Exhaust Emission Rates for Heavy-Duty Onroad Vehicles in MOVES201X

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1 Principles of Modeling Heavy-duty Emissions in MOVES

This report describes the analyses conducted to generate emission rates and energy rates representing exhaust emissions and energy consumption for heavy-duty vehicles in MOVES. Heavy-duty vehicles in MOVES are defined as any vehicle with a Gross Vehicle Weight Rating (GVWR) above 8,500 lbs. This report discusses the development of emission rates for total hydrocarbons (HC), carbon monoxide (CO), nitrogen oxides (NO_X), and particulate matter (PM).

From HC emissions, MOVES generates other estimates of organic gas emissions, including volatile organic compounds (VOCs) and total organic gases (TOG). MOVES then applies fuel effects to 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 emissions in terms of elemental carbon (EC) and the remaining non-elemental carbon PM (nonEC). This report covers the derivation of EC/PM fractions used to estimate elemental carbon (EC), and the remaining non-elemental carbon PM (nonEC). MOVES also estimates 18 PM subspecies beyond elemental carbon, such as organic carbon, sulfate and nitrate, through the use of speciation profiles as documented in the Speciation Report.[1]**Error! Bookmark not defined.**

This report also documents the energy consumption rates for heavy-duty vehicles. For heavy-duty diesel vehicles, the energy rates were developed based on a carbon balance method using the measurements of carbon dioxide (CO_2), CO and total hydrocarbons (HC), from the same tests and measurements used to estimate the MOVES CO and HC emission rates. We developed emission and energy rates for heavy-duty vehicles powered by diesel, gasoline, and compressed natural gas (CNG) fuels, although emissions from the heavy-duty sector predominantly come from diesel vehicles. As a result, the majority of the data analyzed were from diesel vehicles.

In MOVES201X, the following emission rates were updated:

- Gaseous running emission rates for model year (MY) 2010+ heavy-duty diesel trucks (Section 2.1)
- Energy rates for MY 2010+ trucks, including the impact of the Heavy-Duty Greenhouse Gas Phase 2 rulemaking (Section 2.1.4)
- Fraction of elemental carbon and non-elemental carbon fractions of $PM_{2.5}$ exhaust emissions from pre-2007 diesel trucks (Section 2.1.2.2.8)
- Gaseous and $PM_{2.5}$ start emission rates for MY 2010+ heavy-duty diesel trucks (Section 2.2)
- Extended idle and auxiliary power emission rates for heavy-duty diesel vehicles for all model years (Section 2.3)
- Heavy-duty gasoline energy rates were updated to reflect the adoption of Heavy-Duty Phase 2 greenhouse gas emissions standards (Section 3.1.3)
- Gaseous and PM running exhaust emission rates for MY 2007+ CNG heavy-duty vehicles. Further, CNG fuel-type is allowed for all heavy-duty source types (Section 4)

This report first introduces the principles used to model heavy-duty vehicles in MOVES. Then, Sections 2 through 4 document the emission rates for heavy-duty diesel, heavy-duty gasoline, and heavy-duty CNG vehicles. Section 5 documents the crankcase emission rates used for each fuel type of heavy-duty vehicles. Section 6 documents the methods used to estimate nitric oxide (NO), nitrogen dioxide (NO_2), and nitrous acid (HONO) emissions from NO_X emissions using ratios.

Emission rates for criteria pollutants (HC, CO, NO_X, and PM) are stored in the "EmissionRateByAge" table in the MOVES database according to the following:

- MOVES regulatory class
- Fuel type (diesel, gasoline, and CNG)
- Model year group
- Vehicle age
- Emission process (e.g., running exhaust, start exhaust, crankcase emissions)
- Vehicle operating mode

Energy emission rates are stored in the "EmissionRate" table, which is similar to the "Emission RateByAge" 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 the next sections, the following parameters used to classify heavy-duty emissions in MOVES are discussed in more detail: heavy-duty regulatory classes, emission processes, vehicle operating modes, and vehicle age. Although not discussed in detail, the model year groupings are designed to represent major changes in EPA emission standards.

1.1 Heavy-Duty Regulatory Classes

The MOVES heavy-duty regulatory classes group vehicles that have similar emission standards and 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. However, there are additional criteria that define heavy-duty regulatory classes in MOVES. For example, Urban Bus engines 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.[3] Urban bus is a regulatory class that is also defined by its intended use, and not just the GVWR ("heavy heavy-duty diesel-powered passenger-carrying vehicles with a load capacity of fifteen or more passengers and intended primarily for intra-city operation[4]").

Regulatory class LHD≤10K (regClassID 40) and LHD≤14K (regClassID 41) are also defined according to additional criteria than GVWR. LHD≤10K is defined as trucks with GVWR between 8,500 lbs. and 10,000 lbs. (Class 2b trucks) with only two axles and four tires. Class 2b trucks with two axles and six tires are classified in regulatory class LHD ≤14K, as well as all trucks between 10,000 lbs. and 14,000 lbs. (Class 3 trucks). Unlike Urban Buses, the distinction between LHD≤10K and LHD≤14K in MOVES is not caused by differences in EPA exhaust emission standards. The reasons for the distinction between regulatory class LHD≤10K and LHD≤14K is due to (1) available activity information, and (2) the assignment of operating modes within MOVES source types.

As discussed in the Population and Activity Report[5], the FHWA reports vehicle-miles traveled (VMT) of Class 2b trucks with two axles and four tires in the light-duty vehicle categories, which correspond to MOVES source types, Passenger Trucks (sourceTypeID 31) and Light-Commercial Trucks (sourceTypeID 32). FHWA reports VMT from Class 2b trucks with two axles and six tires, as heavy-duty vehicles. MOVES includes LHD≤14K trucks within the following vocational heavy-duty source types: Intercity Buses (sourceTypeID 41), School Buses (sourceTypeID 43), Refuse Trucks (sourceTypeID 51), Single Unit Short-haul (sourceTypeID 52), Single Unit Long-Haul (sourceTypeID 53), and Motor Homes (sourceTypeID 54).

As discussed in the Population and Activity Report[5], MOVES assigns operating modes according to source type. For light-duty source types (including passenger trucks and light-commercial trucks), the running operating modes are assigned according to Vehicle Specific Power (VSP). For single-unit source types, the running operating modes are assigned according to Scaled Tractive Power (STP). As discussed in Section 1.3, the emission rates for regulatory class LHD≤10K (regClassID 40) use a different scaling factor when computing STP, such that the emission rates are consistent with VSP-based operating modes. The emission rates for regulatory class LHD≤14K (regClassID 41) are based on the standard STP scaling factor, to be consistent with the way MOVES assigns operating modes for heavy-duty source types.

LHD≤10K (regClassID 40) is a regulatory class introduced in MOVES2014. Previous versions of MOVES classified all light heavy-duty trucks with GVWR under 14,000 lbs. as LHD2b3 (formerly regClassID 41). In MOVES2010b, the emission rates for LHD2b3 and LHD45 were compatible with VSP-based emission rates.[a] As discussed in Section 1.3, the emission rates for LHD≤14K (regClassID 41) and LHD45 (regClassID 42) have been changed to be based on the standard STP scaling factor for heavy-duty trucks. With the addition of LHD≤10K (regClassID 40), and the change to the emission rates for LHD≤14K and LHD45, MOVES can more accurately model the light heavy-duty emission rates that are classified either within the light-duty truck source types or the vocational heavy-duty source types.

As discussed later in the report, the data used to derive the emission rates for regulatory class LHD≤10K (regClassID 40) and LHD≤14K (regClassID 41) trucks are often the same, but analyzed with appropriate scaling factors to derive separate emission rates for each regulatory class. Occasionally, the MOVES2010b regulatory class LHD2b3 is used in this report, to refer to all light heavy-duty trucks with GVWR under 14,000 lbs. Table 1-1 provides an overview of the regulatory class definitions in MOVES for heavy-duty vehicles. Table 1-1 also indicates whether the emission rates are developed to be consistent with VSP- or STP-based operating modes.

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[a] In MOVES2010b, LHD2b3 and LHD45 existed only within the light-duty source types (passenger trucks and light-commercial trucks). In MOVES2010b, the LHD2b3 and LHD45 trucks that existed in vocational source types (buses and single unit trucks) types were replaced with MHD trucks, to essentially use the MHD emission rates as surrogates for the light heavy-duty trucks that existed in the vocational heavy-duty source types. Since 2010, FHWA has updated the definition of light-duty vehicles in the VM-1 Highway Statistics table to only include vehicles that are less than 10,000 lbs. MOVES uses this updated definition, so LHD45 trucks are now exclusively classified within heavy-duty source types, and do not need to be split between VSP and STP based regulatory classes like the LHD2b3 trucks.[5]

Table 1-1. Regulatory Classes for Heavy-Duty Vehicles

Regulatory Class Description	regClassName	regClassID	Gross Vehicle Weight Rating (GVWR) [lb.]	Source Types (sourceTypeID)	Operating Mode Basis[2]
Light Heavy-Duty ≤ 10,000 lbs. (Class 2b Trucks with 2 Axles and 4 Tires.)	LHD≤ 10K	40	8,501 – 10,000	Passenger Trucks (31), and Light-Commercial Trucks (32)	VSP
Light Heavy-Duty ≤ 14,000 lbs. Class 2b (Trucks with 2 Axles and at least 6 Tires or Class 3 Trucks.)	LHD≤14K	41	8,501 – 14,000	Buses (41, 43), and Single Unit Trucks (51, 52, 53, 54)	STP
Light Heavy-Duty 4-5	LHD45	42	14,001 – 19,500	Buses (41, 42, 43) and Single Unit Trucks (51, 52, 53, 54)	STP
Medium Heavy-Duty	MHD	46	19,501 – 33,000	Buses (41,42,43), Single Unit Trucks (51, 52, 53, 54), and Combination Trucks (61, 62)	STP
Heavy Heavy-Duty	HHD	47	> 33,000	Buses (41, 42, 43), Single Unit Trucks (51, 52, 53, 54), and Combination Trucks (61, 62)	STP
Urban Bus	Urban Bus[1]	48	> 33,000	Transit Bus (42)	STP

Notes:
[1] see CFR § 86.091(2).
[2] MOVES assigns operating modes based on vehicle-specific power (VSP) or scaled tractive power (STP), depending on source type

1.2 Emission Pollutants and Processes

MOVES models vehicle emissions from fourteen different emission processes as listed in Table 1-2. 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) for HC, CO, NO_X and PM. The running process occurs as the vehicle is operating on the road either under load or in idle mode. This process is further delineated by 23 operating modes as discussed in the next subsection. The start exhaust process includes the incremental emissions that occur from starting a vehicle, including the incremental emissions that occur after the engine start before the aftertreatment system is fully functional.

The extended idle process 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 can result in different emissions than incidental idle 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, that are used in place of the main engine during periods of hotelling. Documentation of the extended idle and auxiliary power exhaust emissions for heavy-duty diesel trucks are in Section 2.3.

Crankcase 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 significant sources of emissions from heavy-duty compression ignition engines, and are discussed for all heavy-duty source types and fuels in Section 5.

Estimation of energy consumption rates for heavy-duty vehicles is also covered in this report. Energy consumption (in units of kJ) is modeled for running exhaust, start exhaust, extended idle exhaust, and auxiliary power exhaust. Estimation of the emissions of nitrous oxide (N_2O), and ammonia (NH_3) for diesel, gasoline, and CNG heavy-duty vehicles are unchanged from MOVES2014 and are documented in separate reports.[6, 7] The methane (CH_4) emissions are estimated as a fraction of total hydrocarbon (THC) emissions. The CH_4/THC fractions are documented in the MOVES speciation report.[41]

Evaporative and refueling emissions from heavy-duty vehicles are not covered in this report. Estimation of evaporative hydrocarbon emissions from heavy-duty gasoline vehicles is described in the evaporative report.[8] 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.[8] Brake and Tire wear emission rates from heavy-duty vehicles are discussed in the Brake and Tire Wear Report.[10]

Table 1-2. 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 Operating Modes

Operating modes for heavy-duty vehicles and 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. Light-Duty vehicles are tested on full chassis dynamometers, and emission standards are in units of grams per mile. Thus, the emission standards are largely independent of the weight (and other physical characteristics) of the vehicle and depend on distance (or miles). More in depth discussion of VSP is contained in the light-duty emission rate report.[9]

For heavy-duty vehicles, we relate emissions to power output, but in a different way. Heavy-duty vehicles are regulated using engine dynamometer testing, and emissions standards are in units of grams per brake-horsepower-hour (g/bhp-hr). With these work-based emission standards, emission rates relate strongly to power and are not independent of vehicle mass, so normalizing by mass is not appropriate. Thus, for heavy-duty modal modeling, the tractive power is used in its natural form and simply scaled by a constant to bring its numerical values into the same range as the VSP values used for light-duty vehicles. We refer to this heavy duty parameter as “scaled-tractive power” (STP).

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

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

Where: P_{axle} is the power demand at the axle for the heavy-duty truck. As discussed later, 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. Also, wind speed and wind direction, which can have a significant effect on aerodynamic drag, are not typically measured in onroad tests. Additionally, the road load equations may not reflect the actual vehicle test weight, and the tests may not have accurate road grade information for the entire route tested. Thus, for onroad tests, we generally use power calculated from the ECU measurements, because the vehicle and environmental characteristics determine the axle power (Section 2.1.1.2).

In chassis dynamometer tests, the road load equation works well because it directly determines the axle power during the test. For data collected on chassis dynamometer tests, with vehicles that do not have ECU measurements, we use road load equation (Equation 1-2) to estimate power (Section 2.1.2.2.1).

The values of f_{scale} are located in Table 1-3 As mentioned previously, the operating modes for regulatory class LHD≤10K (regClassID 40) are VSP-based, because regulatory class LHD≤10K (regClassID 40) are modeled as passenger trucks and light-commercial trucks. Thus, for LHD≤10K (regClassID 40), f_{scale} is equal to the mean source mass of light-commercial trucks[5], to yield emission rates that are consistent with VSP-based operating modes.

In contrast, all other heavy-duty source types use a constant 17.1 power scaling factor, which is approximately the average running weight for all heavy-duty vehicles, and yields STP ranges that are within the same range as the definitions for VSP, as shown in Table 1-3. 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.

Table 1-3. Power Scaling Factor f_{scale}

Regulatory Class (regClassID)	Power scaling factor (metric tons)
LHD≤10K (40)	2.06
LHD≤14K (41), LHD45 (42), MHD (46), HHD (47), Bus (48)	17.1

In cases where the power is not measured at the engine, it can be estimated from instantaneous speed, vehicle mass, and road load coefficients, as shown in Equation 1-2:

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

Where:

STP_t = the scaled tractive power at time t [scaled kW or skW]
A = the rolling resistance coefficient [kW·sec/m],
B = the rotational resistance coefficient [kW·sec^2/m^2],
C = the aerodynamic drag coefficient [kW·sec^3/m^3],
m = mass of individual test vehicle [metric ton],
f_{scale} = fixed mass factor (see Table 1-3),
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

This is the equation used by MOVES to estimate the operating mode distribution from average speed and second-by-second driving cycles as discussed in the Population and Activity Report. However, the equation is also used here to estimate the STP-based emission rates from emission tests where a more direct measure of P_{axle} is not available. The derivation of the load road parameters is discussed in the Population and Activity Report.[5]

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			$a_t + g \cdot sin(\theta_t) \leq -2.0$ OR $[a_t + g \cdot sin(\theta_t) < -1.0$ AND $a_{t-1} + g \cdot sin(\theta_{t-1}) < -1.0$ AND $a_{t-2} + g \cdot sin(\theta_{t-2}) < -1.0)$
1	Idle		$v_t < 1.0$	
11	Coast	$STP_t < 0$	$1 \leq v_t < 25$	
12	Cruise/Acceleration	$0 \leq STP_t < 3$	$1 \leq v_t < 25$	
13	Cruise/Acceleration	$3 \leq STP_t < 6$	$1 \leq v_t < 25$	
14	Cruise/Acceleration	$6 \leq STP_t < 9$	$1 \leq v_t < 25$	
15	Cruise/Acceleration	$9 \leq STP_t < 12$	$1 \leq v_t < 25$	
16	Cruise/Acceleration	$12 \leq STP_t$	$1 \leq v_t < 25$	
21	Coast	$STP_t < 0$	$25 \leq v_t < 50$	
22	Cruise/Acceleration	$0 \leq STP_t < 3$	$25 \leq v_t < 50$	
23	Cruise/Acceleration	$3 \leq STP_t < 6$	$25 \leq v_t < 50$	
24	Cruise/Acceleration	$6 \leq STP_t < 9$	$25 \leq v_t < 50$	
25	Cruise/Acceleration	$9 \leq STP_t < 12$	$25 \leq v_t < 50$	
27	Cruise/Acceleration	$12 \leq STP_t < 18$	$25 \leq v_t < 50$	
28	Cruise/Acceleration	$18 \leq STP_t < 24$	$25 \leq v_t < 50$	
29	Cruise/Acceleration	$24 \leq STP_t < 30$	$25 \leq v_t < 50$	
30	Cruise/Acceleration	$30 \leq STP_t$	$25 \leq v_t < 50$	
33	Cruise/Acceleration	$STP_t < 6$	$50 \leq v_t$	
35	Cruise/Acceleration	$6 \leq STP_t < 12$	$50 \leq v_t$	
37	Cruise/Acceleration	$12 \leq STP_t < 18$	$50 \leq v_t$	
38	Cruise/Acceleration	$18 \leq STP_t < 24$	$50 \leq v_t$	
39	Cruise/Acceleration	$24 \leq STP_t < 30$	$50 \leq v_t$	
40	Cruise/Acceleration	$30 \leq STP_t$	$50 \leq v_t$	

Note:
[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.

