_{scale}$ of 10 metric tons. Note that the emission rates for $CO_2$ have more consistent trends than other measured pollutants; because of this, fewer of the high power operating modes were replaced with extrapolated rates than for the THC, CO, and $NO_x$ emission rates. In this case, we decided to only replace one operating mode with limited data (operating mode 39 for the Isuzu vehicle), because it was only based on one route (which is why there are no error bars).

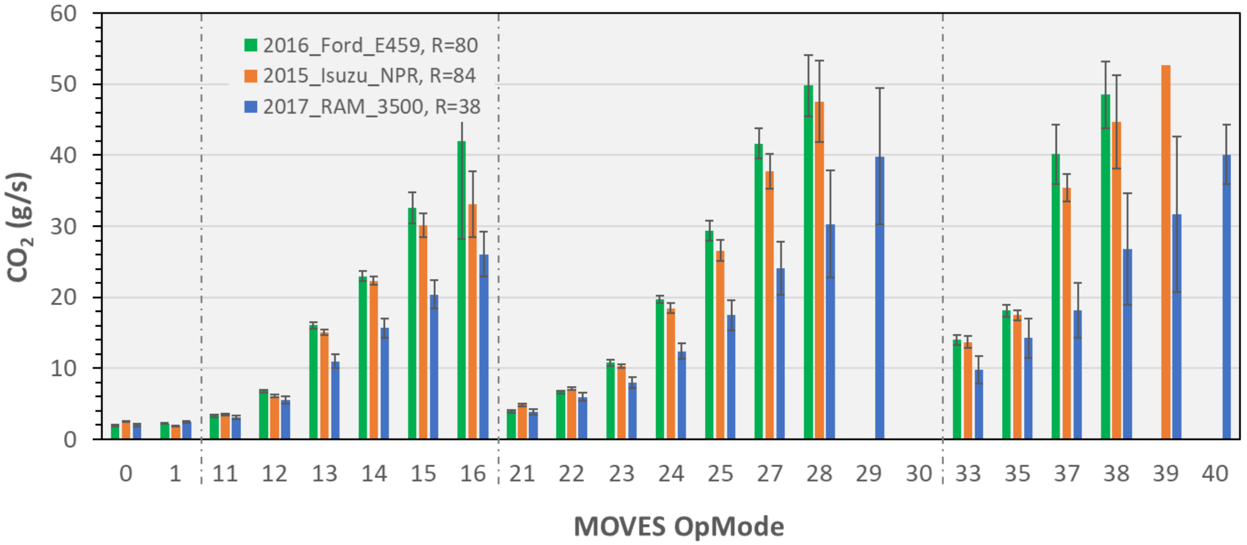

**Figure I-8.Mean Heavy-duty Gasoline $CO_2$ Emission Rates by Operating Mode and Vehicle Calculated for HHD using an *f<sub>scale</sub>* of 10 metric tons**

The figure below shows the mean $CO_2$ emission rates using an $f_{scale}$ of 10 metric tons with extrapolated emission rates for the high power bins. For the Ford and Isuzu vehicles operating modes 29 and 30 were extrapolated from operating mode 28, and operating modes 39 and 40 were extrapolated from 38. For the RAM, operating mode 30 was extrapolated from 29.