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 different soak times, varying 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).

1.4 Vehicle Age

Emission rates for HC, CO, NO_X, and PM are differentiated by vehicle age. The start and running emission rates for HC, CO, NO_X, and PM 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 are developed separately for gasoline and diesel vehicles. For diesel vehicles, we estimated the effects of tampering and mal-maintenance on emission rates as a function of age. We adopted this approach due to the lack of adequate data to directly estimate the deterioration for heavy-duty vehicles. 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 (Appendix B). For gasoline vehicles, the age effects are estimated directly from the emissions data, or are adopted from light-duty deterioration as discussed in Section 3.1.1.1.

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	~

Energy rates are stored in the "EmissionRate" table, where rates are not distinguished by age. This table also includes HC, CO, NO_X, PM, 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. This report documents the HC, CO, NO_X, and PM emissions from extended idle and APU usage, however the documentation of heavy-duty nitrous oxide and ammonia[7] and tire and brake wear[10] emission rates are documented elsewhere.

2 Heavy-Duty Diesel Emissions

This section details our analysis of data 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 1-1) and model year group. As mentioned in subsections 1.1 and 1.3, 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[11], 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 level (FEL) (or 1.25 standard or FEL, when FEL > 1.50 g/bhp·hr)
2007-2009	1.2[1,2]	
2010+	0.2	

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, 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.[12] 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.[13] 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).[14,15,16] 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 in 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 (HDIU). The in-use testing program for heavy-duty diesel vehicles was promulgated in June 2005 to monitor the emissions performance of the engines operated under a wide range of real world driving conditions, within the engine's useful life.[17] 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 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 MOVES201X, we looked at data from engines selected for testing in calendar years 2010 through 2015. These engines cover model years 2010 to 2013. The MY 2010+ data set included 30 unique engine families, 231 vehicles, and over 6 million seconds of quality-assured second-by-second data.

Houston Drayage Data. In coordination with the Texas Commission on Environmental Quality (TCEQ), the Houston-Galveston Area Council (H-GAC), and the Port of Houston Authority (PHA), EPA conducted a study collecting emissions data from trucks in drayage service using portable emission measurement systems (PEMS) from December 2009 to March 2010.[18] 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 conduct 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.

For MOVES2014, only MY2007-2009 rates were updated because the CY2005-2010 HDIU and Houston Drayage data only included engines up to MY2009. The rates for MY2010+ in MOVES2014 were simply scaled down from pre-2010 rates as per the more stringent NO_X emissions standards that went into effect in 2010. However, for MOVES201X, MY2010+ rates were updated based on more recent data available from the HDIU program, as described in Sections 2.1.1.3.2 and 2.1.1.4.1.

From each data set, we used only tests we determined to be valid. For the ROVER dataset, we eliminated all tests that indicated any reported problems, including GPS malfunctions, PEMS malfunctions, etc., whether or not they affected the actual emissions results. For HDIU 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, HDIU (MY2009 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 HDIU (MY2009 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 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.

For MOVES201X analysis of the HDIU data for MY 2010+, we checked the time-alignment and deleted any second of data that met any of the following conditions: (1) Instrument is undergoing zeroing, as marked by the zero flag field; (2) engine RPM is below 500; (3) vehicle speed is missing or below zero; (4) acceleration is missing; (5) engine torque is missing; (6) measured exhaust flow rate is missing, or less than or equal to zero; and as catch-all, we also checked if the calculated STP and OpMode are an invalid number.

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

		Regulatory Class			
Data Source	**MYG**	**HHD**	**MHD**	**LHD**	**BUS**
ROVER and Consent Decree Testing	**1991-1997**	19	-	-	2
	1998	12	-	-	-
	1999-2002	78	30	-	25
	2003-2006	91	32	-	19
HDIU	**2003-2006**	40	25	15	-
	2007-2009	68	71	24	-
	2010+[a]	121	48	52	10
Houston Drayage	**1991-1997**	8	-	-	-
	1998	1	-	-	-
	1999-2002	10	-	-	-
	2003-2006	8	-	-	-

Note:
[a] New data used to update heavy-duty diesel MY 2010 and beyond rates in MOVES201X

2.1.1.2 Calculate STP from 1-Hz data

With onroad testing, using vehicle speed and acceleration to estimate tractive power is not accurate given the effect of road grade and wind speed. As a result, we needed to find an alternate approach. Therefore, we decided to use tractive power from engine data collected during operation. 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 ω_{eng} and torque τ_{eng} from the ECU were used to determine engine power P_{eng}, as shown in Equation 2-1. Only torque values greater than zero were used so as to only include operation where the engine was performing work.

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

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. The calculation of the accessory load requirements is derived below.

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 highway, or high, vehicle speeds. Table 2-3 identifies the predominant accessory use within each of the vehicle speed and load areas.

At this point, we also translated the vehicle speed and engine load map into engine power levels. The 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.

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

		Vehicle Speed		
		Low (0-25 mph)	**Mid (25-50 mph)**	**High (above 50 mph)**
Engine Power (of max hp)	**Lowest Third**	Cooling Fan Air cond. Engine Access. Alternator Air Compress	Air cond. Engine Access. Alternator Air Compress	Air cond. Engine Access. Alternator
	Middle Third	Cooling Fan Air cond. Engine Access. Alternator Air Compress	Cooling Fan Air cond. Engine Access. Alternator Air Compress	Air cond. Engine Access. Alternator
	Highest Third	Cooling Fan Air cond. Engine Access. Alternator Air Compress	Cooling Fan Air cond. Engine Access. Alternator Air Compress	Cooling Fan Air cond. Engine Access. Alternator

We next 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*."[19]

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 a STP bin 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. In MOVES2014, LHD losses were set to zero for all model years. For MOVES201X, we estimated losses for MY 2010+ LHD vehicles 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 for low power band and 70 percent for mid and high power bands of the MHD losses for the corresponding power bands. We acknowledge this assumption is not data driven, but we believe it is a step forward from having LHD losses equal to zero (as was the case in MOVES2014).

Table 2-4. Estimates of Accessory Load in kW by Power Range

Engine power	HDT	MHD	LHD[a] (pre-2010)	LHD[a] (2010+)	Urban Bus
Low	8.1	6.6	0.0	4.1	21.9
Mid	8.8	7.0	0.0	4.8	22.4
High	10.5	7.8	0.0	5.5	24.0

Note:
[a] In MOVES2014, the accessory load losses for LHD (RegClassID 40, 41, and 42) were assumed to be zero for all model years. In MOVES201X, MY 2010+ LHD data (Table 2-2) is analyzed with accessory load losses as non-zero. However, pre-2010 MY LHD continues to assume accessory load loss of zero.

We then accounted for the driveline efficiency. The driveline efficiency accounts for 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, we estimated an average value for driveline efficiency.[20,21,22,23,24,25,26,27,28] Table 2-5 summarizes our findings.

Table 2-5. Driveline Efficiencies Found in the Literature

General truck:	
Barth (2005)	80-85%
Lucic (2001)	75-95%
HDT:	
Rakha	75-95%
NREL (1998)	91%
Goodyear Tire Comp.	86%
Ramsay (2003)	91%
21st Century Truck (2000)	94%
SAE J2188 Revised OCT2003:	
Single Drive/direct	94%
Single Drive/indirect	92%
Single Drive/double indirect	91%
Tandem Drive/direct	93%
Tandem Drive/indiriect	91%
Tandem Drive/double indirect	89%
Bus:	
Pritchard (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}.

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

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

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

We then constructed operating mode bins defined by STP and vehicle speed according to the methodology outlined earlier in Table 1-4.

2.1.1.3 Calculate emission rates

2.1.1.3.1 *Emission Rates for pre-2010 Model Years*

Emissions in the data set were reported in grams per second. First, we 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).

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

Where:

n_j = the number of 1-Hz data points *(for a given operating mode bin)* for each vehicle *j*,

n_{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 operating mode bin combination. Examples of mean emission rates derived using this method are displayed in Section 2.1.1.7, starting with Figure 2-6.

2.1.1.3.2 *Emission Rates for 2010 and beyond Model Years*

In calculating the mean emission rates for MY 2010+ vehicles (updated in MOVES201X), we made two additions to the method described in Section 2.1.1.3.1:

1. For a given regulatory class (HHD, MHD, LHD), and irrespective of engine model year (as long as it is MY 2010+), we grouped the vehicles in HDIU into three NO_X family emission

limit (FEL) groups. We first calculated the OpMode-based average emission rate for each vehicle by regulatory class and NO_X FEL group (Equation 2-5, this step is unchanged from MOVES2014). Then, we calculated the OpMode-based average emission rate for all vehicles in the NO_X FEL group (Equation 2-6). This means, for a given regulatory class and NO_X FEL group, we are not distinguishing between manufacturers or model years.

2. We weighted the OpMode-based average emission rates for each of the three NO_X FEL groups within a regulatory class by the, per model year, production volume of the engines in the NO_X FEL group to the total production volume of the regulatory class (Equation 2-7). Thus, for a given regulatory class, we now have a OpMode-based average emission rates per model year.

More details about the NO_X FEL grouping and production volume weighting are provided below.

$$ER_{pol,OM,C,FEL,veh} = \frac{\sum_{sec} ER_{pol,OM,C,FEL,veh,sec}}{sec_{count}}$$ **Equation 2-5**

$$ER_{pol,OM,C,FEL} = \frac{\sum_{veh} ER_{pol,OM,C,FEL,veh}}{veh_{count}}$$ **Equation 2-6**

$$ER_{pol,OM,C,MY} = \sum_{FEL}\left(ER_{pol,OM,C,FEL} * \frac{PV_{C,MY,FEL}}{\sum_{FEL} PV_{C,MY,FEL}}\right)$$ **Equation 2-7**

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)
MY	= Model year (2010+)
OM	= running exhaust emissions operating mode
pol	= Pollutant (NO_X, HC, 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

Creation of NO_X FEL Groups

We grouped engines, within a regulatory class, by their NO_X FEL. We created three groups:

- "0.20" (0.00 g/bhp-hr < NO_X FEL ≤ 0.20 g/bhp-hr)
- "0.35" (0.20 g/bhp-hr < NO_X FEL ≤ 0.35 g/bhp-hr)
- "0.50" (0.35 g/bhp-hr < NO_X FEL ≤ 0.50 g/bhp-hr)

Each test vehicle 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+ 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 all MY 2010+ engine families reported in the certification database (and not just the engine families tested under the HDIU program). The NO_X FELs for all MY 2010+ HD diesel engine families in the certification database is shown in Figure 2-1. 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.

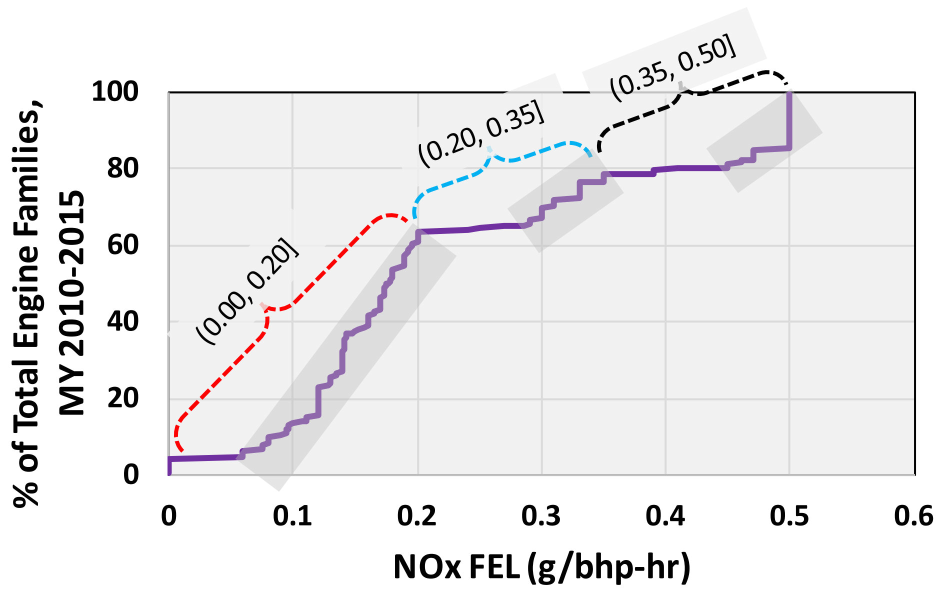


Figure 2-1 Distribution of NO_X Family Emission Limit (FEL) for Model Year 2010 and Beyond Heavy-Duty Diesel Engine Families, as Reported in the Certification Database

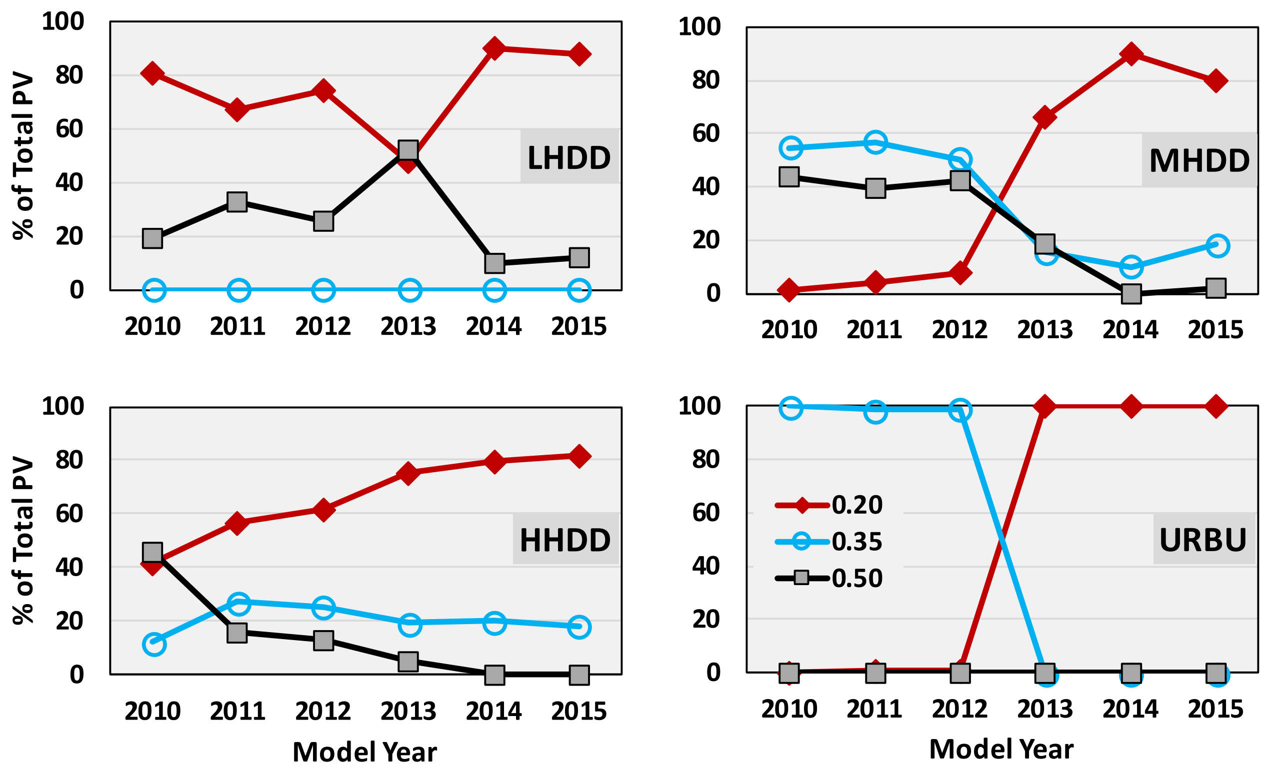
Table 2-6 shows the number of vehicles by regulatory class and NO_X FEL group for MY2010+ engines in the HDIU program. The number of vehicles by regulatory class in this table match the number of vehicles in Table 2-2.

Table 2-6 Number of Diesel Vehicles with MY 2010+ Engines by NO_X FEL Group from the HDIU Program Used for Emission Rate Analysis

Regulatory Class	NO_X FEL Group			Total
	0.20	0.35	0.50	
HHD	65	21	35	121
MHD	16	23	9	48
LHD	42	0	10	52
Urban Bus	0	10	0	10
Total	123	54	54	**231**

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 across all model years) 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 starting from 2010 and up to the model year where we have production volume data (which as of now is MY 2015). For MY 2016+, we decided to maintain the production volume weighting from MY 2015. The per-model-year production volume weighting, by regulatory class and NO_X FEL groups, is shown in Figure 2-2. This method allows us to better represent the technology adoption landscape in the heavy-duty domain. For example, for HHDD, 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 being used in the fleet.



Production volume percent contributions of the three NO_X FEL groups, in a given regulatory class and model year, add up to 100 percent of the production volume for the regulatory class and model year.

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

Other Considerations

One aspect in our current approach is that for FEL group average emission rates, we do not differentiate between manufacturers and engine model years. Thus, a HHD MY 2010 engine from manufacturer A with NO_X FEL of 0.10 and a HHD MY 2013 engine from manufacturer B with NO_X FEL of 0.20 are both put in the HHD 0.20 group and averaged. If future data shows significant differences in real-world performance of engines with similar NO_X FEL but different model years, a possible area of improvement would be to differentiate between model years even when arriving at the FEL group-based average emission rate (which then gets weighted by production volume). Similarly, we could additionally differentiate between manufacturers or even between engine families by the same manufacturer. Each of these additional steps may provide increased ability to distinguish the differences, however, the drawbacks are more complex analysis and need to make assumptions due to lack of data (for example, we do not have emissions data from each engine family or even each manufacturer for each model year). We believe the approach adopted here provides emissions rates, for MY 2010+, that are sufficiently representative of the real-world while working within the constraints of resources and technical data.

2.1.1.3.3 *Statistics*

Estimates of uncertainty were calculated for all the emission rates. Because the data represent subsets of points "clustered" by vehicle, we calculated and combined two variance components, representing "within-vehicle" and "between-vehicle" variances. First, we calculated the overall within-vehicle variance s^2_{with} using Equation 2-8.

$$s^2_{with} = \frac{\sum_{j=1}^{n_j}(n-1)s_j^2}{n_{tot} - n_j} \qquad \textbf{Equation 2-8}$$

Where:

s_j^2 = the variance within each vehicle, and

n_{tot} = the total number of data points for all the vehicles.

Then we calculated the between-vehicle variance s^2_{betw} (by source bin, age group, and operating mode) using the mean emission rates for individual vehicles ($\bar{r}_{p,j}$) as shown in Equation 2-9.

$$s^2_{\text{betw}} = \frac{\sum_{j=1}^{n_\text{j}}\left(\bar{r}_{p,j} - \bar{r}_p\right)^2}{n_\text{j} - 1} \qquad \textbf{Equation 2-9}$$

Then, we estimated the total variance by combining the within-vehicle and between-vehicle variances to get the standard error $s_{\bar{r}_p}$ (Equation 2-10) and dividing the standard error by the mean emission rate to get the coefficient-of-variation of the mean c_p (Equation 2-11). We used the standard error to estimate the 95 percent confidence intervals of the mean emission rate, which are displayed in Figure 2-6 through Figure 2-23 for a subsample of the NO_X heavy-duty emission rates. For each emission rate the coefficient of variation is stored in the emissionRateByAge table.

$$s_{\bar{r}_p} = \sqrt{\frac{s^2_\text{betw}}{n_\text{j}} + \frac{s^2_\text{with}}{n_\text{tot}}} \qquad \textbf{Equation 2-10}$$

$$c_p = \frac{s_{\bar{r}_p}}{\bar{r}_p}$$ **Equation 2-11**

2.1.1.4 Hole-filling Emission Rates

The data included in the emissions analysis does not allow populating the rates for all operating modes or vehicle-type and model year combinations needed for MOVES. In this section, we discuss the "hole-filling" methodology used to fill missing operating mode bins, and missing vehicle-type and model year combinations. 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 *Hole-filling Missing Operating Modes*

Hole-filling is required for the high-power OpModes (mostly in the medium- and high-speed bins) because the test vehicle do not typically operate in those power-speed bins. For MY 2010+ criteria pollutant emissions rates, we adopted a different methodology in MOVES201X for hole-filling of OpModes where data is missing or sparse. For CO_2, for all model years, we continue to use the same methodology developed for MOVES2014.

Criteria pollutants and CO_2 rates for pre-2010 MY and CO_2 rates for MY 2010+

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, and MHD vehicles and buses exert even lower levels. As a result, data are very limited in these modes.

To estimate rates in the modes beyond the ranges of available data, we linearly extrapolated the rates from the highest operating mode in each speed range where significant data were collected for each model year group. In most cases, this mode was mode 16 for the lowest speed range, 27 or 28 for the middle speed range, and 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>50mph) 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 2-12 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.

$$Emission\ Rate_{opModeID\ 40} = Emission\ Rate_{opModeID\ 37} \times \left(\frac{STP_{opModeID\ 40}}{STP_{opModeID\ 37}}\right)$$ **Equation 2-12**

Criteria pollutants rates for MY 2010+

For MY 2010+ rates for criteria pollutants in MOVES201X, compared to the extrapolating method of MOVES2014, we combined the data in sparsely populated OpModes with the nearest sufficiently populated OpMode and applied the same rate to all higher power OpModes (within the same speed band). Thus, for example, if OpMode 27 had sufficient data, OpMode 28 had little data, and OpModes 29 and 30 had no data, we combined the rates for OpModes 27 and 28, on a time-weighted basis, and applied the calculated rate to OpModes 27-30. Figure 2-3 compares real-world measured data (showing missing OpModes), MOVES201X, and MOVES2014 methods.

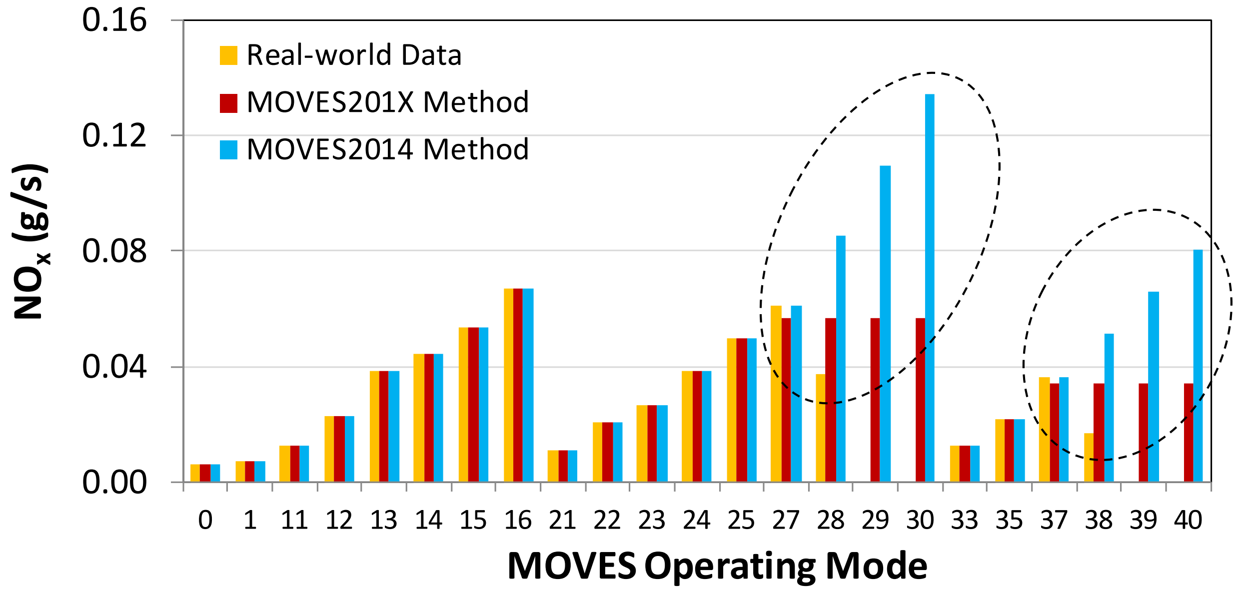


Figure 2-3. Comparison of Real-world Data and Methods for Hole-filling of High-power OpModes[b]

2.1.1.4.2 *Hole-Filling Missing Regulatory Class and Model Year Combinations*

For regulatory class/model year combinations with missing data, we proportionally adjusted from the existing emissions data using certification data or vehicle emission standards. For 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. The certification levels came from analysis conducted for MOBILE6.[29] We applied the 1988-1989 emission rates to model years 1987 and earlier.

For model year 1998, data existed for HHD trucks but not buses. In these cases, the ratio of emission rates between the Urban Bus regulatory class and HHD regulatory class from the 1999-2002 model year group was used to calculate rates for the buses by multiplying that ratio by the existing HHD emission rates for the corresponding model year group, as shown in Equation 2-13.

$$Urban\ Bus\ rates_{1998} = \frac{HHD\ rates_{1998}}{HHD\ rates_{1999-2002}} \times Urban\ Bus\ rates_{1999-2002} \qquad \textbf{Equation 2-13}$$

[b] Rates calculated from ten MY 2010-2013 combination long-haul trucks in HDIU data.

As noted in Table 2-2, the ROVER and Consent Decree Testing did not contain any data on LHD vehicles. We used MHD emission rates as surrogates for the LHD45 and LHD≤14K, because they use the same mass scaling factor, and are subject to the same emission standards as MHD vehicles. As discussed in Appendix C-3, we confirmed that the MHD rates were consistent with NO_X emission rates measured from 2003-2006 and 2007-2009 LHD trucks measured in the Heavy-Duty In-Use testing program (HDIU).

For LHD≤10K vehicles, the emission rates in 1998 were used as base rates to back-cast emission rates for 1991-1997 model years, using the ratio of emission standards between these two model years (5/4 or 1.25 percent increase in 1991-1997 vs. 1998). Table 2-8 provides a summary of the assumptions used to estimate emission rates for regulatory class-model year groups with missing data.

2.1.1.4.3 *Forecasting HHD, MHD, Urban Bus, and LHD45 and LHD≤14K Emissions*

The 2007 Heavy-Duty Rule[99] required the use of ultra-low sulfur diesel fuel, necessary for diesel engines to be equipped with diesel particulate filters in order to reach the 0.01 g/bhp-hr PM standard beginning in 2007. In addition, the 2007 Heavy-Duty Rule[99] 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 2010. Rather than phasing in the aftertreatment technology needed to meet the new standard, most manufacturers decided to meet a 1.2 g/bhp-hr standard for MY2007-2009 (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 HDIU program as discussed in Appendix C. For the NO_X emission rates within the 2007-2009 model year group for MHD, Urban Bus, LHD45 and LHD≤14K, we estimated the NO_X emission rates were 50 percent lower than the corresponding 2003-2006 emissions (proportional to the reduction in the NO_X emission standards mentioned above).

For MOVES201X, the MY 2010 and beyond emission rates for HHD, MHD, Urban Bus, and LHD45 & LHD≤14K are based on analysis of the HDIU data and production volume weighting (as described in Section 2.1.1.3.1). The rates for HHD, MHD, and the two LHD classes use data from HHD, MHD, and LHD engine family equipped vehicles, respectively. The rates for Urban Bus are the same as HHD rates because: urban buses are in the same GVWR class as HHD; some engines certified under 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. In MOVES2014 (and MOVES2010), these rates were generated by decreasing the MY2003-2006 rates by 90 percent assuming the use of SCR to meet the reduction in the emission standard from 2.4 g/bhp-hr to 0.2 g/bhp-hr. The NO_X emissions are projected to remain constant for 2010 and later vehicles for regulatory classes HHD, MHD, and Urban Buses. The LHD trucks are projected to have a further decrease in NO_X emissions through the implementation of the Tier 3 program as discussed in Section 2.1.1.4.5.

2.1.1.4.4 *Forecasting LHD≤10K Emissions*

For LHD≤10K trucks in 2007-2009, we accounted for the penetration of Lean NO_X Trap technology[c]. Cummins decided to use Lean NO_X Trap (LNT) aftertreatment starting in 2007 in engines designed to meet the 2010 standard and used 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). At regular intervals, the DPF must be regenerated 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 emission rates, because only one vehicle was tested. Rather, adjustments were made from the 2003-2006 model year group to develop emission rates for this model year group and regulatory class. During PM 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 90 percent from 2003-2006 levels. These assumptions result in an estimated NO_X reduction of 81 percent for LNT equipped trucks between 2003-2006 and 2007-2009, as shown in Equation 2-14.

$$\frac{LNT\ NOx\ emissions}{Baseline\ LHD \le 10K\ (2003-2006)\ NOx\ emissions} = (normal\ op.frequency) \times \left(\frac{LNT\ normal\ emissions}{baseline\ emissions}\right) + (DPF\ reg.frequency) \times \left(\frac{baseline\ emissions}{baseline\ emission}\right) = (0.90)\times(0.10) + (0.10)\times(1) = 0.19$$

Equation 2-14

Because we assume that LNT-equipped trucks account for about 25 percent of the LHDDT market in model years 2007-2009, we again weighted the rates for the LHD≤10K regulatory class (regClassID 40) for model years 2007 and later. For MY 2007-09, we assume that the remaining 75 percent of LHD≤10K diesel trucks will not have aftertreatment and will exhibit the 2007-2009 model year emission rates described earlier in this section. Overall, these assumptions result in a 58 percent reduction in NO_X emission rates in 2007-2009 from the MY 2003-2006 NO_X emission rates as shown in Equation 2-15.

[c] In MOVES, there is a distinction between LHD≤10K and LHD≤14K to account for STP and VSP-based operating modes. LHD≤10K includes the Lean-NOx trap assumptions. In contrast, the emission rates for LHD≤14K do not include the Lean-NOx trap assumptions.

$$\frac{2007-2009\ LHD \leq 10K\ NOx\ emissions}{2003-2006\ LHD \leq 10K\ NOx\ emissions} = (LNT\ market\ share)\left(\frac{LNT\ NOx\ emissions}{2003-2006\ LHD \leq 10K\ NOx\ emissions}\right) + (non-LNT\ market\ share)\left(\frac{2007-2009\ emission\ standerds}{2003-2006\ NOx\ emissions\ standerds}\right)$$

Equation 2-15

$$= (0.25)\times(0.19) + (0.75)\times(0.5) = 0.4225$$

For MOVES201X, the MY 2010 and beyond emission rates for LHD≤10K are based on analysis of the LHD engine family equipped vehicles in the HDIU data and production volume weighting (as described in Section 2.1.1.3.1. For LHD≤10K rates, the analysis is conducted with fixed mass factor of 2.06 rather than the 17.1 fixed mass factor used for all other HD rates (Table 1-3).

2.1.1.4.5 *Incorporation of Tier 3 Standards*

In addition to regulating light-duty vehicles, the Tier 3 vehicle emission standards[30] will affect light heavy-duty diesel vehicles, i.e., vehicles in regulatory classes LHD≤10K and LHD≤14K (regClassID = 40, 41, respectively). For these LHD diesel vehicles, reductions in emission rates attributable to the introduction of Tier 3 standards are applied only to rates for NO_X.

For HC and CO emissions, the emission rates currently in MOVES imply that current levels on the FTP cycle are substantially below the Tier 3 HC and CO standards. For example, when MOVES rates are combined to estimate a simulated FTP estimate 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. Consequently, we assumed that no additional reductions in HC and CO emissions would be realized through implementation of the Tier 3 standards on LHD diesel vehicles.
By contrast, we estimate that the Tier 3 NO_X standard will result in a reduction of emissions from diesel vehicles in regulatory classes LHD≤10K and LHD≤14K. Because emission standards tend to impact start and running emissions differently, 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 2-7.