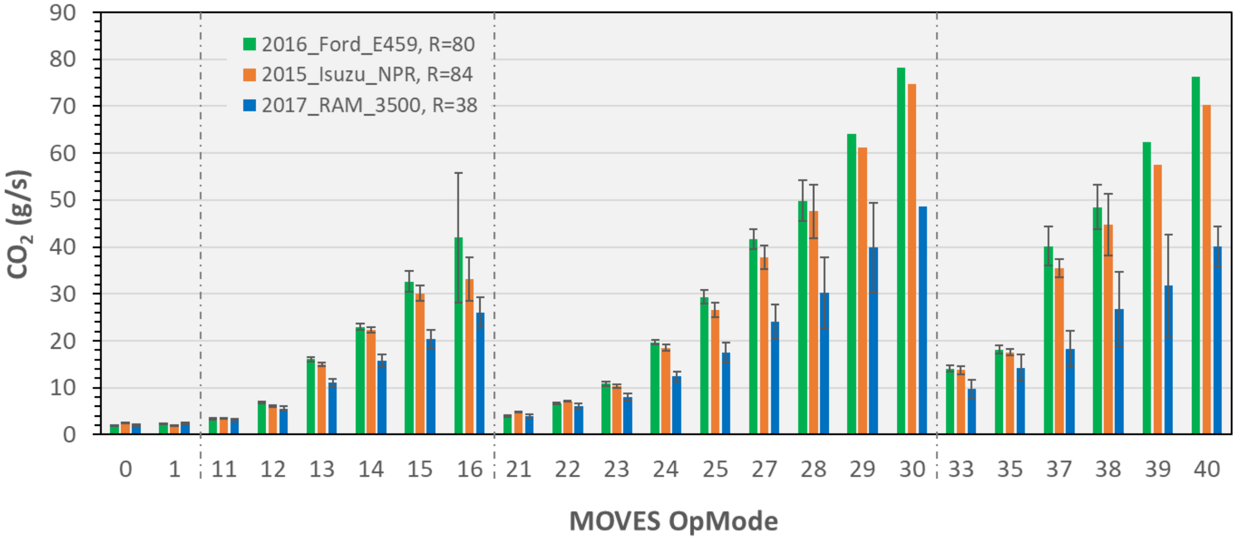

**Figure I-9. Mean Heavy-duty Gasoline $CO_2$ Emission Rates by Operating Mode and Vehicle Calculated for HHD using an $f_{scale}$ of 10 metric tons with Extrapolated Means for High Power Bins.**

The figure below shows the weighted average $CO_2$ emission rate calculated by averaging the three vehicles together according to their production volume sales. Note that the $CO_2$ have stronger increasing trends with power compared to $NO_x$.

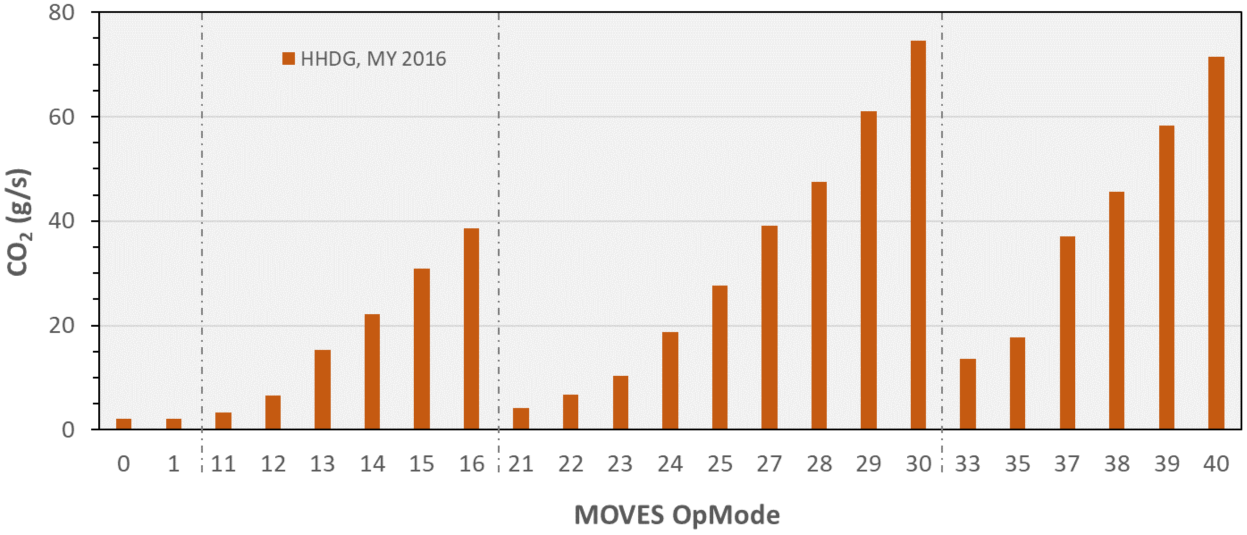

**Figure I-10. Weighted Average Heavy-duty Gasoline $CO_2$ Emission Rates by Operating Mode for HHD Using Production Volumes**