Table 2-7. Phase-in Assumptions for Tier 3 NO_X Standards for Light Heavy-Duty Diesel Vehicles

Model Year	Phase-in fraction (%)	Reduction in Running Emission Rate (%)[a]	Reduction in Start Emission Rate (%)[a]
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:
[a] 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 LHD≤10K and LHD≤14K rates for MY2016. The ending point, representing full Tier 3 control, was model year 2022. These rates were calculated by multiplying the rates for MY2017 by a fraction of 0.3855. This fraction reflects application of the reduction fraction for running rates in MY2022 as shown in Table 2-7.

Rates in MY 2018 and later were calculated as weighted averages of the values for MY2017 and MY2022, using the same fractions applied to gasoline vehicles, as shown in Table 3-16 and Equation 3-2. Note that these calculations were applied to running rates for the LHD≤10K regulatory class (based on STP with a fixed mass factor of 2.06) and to those for the LHD≤14K regulatory class (based on STP with a fixed mass factor of 17.1). Examples of rates for selected operating modes are shown in Figure 2-4. Note that on the logarithmic scale used, the parallelism of the trends shows that the proportional reductions are identical for both regulatory classes.

In addition to tightening emission standards, the Tier 3 regulations require an increase in the regulatory useful life. An increase in the useful life is interpreted as an improvement in durability, which is expressed through a delay in deterioration effects. To express this effect, rates estimated for the 0-3 year ageGroup are replicated to the 4-5 year ageGroup, i.e., the onset of deterioration is delayed until the 6-7 year ageGroup (as shown in Figure 2-5). This effect is realized partially for model years 2018-2020 and fully in 2021.

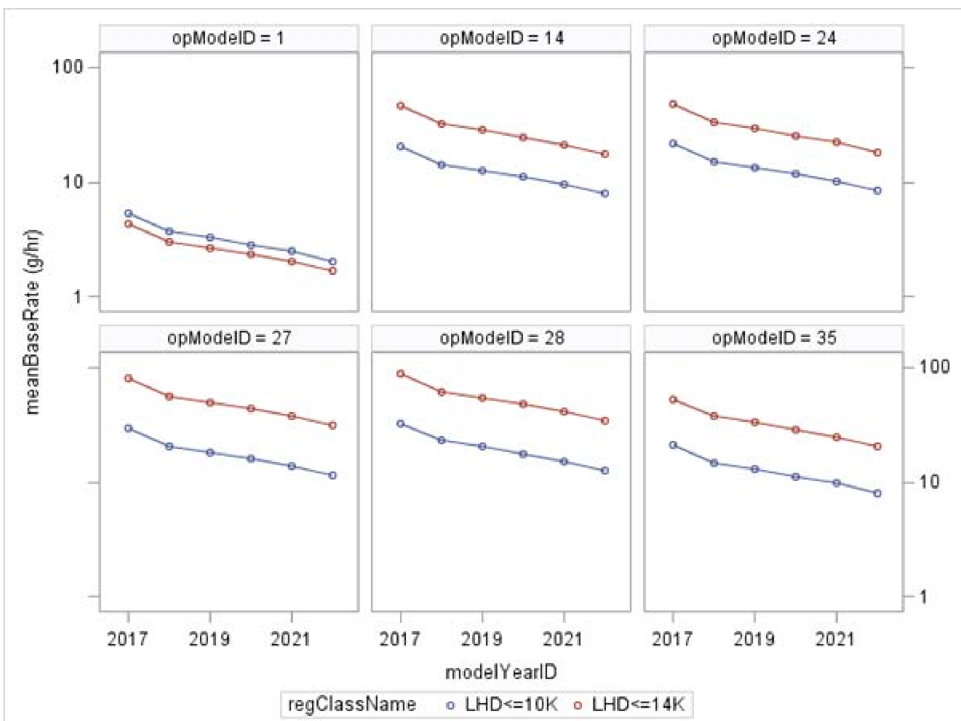


Figure 2-4. NO_X: Emission Rates for Running Exhaust Operation in Selected Operating Modes vs. Model Year, for Two Light Heavy-Duty Regulatory Classes (LOGARITHMIC SCALE)

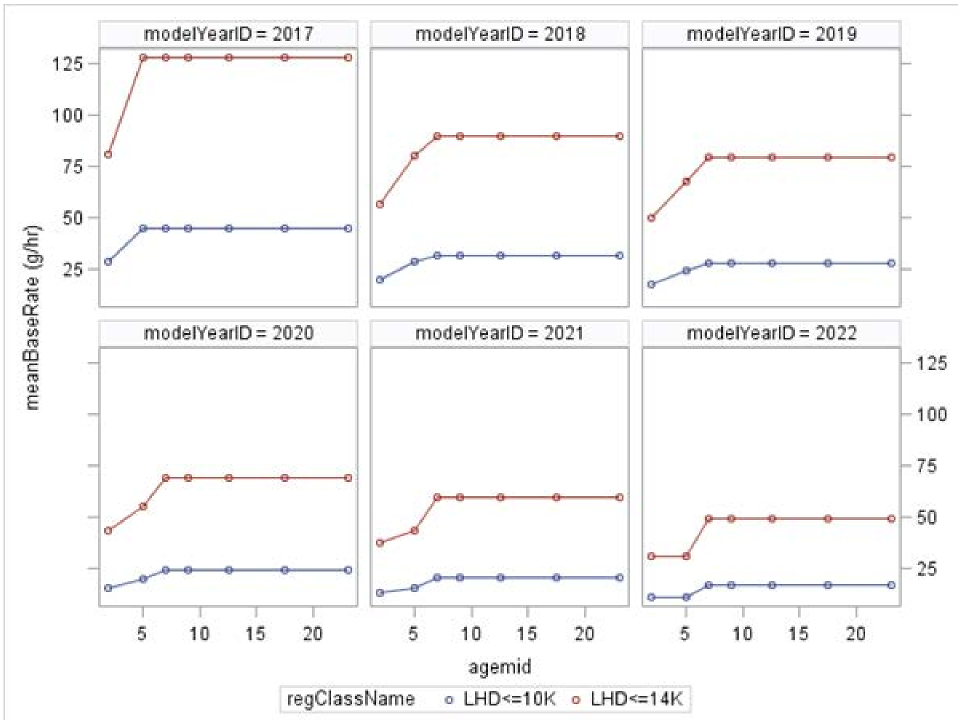


Figure 2-5. NOx: Emission Rates for Running Exhaust Operation in a Single Operating Mode (27) vs. Age, for Two Light Heavy-Duty Regulatory Classes (LINEAR SCALE)

2.1.1.5 Summary

Table 2-8 summarizes the methods used to estimate emission rates for each regulatory–class/model-year-group combination. The emission rates in MOVES are based on the analysis of ROVER, Consent Decree testing data, and HDIU data. Using the HDIU data, we updated the HHD rates for model year group 2007-2009 in MOVES2014 and updated the HHD, MHD, and LHD rates for MY 2010+ vehicles in MOVES201X. MOVES also includes the impact of the Tier 3 regulations on the LHD≤14K and LHD≤10K regulatory classes.

Table 2-8. Summary of Methods for Heavy-Duty Diesel NO_X Emission Rate Development for Each Regulatory Class and Model Year Group

Model year group	HHD	MHD	Urban Bus	LHD45 and LHD≤14K	LHD≤10K
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	Same rates as HHD	LHD ≤10K 1991-1993 rates proportioned to LHD certification levels
1991-1997	Data analysis[a,c]	Same rates as HHD	Data analysis[a]	Same rates as HHD	Proportioned to 1998 FTP standards per Table 2-1
1998	Data analysis[a,c]	Same rates as HHD	Urban Bus 1999-2002 rates proportioned using ratio of HHD 1998 rates to HHD 1999-2002 rates	Same rates as HHD	Same rates as 1999-2002
1999-2002	Data analysis[a,c]	Data analysis[a]	Data analysis[a]	Same rates as MHD	MHD engine data with 2.06 mass factor
2003-2006	Data analysis[a,c]	Data analysis[a,c]	Data analysis[a]	Same rates as MHD	Data analysis with 2.06 mass factor[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	Same rates as MHD	LNT specific reductions from the MOVES2010 2003-2006 rates, and same rates as 2003-2006 (non-LNT)[c]
2010 - 2016	Data analysis[b]	Data analysis[b]	Same as HHD	Data analysis[b]	Data analysis with 2.06 mass factor[b]
2017-2050	Same as HHD 2010-2016	Same as MHD 2010-2016	Same as Urban Bus 2010-2016	LHD45 and LHD≤14K rates for MY 2016 proportioned to Tier 3 standards	LHD≤10K rates for MY 2016 proportioned to Tier 3 standards

Notes:
[a] Analysis based on ROVER and Consent Decree testing data
[b] Analysis based on HDIU data
[c] Confirmed by HDIU and Houston Drayage data

2.1.1.6 Tampering and Mal-maintenance

Table 2-9 shows the estimated aggregate NO_X emissions increases due to Tampering and Mal-maintenance (T&M) by regulatory class and model year group. As described in Appendix B, the T&M emission increases in Table 2-9 are calculated by combining information regarding the assumed frequency rate of an equipment failure at the useful life of the engine, combined with the estimated emission impact of the equipment failure. The emission increases are reduced for ages that are below the useful life of the engine, as shown in Table B-2 (Appendix B-1), and the emission increases by age differ for the LHD, MHD, HHD and Bus regulatory classes. Thus, the aged emission rates for regulatory classes with the same zero-mile emission rates (Table 2-8) may be different due to the T&M NO_X effects (Table 2-9) and phase-in of T&M effects by age (Table B-2) that differ according to regulatory classes.

The LHD≤10K trucks have different T&M NO_X increases than LHD≤14K trucks, due to the assumed penetration of lean NO_X trap (LNT) aftertreatment which was assumed to penetrate 25 percent of LHD≤10K trucks in 2007-2009, consistent with the assumptions previously made in Section 2.1.1.4.4.

The T&M values for 2010 and later vehicles include the impact of the implementation of heavy-duty on-board diagnostics (OBD). For LHD2b/3 trucks, OBD systems were assumed to be fully implemented in MY 2010 and onward. For Class 4 through 8 trucks, (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 2-9 with the assumptions and calculations detailed in Appendix B.

Table 2-9. Fleet-average NO_X Emissions Increases in MOVES from Zero-mile Levels over the Useful Life due to Tampering and Mal-maintenance (T&M)

Model years	NO_X **increase (TM_{NOx}) for LHD≤10K trucks [%]**	NO_X **increase (TM_{NOx}) for LHD≤14K trucks [%]**	NO_X **increase (TM_{NOx}) for all other HD trucks [%]**
1994-1997	0	0	0
1998-2002	0	0	0
2003-2006	0	0	0
2007-2009	18	0	0
2010-2012	56	58	77
2013+	56	58	58

Using the assumptions included in Appendix B (Table B-4), we originally calculated small (9-14 percent) T&M NO_X emission increases for model year groups before 2010. However, we did not implement these increases in MOVES, for MY 2009 and earlier, because we assumed that NO_X increases due to T&M only occurred in engines equipped with NO_X aftertreatment technologies. This is due to a few reasons:

- The WVU MEMS data did not show an increase in NO_X emissions with odometer (and consequently, age) during or following the regulatory useful life.[31] 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.
- Manufacturers often certify zero or low deterioration factors for these engines.
- Starting with MY 2010, we expect tampering and mal-maintenance to substantially increase emissions over time compared to the zero-mile level, because these engines rely on the use of an aftertreatment emission control systems, to meet 2010 and later emission standards, and a control system failure will substantially increase emissions.

The NO_X deterioration value for SCR-equipped heavy-duty diesel vehicles in 2010-2012 is a 77 percent increase. Though 77 percent may appear to be a large increase in fleet-average emissions over time, it should be noted that the 2010 model year standard (0.2 g/bhp-hr) is about 83 percent lower than the 2009 model year effective standard (1.2 g/bhp-hr). This still yields a substantial reduction of about 71 percent from 2009 zero-mile levels to 2010 fully deteriorated levels.

2.1.1.7 Defeat Device and Low-NO_X Rebuilds

The default emission rates 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. Reflashes reduce NO_X emissions from these engines by reconfiguring certain engine calibrations, such as fuel injection timing. The MOVES database also includes a set of alternate emission rates for model years 1991 through 1998 assuming a hypothetical fully reflashed fleet.

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 calculated the ratios from the emission rates in modes 27 and 37 to that for opMode 16, for model year 1999 (the first model year with not-to-exceed emission limits). We then multiplied the MY 1999 ratios by the emission rates in 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 2-16 and Equation 2-18. 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 2-17 and Equation 2-19.

.

$$\bar{r}_{reflash,91-98,27} = \bar{r}_{91-98,16}\left(\frac{\bar{r}_{1999,27}}{\bar{r}_{1999,16}}\right)$$ **Equation 2-16**

Where: Operating modes (OM) 21-30

$$\bar{r}_{reflash,91-98,\mathrm{OM}x} = \bar{r}_{reflash,91-98,27}\left(\frac{\bar{r}_{91-98,\mathrm{OM}x}}{\bar{r}_{91-98,27}}\right)$$ **Equation 2-17**

$$\bar{r}_{reflash,91-98,37} = \bar{r}_{91-98,16}\left(\frac{\bar{r}_{1999,37}}{\bar{r}_{1999,16}}\right)$$ **Equation 2-18**

Where: Operating modes (OM) 31-40

$$\bar{r}_{reflash,MY1991-1998,OMx} = \bar{r}_{reflash,91-98,37}\left(\frac{\bar{r}_{91-98,\mathrm{OM}x}}{\bar{r}_{91-98,37}}\right)$$ **Equation 2-19**

The default emission rates were also slightly adjusted for age for the consent decree model years. An EPA assessment shows that about 20 percent of all vehicles eligible for reflash had been reflashed by the end of 2008.[32] We assumed that vehicles were receiving the reflashes after the heavy-duty diesel consent decree (post 1999/2000 calendar year) steadily, such that in 2008, about 20 percent had been reflashed. We approximated a linear increase in reflash rate from age zero.

2.1.1.8 Sample results

The charts in this sub-section show examples of the emission rates that resulted from the analysis of the data described in Section 2.1.1.1. Not all rates are shown; the intention is to illustrate the most common trends and hole-filling results.

Figure 2-6 through Figure 2-8 show that NO_X emission rates increase with STP for HHD trucks. Figure 2-9 adds the MHD and Urban Bus regulatory classes, with the error bars removed for clarity. As expected, the emissions increase with power, with the lowest emissions occurring in the idling/coasting/braking bins.

The highest operating modes in each speed range will rarely be attained due to the power limitations of heavy-duty vehicles, but are included in the figures (and in MOVES) for completeness. Nearly all of the 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. In some model year groups, the MHD and HHD classes use the same rates, based on lack of significant differences between those two classes' emission rates.

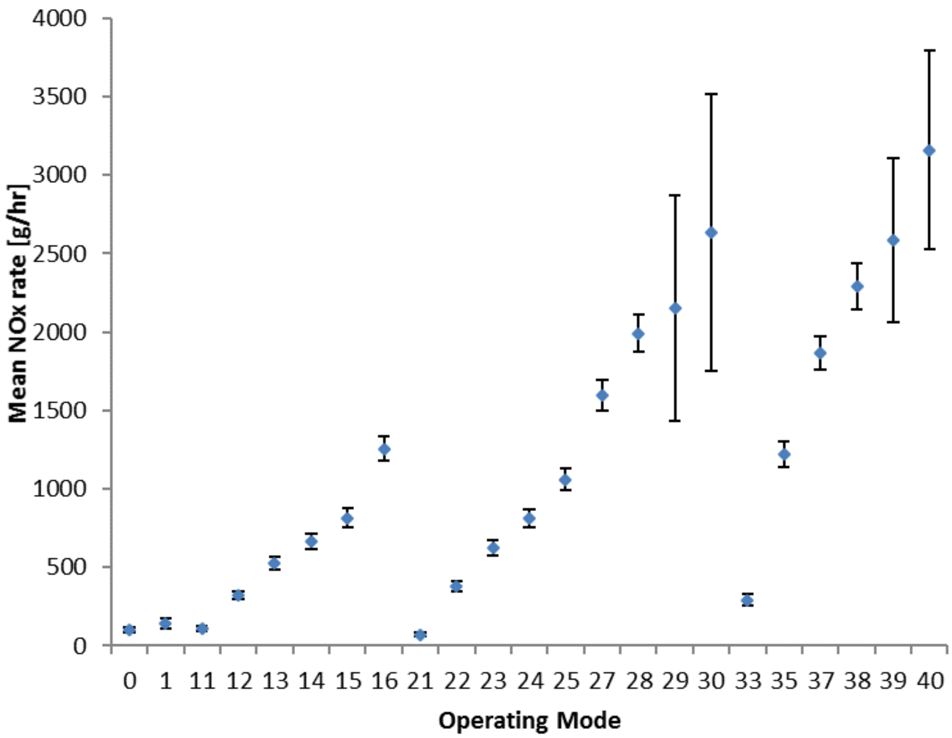


Figure 2-6. Trends in NO_X Emissions by operating mode from HHD trucks for model year 2002. Error bars represent the 95 percent confidence interval of the mean

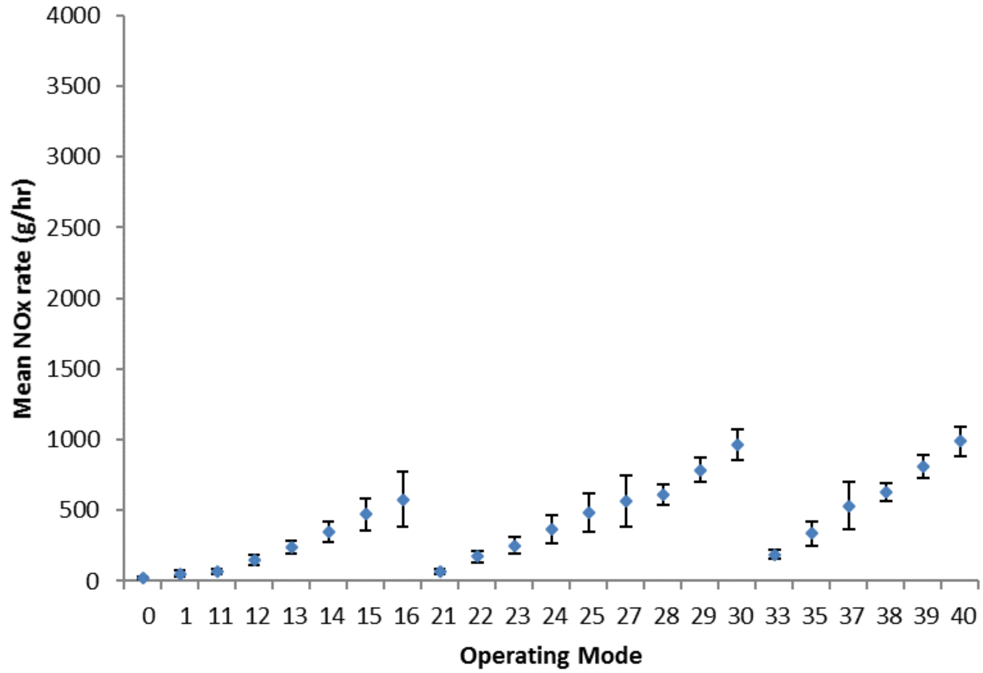


Figure 2-7. Trends in NO_X Emissions by operating mode from HHD trucks for model year 2007. Error bars represent the 95 percent confidence interval of the mean

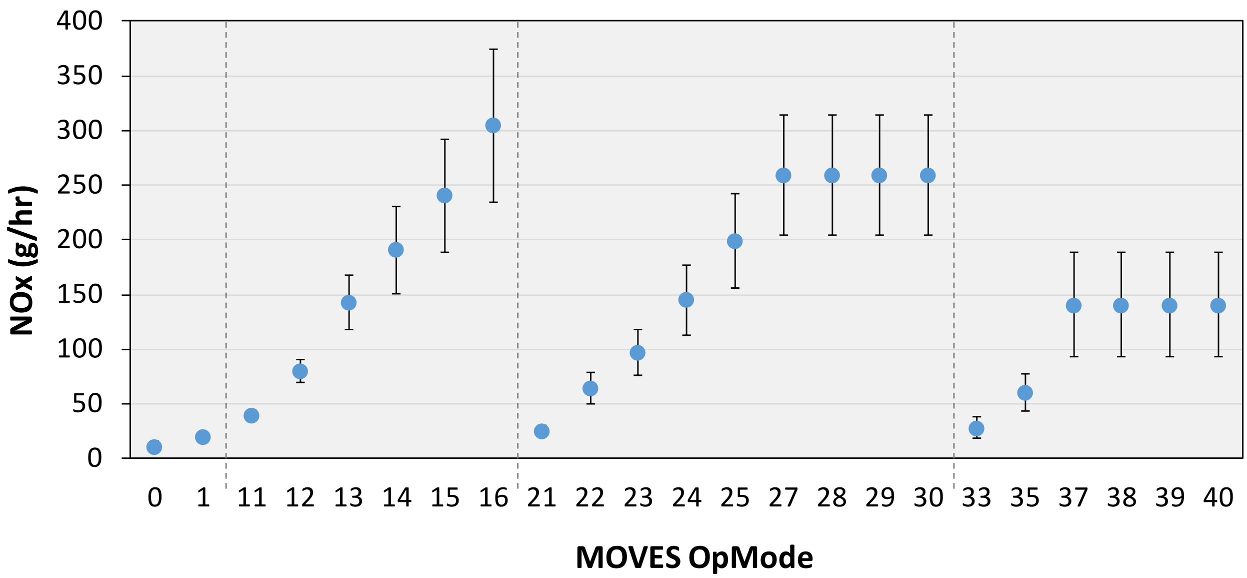


Figure 2-8 Trends in NO_X Emissions by operating mode from HHD trucks for model year 2013. Error bars represent the 95 percent confidence interval of the mean

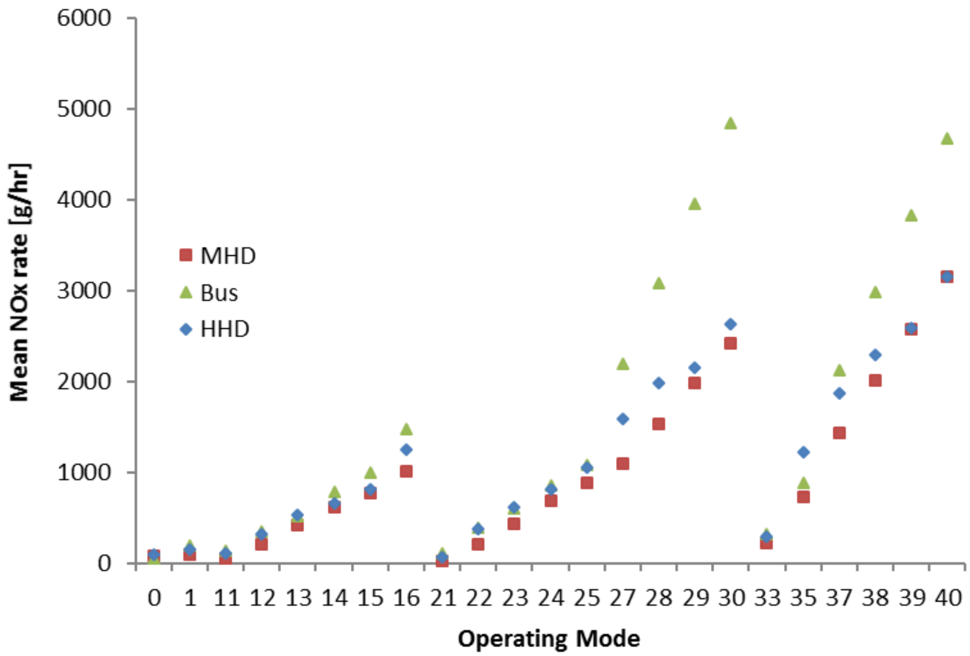


Figure 2-9. Trends in NO_X emissions by operating mode from LHD≤14K, LHD45, MHD, HHD, and bus regulatory classes for model year 2002. LHD≤14K, LHD45, and MHD have the same NO_X zero-mile NO_X emission rates

The effects of model year, representing a rough surrogate for technology or standards, can be seen in Figure 2-10, which shows decreasing NO_X rates by model year group for a sample operating mode (opModeID 24) for HHD trucks. Other regulatory classes show similar trends. The rates in this chart were derived with a combination of data analysis (model years 1991 through 2009) and hole-filling. The trends in the data are expected, since the model year groups were formed on the basis of NO_X standards. Increasingly stringent emissions standards have caused NO_X emissions to decrease significantly.

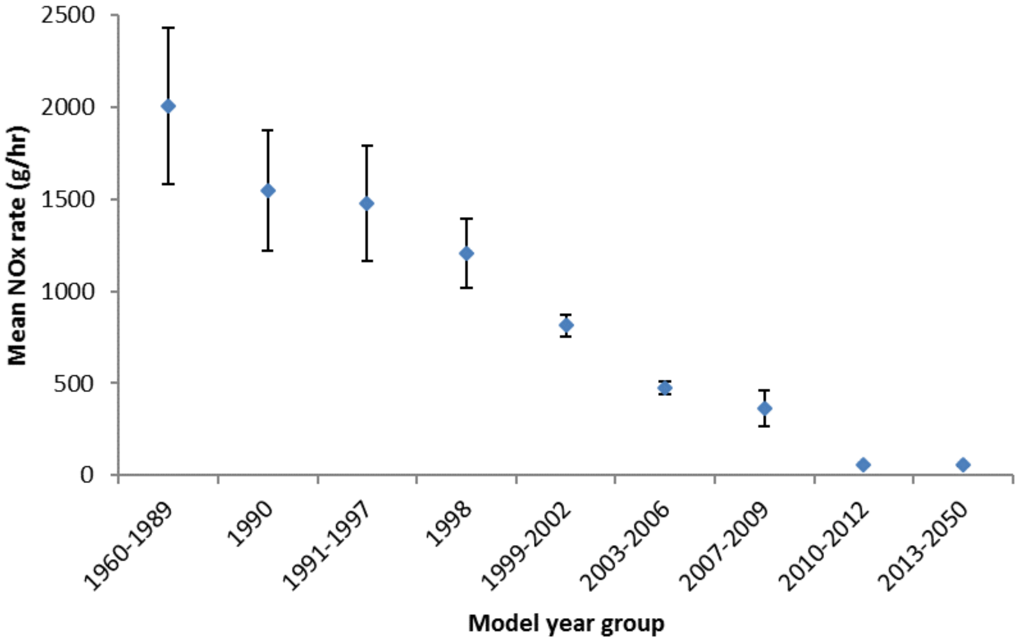


Figure 2-10. Trends in NO_X by model year for HHD trucks in operating mode 24. Error bars represent the 95 percent confidence interval of the mean

Age effects were implemented for aftertreatment-equipped trucks only (mostly model year 2010 and later) based on an analysis of tampering and mal-maintenance effects. Due to faster mileage accumulation, the heavy heavy-duty trucks reach their maximum emission at the youngest ages, as shown in Figure 2-11. Standard Errors (based on coefficients-of-variation for means) from previous model year groups were used to estimate uncertainties for MY 2010.

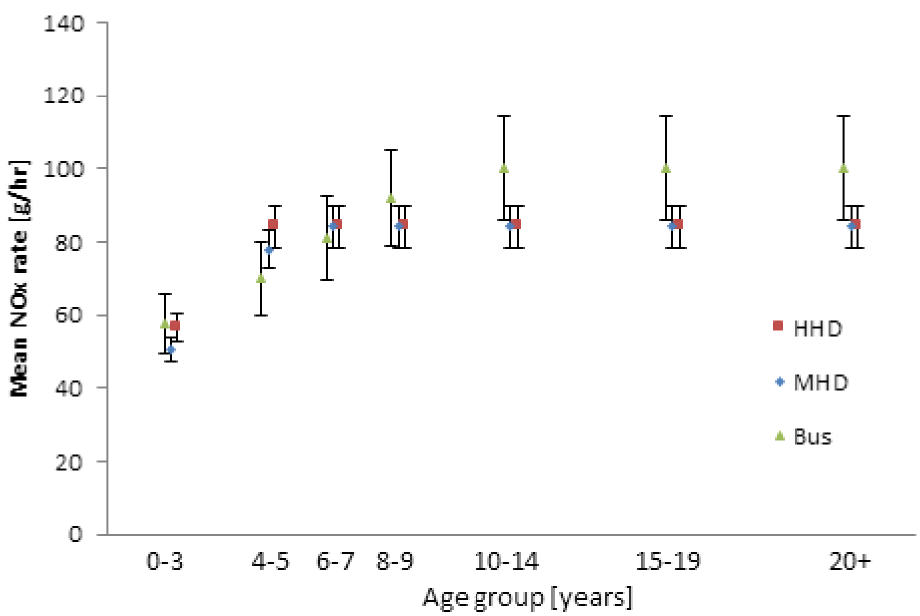


Figure 2-11. Modeled NO_X trends by age for model year 2010 for operating mode 24 for MHD, HHD, and Urban Bus regulatory classes. Error bars represent the 95 percent confidence interval of the mean

Figure 2-12 and Figure 2-13 show the mean emission rates for LHD≤ 10K trucks for model years 2003-2006 and 2007-2009, respectively. The estimated uncertainties are greater than for the other heavy-duty regulatory classes, since there were fewer vehicles in our test data. As described previously, model years 2007-2009 vehicles include vehicles with LNTs (with NO_X increases during PM regeneration) and vehicles without any aftertreatment.

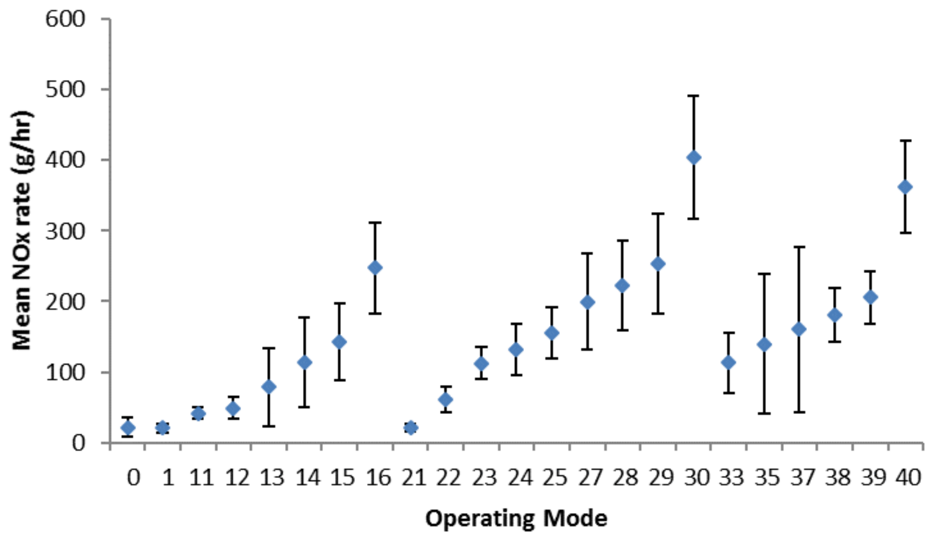


Figure 2-12. Mean NO_X rates by operating mode for model years 2003-2006 LHD≤10K (regClassID 40) trucks age 0-3. Error bars represent the 95 percent confidence interval of the mean

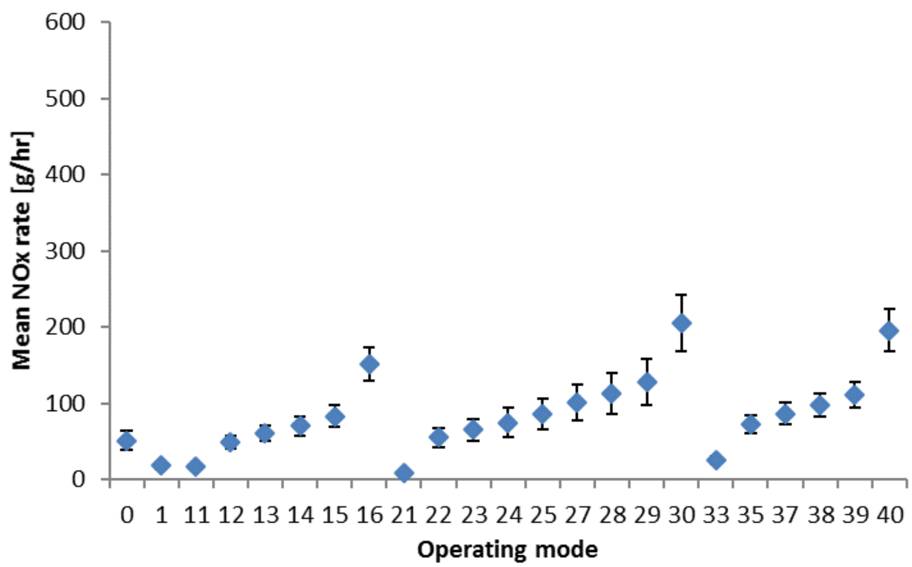


Figure 2-13. Mean NO_X rates by operating mode for model years 2007-2009 LHD≤10K (regClassID 40) trucks age 0-3. Error bars represent the 95 percent confidence interval of the mean

2.1.2 Particulate Matter (PM)

In this section, particulate matter refers to particles emitted from heavy-duty engines which have a mean diameter less than 2.5 microns, known as $PM_{2.5}$. Conventional diesel particulate matter is primarily carbonaceous, measured as elemental carbon (EC) and organic carbon (OC). Particles also contain a complex mixture of metals, elements, and other ions, including sulfate.