Similar calculations were repeated for the MHD vehicles calculated using an $f_{scale}$ of 7 metric tons.

# Appendix J PM Composition Measurements from Auxiliary Power Units

Table J-1 reports the organic carbon (OC), elemental carbon (EC) and total carbon (TC) measurements conducted in the study conducted by Texas Transportation Institute (TTI, 2014[95]). All the measurements were collected on APU 1. TTI collected the particulate sample on quartz fiber filters, and Sunset Laboratory Inc. analyzed the filters using thermal optical reflectance (TOR) using the IMPROVE (Interagency Monitoring of Protected Visual Environments) procedures. Total Carbon (TC) is the sum of Elemental Carbon (EC) and Organic Carbon (OC).

**Table J-1. Organic Carbon, Elemental Carbon, and Total Carbon Measurements from the IMPROVE_TOR measured on APU 1**

| Sample ID | Min. | DR | Test | OC | OC uncertainty | EC | EC uncertainty | TC | TC uncertainty | EC/TC ratio |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | (μg/cm$^2$) | (μg/cm$^2$) | (μg/cm$^2$) | (μg/cm$^2$) | (μg/cm$^2$) | (μg/cm$^2$) | |
| APU_005 | 10 | 30/1 | Hot Test 1 | 66.35 | 3.42 | 12.98 | 0.75 | 79.33 | 4.17 | 0.16 |
| APU_006 | 10 | 30/1 | Hot Test 2 | 65.26 | 3.36 | 13.45 | 0.77 | 78.70 | 4.14 | 0.17 |
| APU_007 | 10 | 30/1 | Hot Test 3 | 59.24 | 3.06 | 10.51 | 0.63 | 69.75 | 3.69 | 0.15 |
| APU_009 | 20 | 6/1 | DPF Hot APU 1 | 13.85 | 0.79 | 0.86 | 0.14 | 14.71 | 0.94 | 0.06 |
| APU_010 | 20 | 6/1 | DPF Hot APU 1 | 14.67 | 0.83 | 1.12 | 0.16 | 15.79 | 0.99 | 0.07 |
| APU_011 | 20 | 6/1 | DPF Hot APU 1 | 13.18 | 0.76 | 0.93 | 0.15 | 14.11 | 0.91 | 0.07 |
| APU_012 | 20 | 6/1 | DPF Cold APU 1 | 16.62 | 0.93 | 1.45 | 0.17 | 18.07 | 1.10 | 0.08 |
| APU_013 | 20 | 6/1 | DPF Cold APU 1 | 15.86 | 0.89 | 1.40 | 0.17 | 17.27 | 1.06 | 0.08 |
| APU_014 | 20 | 6/1 | DPF Cold APU 1 | 17.59 | 0.98 | 1.56 | 0.18 | 19.15 | 1.16 | 0.08 |
| APU_015 | 10 | 30/1 | Cold Test 1 | 75.74 | 3.89 | 9.65 | 0.58 | 85.39 | 4.47 | 0.11 |
| APU_016 | 10 | 30/1 | Cold Test 2 | 73.83 | 3.79 | 9.61 | 0.58 | 83.44 | 4.37 | 0.12 |
| APU_017 | 10 | 30/1 | Cold Test 3 | 77.47 | 3.97 | 9.90 | 0.59 | 87.37 | 4.57 | 0.11 |

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