Measurements of total $PM_{2.5}$ emission rates are typically filter-based, including the mass of all the chemical components in the particle-phase. As described above for NO_X, the heavy-duty diesel PM emission rates in MOVES are a function of: (1) source bin, (2) operating mode, and (3) age group. We classified heavy-duty 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. Table 2-10 shows the model year group ranges and the applicable brake-specific emissions standards.

Table 2-10. 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+	0.01

2.1.2.1 Data Sources

All of the data used to develop the MOVES $PM_{2.5}$ emission rates was generated in the CRC E-55/59 research program.[33] The following description by Dr. Ying Hsu and Maureen Mullen of E. H. Pechan, in the "*Compilation of Diesel Emissions Speciation Data – Final Report*"[34] 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 data used in the analysis. Vehicles counts are provided by number of vehicles, number of tests, model year group, and regulatory class (46 = MHD, 47=HHD) in Table 2-11.

Table 2-11. 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 +	0	0
HHD	1960 - 1987	31	6
	1988 - 1990	7	2
	1991 - 1993	14	2
	1994 - 1997	22	5
	1998 - 2006	171	18
	2007 +	0	0

Counts of tests are provided by test cycle in Table 2-12.

Table 2-12. 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

2.1.2.2 Analysis

The $PM_{2.5}$ data from CRC E55/59 was analyzed in several steps to obtain MOVES PM2.5 emission rates. First, STP operating mode bins were calculated from the chassis dynamometer data. 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. These steps are explained in detail in the following subsections.

2.1.2.2.1 Calculate STP in 1-hz data

For each second of operation on the chassis-dynamometer the instantaneous scaled tractive power (STP_t) was calculated using Equation 1-2, 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[35] as determined through previous analyses for EPA's Physical Emission Rate Estimator (PERE). 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 1-2.

Note that this approach differs from the NO_X emission rates analysis described in Section 2.1.1.2, 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.

2.1.2.2.2 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 (out of a total of 75) 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 2-13 provides vehicle and test counts by vehicle class and model year. The HDD Class 6 and Class 7 trucks were combined in the table because there were only seven HDD Class 6 vehicles in the study.

Table 2-13. 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). Equation 2-20 shows the normalization process for a particular one second TEOM measurement.

$$PM_{\text{normalized},\,i,\,j} = \frac{PM_{\text{filter},\,j}}{\sum^{j} PM_{\text{TEOM},\,i}} PM_{\text{TEOM},\,j,\,i} \qquad \textbf{Equation 2-20}$$

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 j,

$PM_{normalized,i,j}$ = an estimated continuous emission result ($PM_{2.5}$) emission result on vehicle j at second i.

Kinsey et al. (2006) [36] demonstrated that time-integrated TEOM measurements compare well with gravimetric filter measurements of diesel-generated particulate matter.

2.1.2.2.3 Compute Average Normalized TEOM measures by MOVES Bin

After normalization, the data were classified into the 23 operating modes by regulatory class, model-year group. Mean average results, sample sizes and standard deviation statistics for $PM_{2.5}$ emission values were computed in terms of g/hour for each 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 $PM_{2.5}$. In cases of insufficient data for particular modes, a regression technique was utilized to impute missing values.

2.1.2.2.4 Missing operating modes

Detailed in Appendix D, a log-linear regression was performed on the existing PM 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.

2.1.2.2.5 Other Regulatory Classes

The TEOM data was only available in quantity for MHD and HHD classes. There were no data available for the LHD or bus classes. The Urban Bus (regulatory class 48) emission rates were proportioned to HHD rates according to differences in the PM standards. Because the certification standards in terms of brake horsepower-hour (bhp-hr) are the same for all of the heavy-duty engines, the emission rate of LHD≤14K and LHD45 is assumed to be equivalent to the MHD emission rate.

The emission rates of LHD≤ 10K (regClassID 40) need to be based on an f_{scale} of 2.06 as discussed in Section 1.3. The PM emission rates for LHD≤10K are based on the VSP-based MHD PM emission factors derived from the E55/59 TEOM data. We use the VSP-based emission rates, because the operating modes are defined according to the mass of each vehicle, which is compatible with the f_{scale} of 2.06, which is the average source mass of light-duty trucks.[d] To estimate the LHD≤10K, we multiplied the MHD PM emission rates by a factor of 0.46 obtained from the MOBILE6.2 heavy-duty conversion factors[37], which accounts for the lower power requirements per mile (bhp-hr/mile) of light heavy-duty trucks versus MHD trucks. Equation 2-21 used to derive the PM emission rates for regulatory class LHD≤10K (regClassID 40) is shown below:

$$LHD \leq 10K\ emission\ rate = 0.46\ \times MHD\ (VSP\_based) emission\ rate$$ **Equation 2-21**

Where the MHD VSP-based emission rate is obtained from MOVES2009.[38]

[d] The current MHD emission rates in MOVEX201X are STP-based, with an f_{scale} of 17.1.

Urban Bus (regClassID 48) emission rates are assumed to be either the same as the HHD emission rates, or for some selected model year groups, to be a ratio of the EPA certification standards. Table 2-14 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 standards are equal to the HHD emission rates multiplied by the ratio in emission standards. In addition, the Urban Bus emissions have different emission deterioration effects as discussed in Appendix B-1.

Table 2-14. Urban Bus PM Standards in Comparison to Heavy-Duty Highway Compression Engine Standards

Engine Model Year	Heavy-Duty Highway Compression-Ignition Engines	Urban Buses	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.

2.1.2.2.6 Model year 2007 and later trucks (with diesel particulate filters)

EPA heavy-duty diesel emission regulations were made considerably more stringent for total $PM_{2.5}$ emissions starting in model year 2007. Ignoring phase-ins and banking and trading issues, the basic emission standard fell from 0.1 g/bhp-hr to 0.01 g/bhp-hr. This increase by a factor of ten in the level of regulatory stringency required the use of particulate trap systems on heavy-duty diesels. As a result, the emission performance of diesel vehicles has changed dramatically.

At the time of analysis, no continuous PM emissions data were available for analysis on the 2007 and later model-year vehicles. However, heavy and medium heavy-duty diesel $PM_{2.5}$ data are available from the EPA engine certification program on model years 2003 through 2007. These data provide a snapshot of new engine emission performance before and after the introduction of particulate trap technology in 2007. The existence of these data makes it possible to determine the relative improvement in PM emissions from model years 2003 through 2006 to model year 2007. This same relative improvement can then be applied to the existing, modal based, 1998-2006 model year PM emission rates to estimate in-use rates for 2007 and later vehicles.

An analysis of the available certification data is shown in Table 2-15 below. It suggests that the actual ratio of improvement due to the particulate trap is reduction of 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 ‘margin of safety’ 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.[39]

Table 2-15. Average Certification Results for Model Years 2003-2007

Certification Model Year	Mean (g/bhp-hr)[a]	St. Dev.	*n*
2003	0.08369	0.01385	91
2004	0.08783	0.01301	59
2005	0.08543	0.01440	60
2006	0.08530	0.01374	60
2007	0.00308	0.00228	21

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

2.1.2.2.7 Tampering and Mal-maintenance

The MOVES model contains assumptions for the frequency and emissions effect of tampering and mal-maintenance on heavy-duty diesel trucks and buses. The assumption of tampering and mal-maintenance (T&M) of heavy-duty diesel vehicles is a departure from the MOBILE6.2 model which assumed such vehicles operated from build to final scrappage at a design emission level which was lower than the prevailing EPA emission standards. Both long term anecdotal data sources and more comprehensive studies now suggest that the assumption of no natural deterioration and/or no deliberate tampering of emission control components in the heavy-duty diesel fleet was likely an unrealistic assumption, particularly with the transition to emission aftertreatment devices with the 2007/2010 standards.

The primary data set was collected during a limited calendar year period, yet MOVES requires data from a complete range of model year/age combinations. As a result, the T&M factors shown below in Table 2-16 were used to forecast or back-cast the basic PM emission rates to predict model year group and age group combinations not covered by the primary data set. 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 ageGroups 0-3, 4-5, 6-7, etc. As a result, unless we assume that the higher emission rates which are were measured on the older model year vehicles have always prevailed – even when they were young, a modeling approach such as T&M must be employed. Likewise, more recent model years could only be tested at younger ages. The T&M methodology used in the MOVES analysis allows for the filling of age and model year group combinations for which no data is available.

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 some 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 this model year group of vehicles, the base emission rates start at low levels, and represent vehicles that are virtually free from T&M.

We followed the same tampering and mal-maintenance methodology and analysis for PM as we did for NO_X, as described in Appendix B-8. The overall MOVES tampering and mal-maintenance effects on PM emissions over the fleet's useful life are shown in Table 2-16. The value of 89 percent for 2010-2012 model years reflects the projected effect of heavy-duty on-board diagnostic deterrence/early repair of Tampering and Mal-maintenance 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 tampering and mal-maintenance emission effects.

Table 2-16. Estimated Increases in PM Emissions Attributed to Tampering and Mal-maintenance over the Useful Life of Heavy-Duty Vehicles

Model Year Group	Percent increase in PM due to T&M
Pre-1998	85
1998 - 2002	74
2003 – 2006	48
2007 – 2009	100
2010 – 2012	89
2013+	67

2.1.2.2.8 Computation of Elemental Carbon and Non-Elemental Carbon Emission Factors

Particulate matter from conventional diesel engines is dominantly composed of elemental carbon emissions. Elemental carbon emissions are often uses synonymously with soot and black carbon emissions. Black carbon is important because of its negative-health effects and to its environmental impacts as a climate forcer.[40] 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 available 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 2-22.

$$\boldsymbol{PM_{2.5} = EC + NonECPM} \qquad \textbf{Equation 2-22}$$

By having emission rates for EC and nonECPM for each operating mode, the MOVES design permits the 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 generally the same within each emission processes.

For pre-2007 diesel trucks, we developed EC and nonECPM emission rates by applying EC/PM ratios 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 operation 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.[41]

For 2007 and later model year DPF-equipped diesel engines, we used the elemental carbon fraction of 9.98 percent measured in Phase 1 of the Advanced Collaborative Emissions Study (ACES) Report.[42] 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 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).

The nonECPM fraction of emissions contains organic carbon (OC), sulfate, and other trace elements and ions. MOVES uses the fuel sulfur content to adjust the sulfate emission contribution to NonECPM as discussed in the MOVES Fuel Adjustment Report.[43] MOVES uses speciation profiles to estimate the composition of organic carbon, ions, and elements in NonECPM as discussed in the MOVES PM Speciation Report.[41]

2.1.2.3 Sample results

Figure 2-24 and Figure 2-25 show the trend of increasing PM rates with STP. 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, but are included in the figures for completeness. At high speeds (greater than 50 mph; operating modes ≥ 30), the overall PM rates are lower than the other speed ranges. For pre-2007 model years, the PM rates are dominated by EC (except for the idle operating mode, opModeID 1). With the introduction of DPFs in model year 2007, we model the large reductions in overall PM rates and the smaller relative EC contribution to PM emissions.

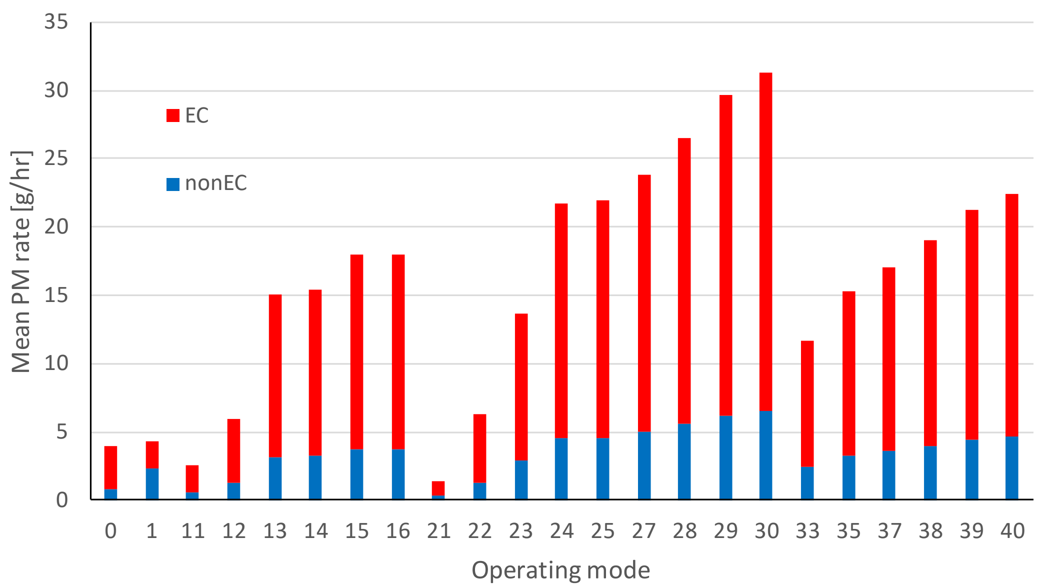


Figure 2-14. Particulate Matter Rates by Operating Mode Representing Medium Heavy-Duty Vehicles (model year 2006 at age 0-3 years)

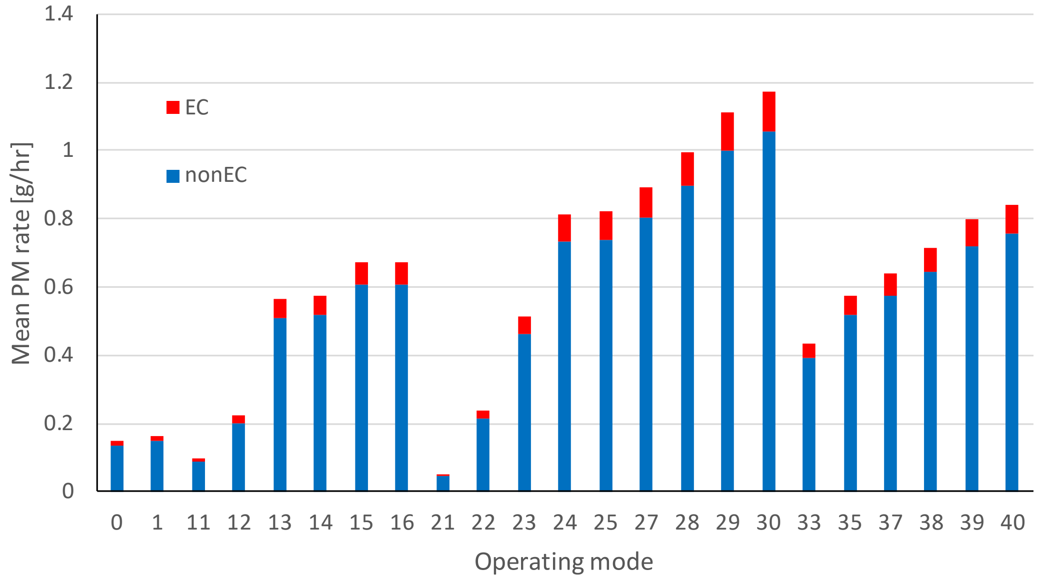


Figure 2-15. Particulate Matter Rates by Operating Mode for Medium Heavy-Duty Vehicles (model year 2007 at age 0-3 years)

Figure 2-26 shows an example of how tampering and mal-maintenance estimates increase PM with age. The EC/PM proportion does not change by age, but the overall rate increases and levels off after the end of useful life. The rate at which emissions increase toward their maximum depends on regulatory class.

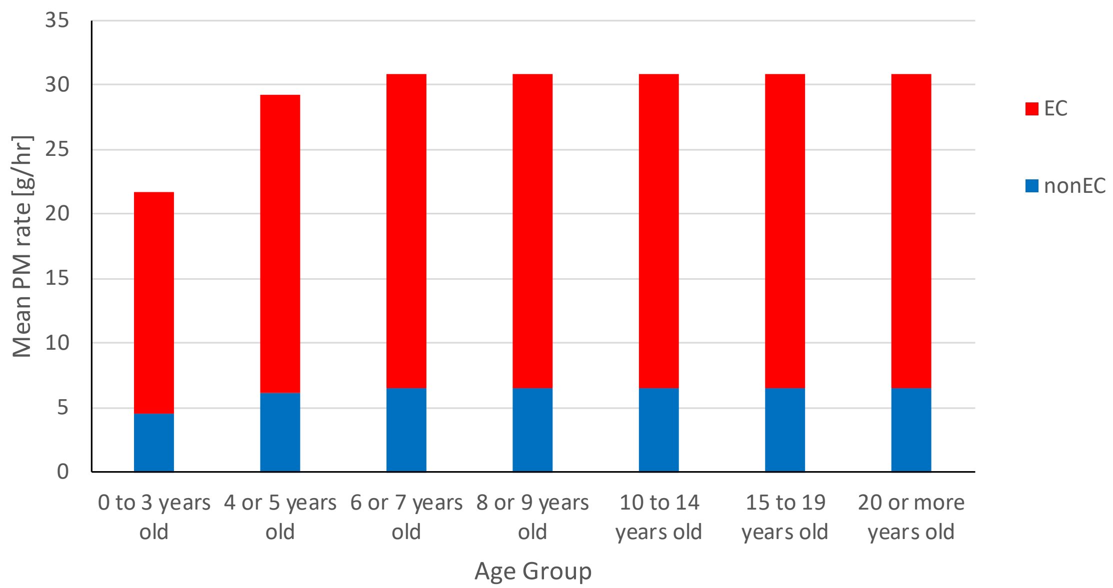


Figure 2-16. Particulate Matter Rates by Age Group for Medium Heavy-Duty Vehicles (model year 2006, operating mode 24)

Figure 2-27 shows the effect of model year on emission rates from a single operating mode (opModeID 24) from medium heavy-duty truck in MOVES. Emissions generally decrease with new PM standards, however there is variability within each operating mode. The EC fraction stays constant until model year 2007, when it is reduced to less than ~10 percent due the implementation of diesel particle filters. The overall PM level is substantially lower starting in model year 2007. The emission rates shown here for earlier model years are an extrapolation of the T&M analysis since young-age engines from early model years could not be tested in the E-55 program.

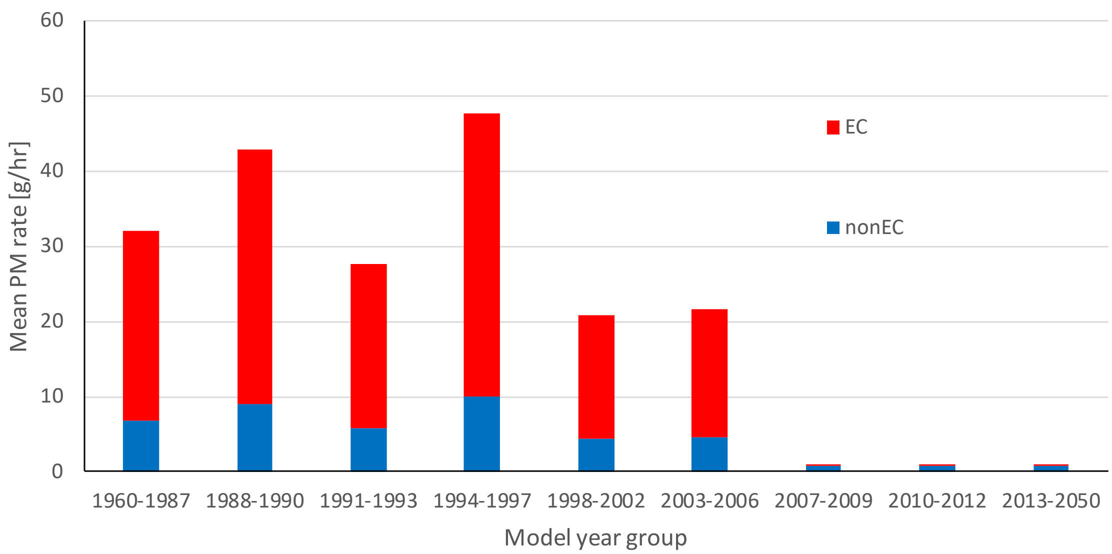


Figure 2-17. Particulate Matter Rates for Medium Heavy-Duty Vehicles by Model Year Group (age 0-3 years, operating mode 24)

2.1.3 Hydrocarbons (HC) and Carbon Monoxide (CO)

Diesel engines account for a substantial portion of the mobile source HC and CO emission inventories. Regulations on non-methane hydrocarbons (NMHC), sometimes in conjunction with NO_X, combined with the common use of diesel oxidation catalysts have yielded reductions in both HC and CO emissions from later model year heavy-duty diesel engines. As a result, data collection efforts do not focus on HC or CO from heavy-duty engines. In this report, hydrocarbons are sometimes referred to as total hydrocarbons (THC).

We used certification levels combined with emissions standards to develop appropriate model year groups. Since standards did not change frequently in the past for either HC or CO, we created fewer model year groups than we did from NO_X and PM. The HC/CO model year groups are:

- 1960-1989
- 1990-2006
- 2007-2009
- 2010+

2.1.3.1 Data Sources

Pre-2010 base rates

The heavy-duty diesel HC and CO emission rate development followed a methodology that resembles the light-duty methodology, 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[33]: 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)[44]:** 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)[45]:** 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 onroad data used for the NO_X analysis was not used since HC 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 HC and CO data sources consistent, we used chassis test programs exclusively for the analysis of these two pollutants. Time-series alignment was performed using a method similar to that used for light-duty chassis test data.

2010 and beyond base rates

We used the HDIU data set, using the same vehicles as used for NO_X and described in Section 2.1.1.1. Past concerns regarding the quality of HC or CO measurements are not applicable here since the HDIU measurements are made using instruments that conform to the requirements described in 40 CFR Part 1065.

The numbers of vehicles in the data sets are shown in Table 2-17.

Table 2-17. 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						
2010+	HHD, MHD, LHD, BUS	See "HDIU 2010+" row in Table 2-2. All vehicles for MY 2010+ are in the 0-3 age group.						

2.1.3.2 Analysis

Pre-2010 base rates

Similar to the analysis done for PM, for each second of operation on the chassis-dynamometer, the instantaneous scaled tractive power (STP_t) was calculated using Equation 1-2, and then 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[5] that were used in the PM analysis.

Using a method similar to that used in the NO_X and PM analysis, we averaged emissions by vehicle and operating mode. We then averaged across all vehicles by model year group, age group, and operating mode. Estimates of uncertainty for each mean rate were calculated using the same equations and methods described in Section 2.1.1.3.3. In populating the emission rates in MOVES, we used the age group that was most prevalent in each regulatory class and model year group combination. These age groups are shown in Table 2-18. We used the MHD to represent the LHD45 and LHD≤14K emission rates.[e]

2010 and beyond base rates

We followed the analysis methodology used for MY 2010+ NO_X rates. The methodology is described in Sections 2.1.1.2 (calculation of STP and assignment of operating modes), 2.1.1.3.1 (calculation of mean emission rates), and 2.1.1.4.1 (hole-filling missing operating modes).

[e] MOVES2010 had LHD45 and LHD2b3 emission rates estimated from the data with a fixed mass factor of 2.06. In MOVES2014, we applied the MHD emission rates to the LHD45 and LHD≤14K, so they would have emission rates based on the fixed mass factor of 17.1.

Table 2-18. Age Groups for which Emission Rates are Populated Directly Based on the Data

Regulatory class	Model year group	Age group
HHD	1960-2002	0-3
HHD	2003-2006	0-3
MHD	1960-2002	15-19
LHD ≤ 10K	1960-2002	0-3
BUS	1960-2002	0-3
HHD, MHD, LHD, BUS	2010+	0-3

Effect of Tampering and Mal-maintenance

We then applied tampering and mal-maintenance effects through that age point, either lowering emissions for younger ages or raising them for older ages, using the methodology described in Appendix B. We applied the same tampering and mal-maintenance effects for CO as HC, which are shown in Table 2-19.

Table 2-19. Tampering and Mal-maintenance Effects for HC and CO over the Useful Life

Model years	Increase in HC and CO Emissions (%)
Pre-2003	300
2003 – 2006	150
2007 – 2009	150
2010 – 2012	29
2013+	22

We multiplied these increases by the T&M adjustment factors from the zero-mile emissions level due to deterioration in Table B-2 in Appendix B-1 to get the emissions by age group. While LHD≤14K and LHD45 and MHD vehicles share the same fully deteriorated emission rates for HC and CO, they deteriorate differently as they age. Table B-2 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 did not analyze emissions data for 2007-2009 heavy-duty trucks. 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 HC and CO starting with model year 2007. The derivation of the T&M effects for 2007 and later trucks presented in Table 2-19 are discussed in Appendix B-9.

2.1.3.3 Sample results

The charts in this sub-section show examples of the emission rates that are derived from the analysis described above. Not all rates are shown; the intent is to illustrate the most common trends and hole-filling results. For simplicity, the light heavy-duty regulatory classes are not shown, but since the medium heavy-duty data were used for much of the light heavy-duty emission rate development, the light heavy-duty rates follow similar trends. Uncertainties were calculated as for NO_X.

In Figure 2-28 through Figure 2-31, we see that HC and CO mean emission rates increase with STP, though there is much higher uncertainty than for the NO_X rates. This pattern could be due to the smaller data set or may truly reflect a less direct correlation between HC, CO and STP. In these figures, the data for HHD and bus classes were combined to generate one set of rates for HHD and buses. Figure 2-29 and Figure 2-31 show the rates for MY 2010 and beyond, generated using the hole-filling method described in Section 2.1.1.4.1 for high power operating modes in medium speed (OpModes 28-30) and high speed (OpModes 38-40).

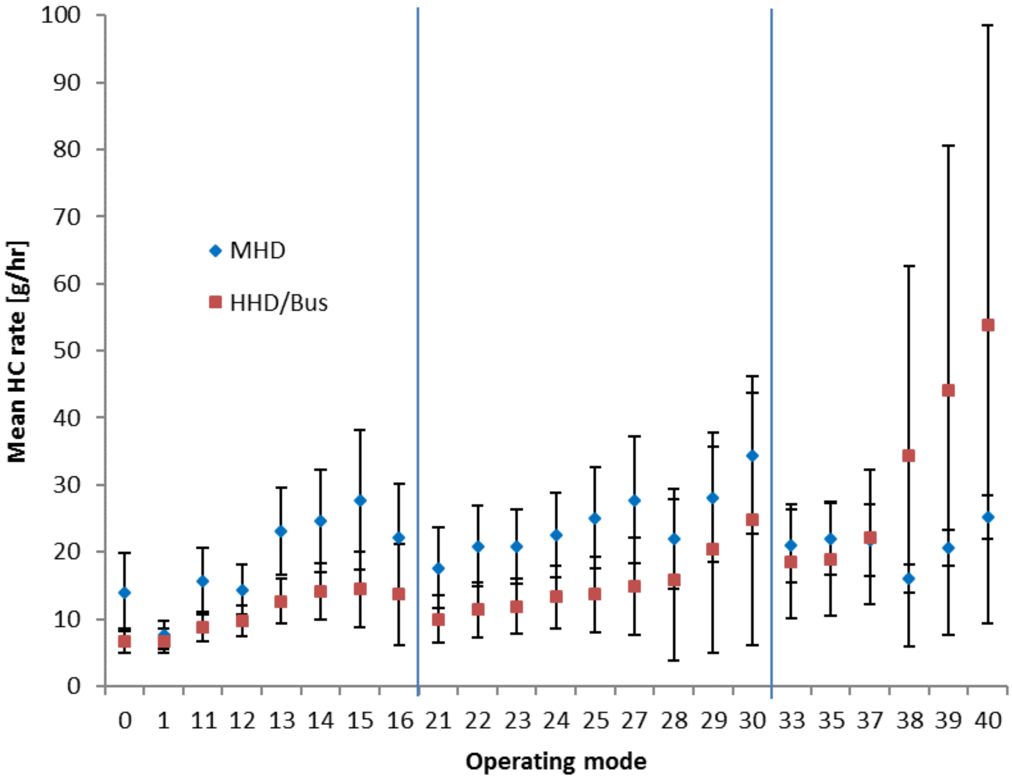


Figure 2-18. THC Emission Rates [g/hr] by Operating Mode for Model Year 2002 and Age Group 0-3. Error Bars Represent the 95 Percent Confidence Interval of the Mean

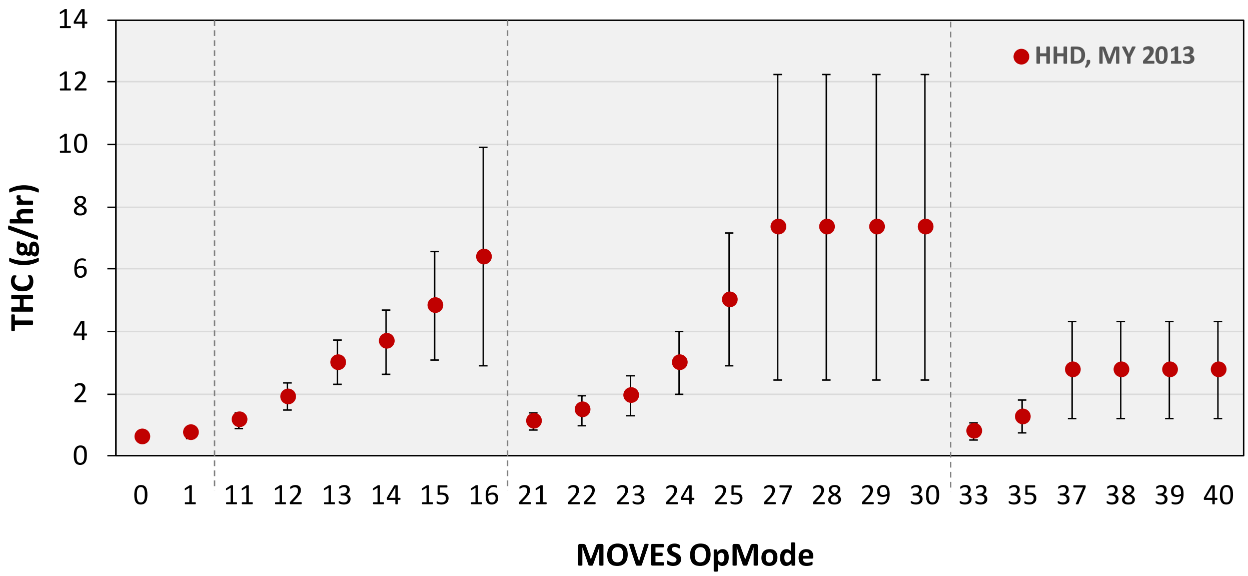


Figure 2-19. THC Emission Rates [g/hr] by Operating Mode for HHD, Model Year 2013, and Age Group 0-3. Error Bars Represent the 95 Percent Confidence Interval of the Mean

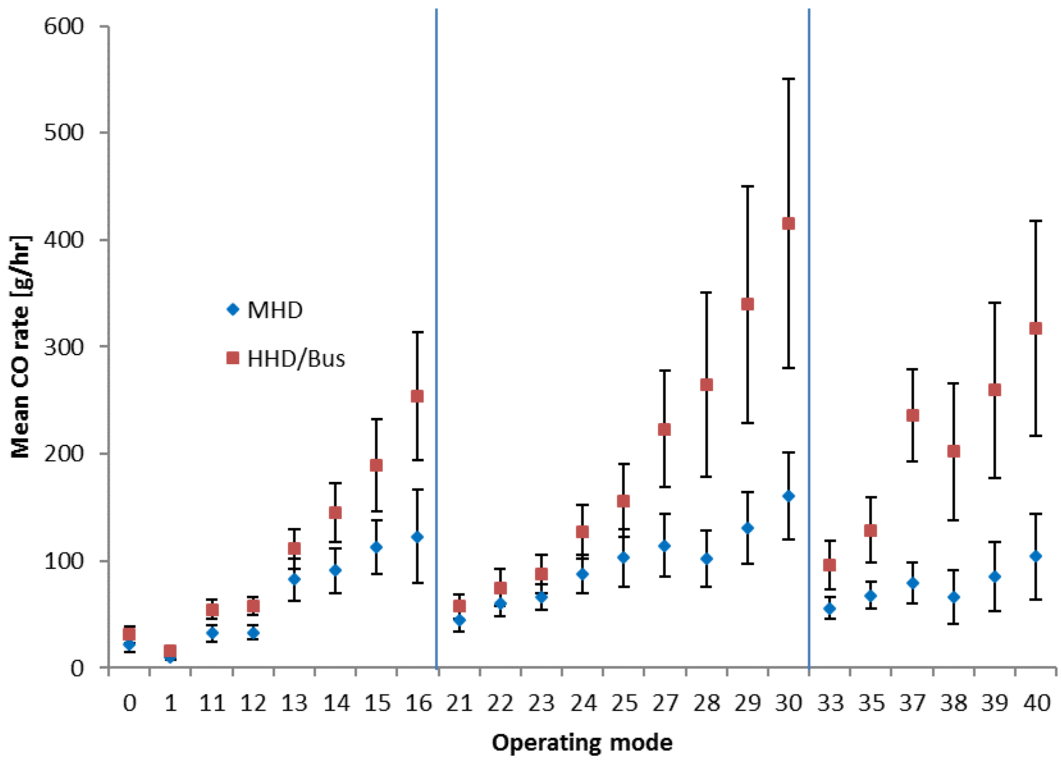


Figure 2-20. CO Emission Rates [g/hr] by Operating Mode for Model Year 2002 and Age Group 0-3. Error Bars Represent the 95 Percent Confidence Interval of the Mean

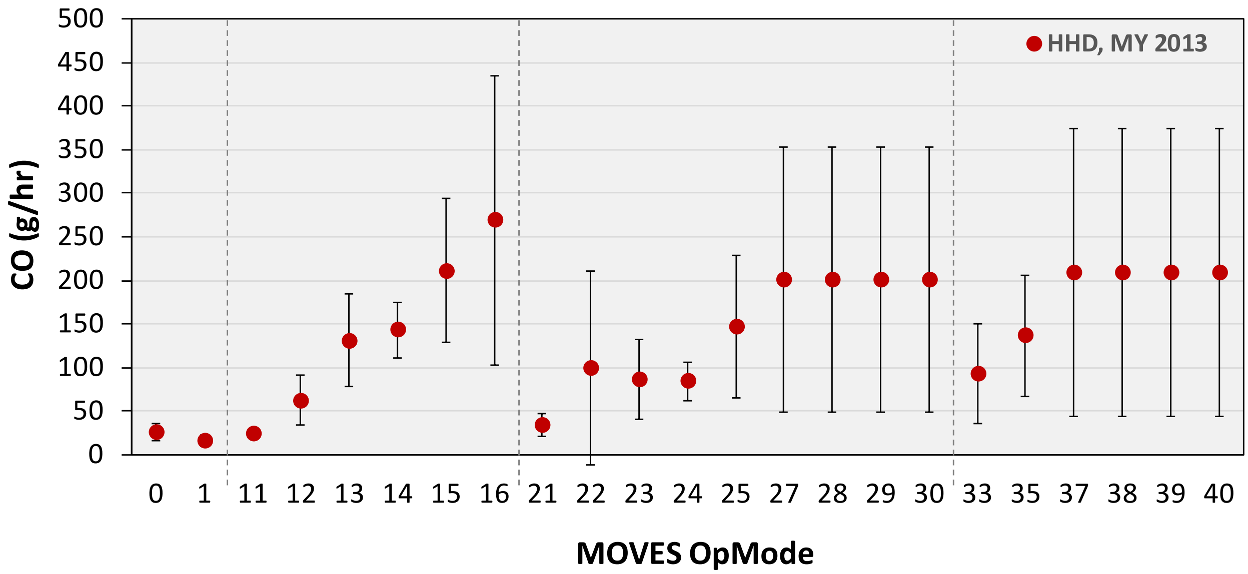


Figure 2-21. CO Emission Rates [g/hr] by Operating Mode for HHD, Model Year 2013, and Age Group 0-3. Error Bars Represent the 95 Percent Confidence Interval of the Mean

Figure 2-32 and Figure 2-33 show HC and CO emission rates by age group. 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 the model, especially in model years where diesel oxidation catalysts are most prevalent (2007 and later).

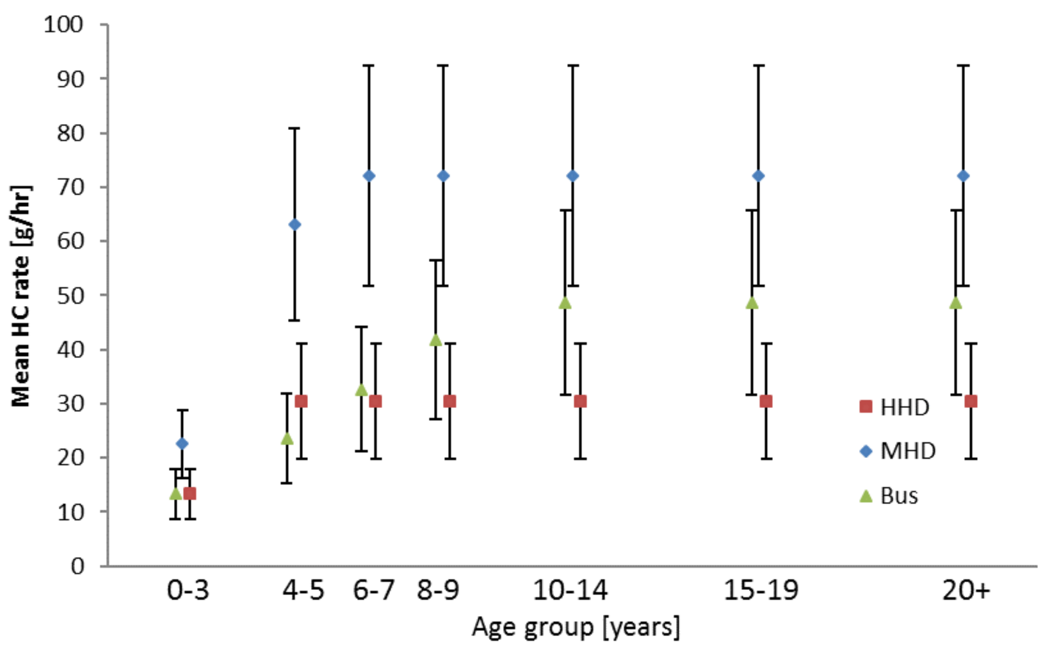


Figure 2-22. THC Emission Rates [g/hr] by Age Group for Model Year 2002 and Operating Mode 24. Error Bars Represent the 95 Percent Confidence Interval of the Mean

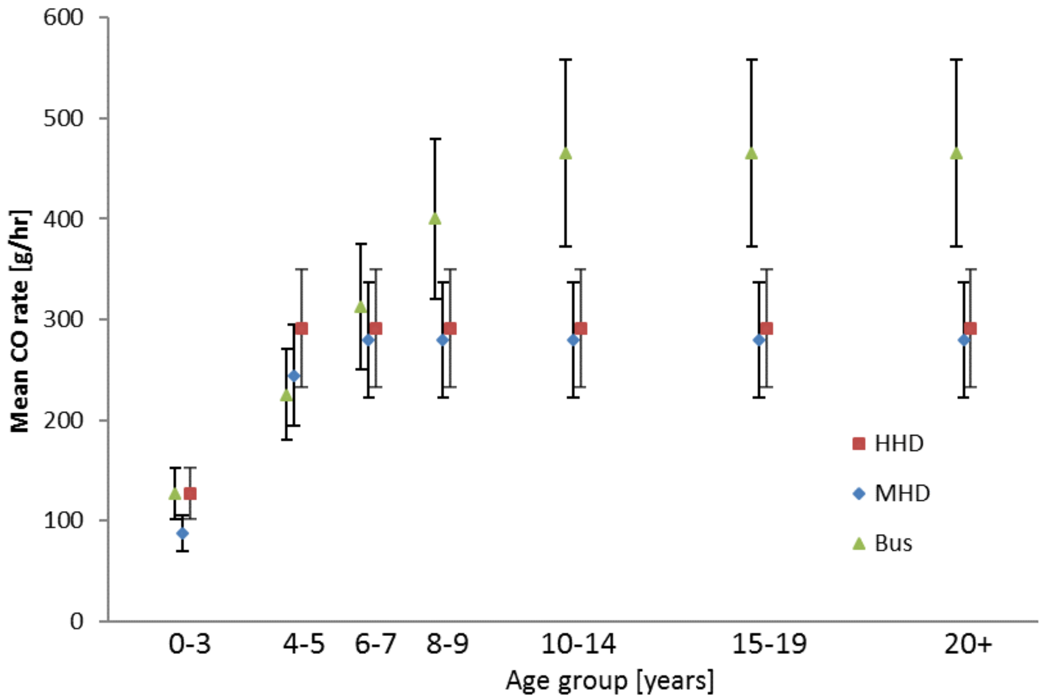


Figure 2-23. CO Emission Rates [g/hr] by Age Group for Model Year 2002 and Operating Mode 24. Error Bars Represent the 95 Percent Confidence Interval of the Mean

Figure 2-34 and Figure 2-35 show sample HC and CO emission rates by model year group for OpModeID 24. For MY 2003–2006, we only analyzed data from vehicles within the HHD regulatory class and thus, the zero-mile emission rates derived for HHD regulatory class are used as the basis for the zero-mile emission rates for the other HD regulatory classes. The MY 2007–2009 emission rates reflect the use of diesel oxidation catalysts and are derived by reducing the CO and HC emissions in MY 2003-2006 by 80 percent and applying the model-year and regulatory class specific T&M adjustment factors. For MY 2010–2050, compared to MY 2007–2009, THC rates are similar while CO rates are considerably higher for HHD.

Due to the sparseness of the data and the fact that HC and CO emissions do not correlate as well with STP (or power) as NO_X and PM do, uncertainties are much greater.

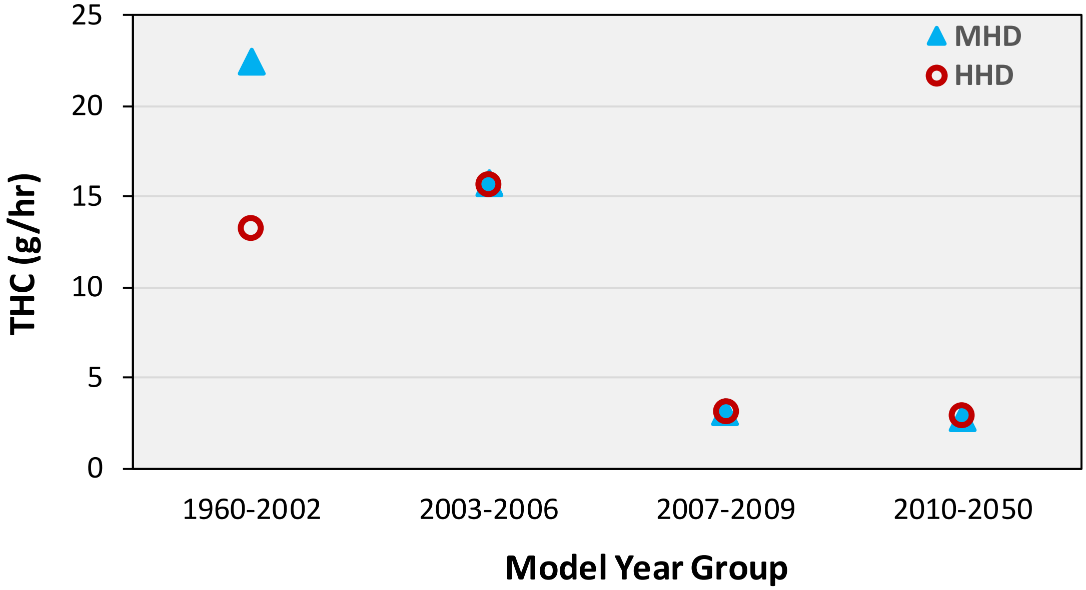


Figure 2-24. THC Emission Rates by Model Year Group for Operating Mode 24 and Age Group 0-3

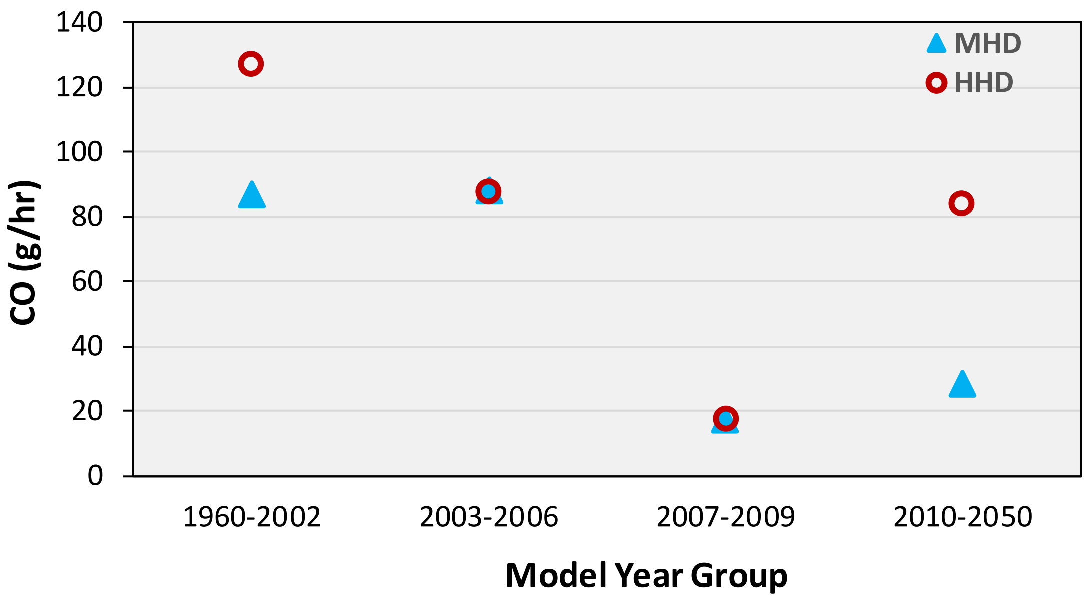


Figure 2-25. CO Emission Rates by Model Year Group for Operating Mode 24 and Age Group 0-3

2.1.4 Energy

2.1.4.1 LHD≤10K Energy Rates for Model Years 1960-2013

In MOVES201X, the energy rates for LHD≤10K for pre-2013 diesel vehicles are unchanged from MOVES2014. The energy rates for this regulatory class, along with the light-duty regulatory classes (regClassIDs 20 and 30), were consolidated across weight classes and engine technologies, as discussed in the MOVES2010 energy updates report.[46] The energy rates were also simplified to be single energy rates for regulatory class, fuel type and model year combinations by weighting across engine size, engine technology, and vehicle weight according to the default population in the MOVES2010 sample vehicle population table. Because this approach uses highly detailed data, coupled with information on the vehicle fleet that varies for each model year, variability was introduced into the aggregated energy rates used in MOVES201X. The average of the emission rates (weighted equally across each operating mode) for these model years are shown in Figure 2-37. We displayed the average trend, because during 1960-2013, the trend of emission rates across model year differs among each operating mode. Although not entirely shown in Figure 2-37, the emission rates from 1960-1982 are constant.

2.1.4.2 LHD≤14K, LHD45, MHD, Urban Bus, and HHD Energy Rates for Model Years 1960-2013

The data used to develop NO_X rates was also used to develop running-exhaust energy rates for most of the heavy-duty source types. 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 2.1.1.2 and 2.1.1.3); 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 2-23), 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[47] for diesel fuel.

$$\bar{r}_{energy} = \bar{r}_{CO_2} \frac{HV}{f_{CO_2}} \qquad \textbf{Equation 2-23}$$

The energy rates for these heavy-duty diesel vehicle classes are shown in Figure 2-36. 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 mean energy rate.

OpMode-based energy consumption rates are the same across regClassIDs 41 through 48. However, the distribution of time spent in the OpModes will vary between these regulatory classes based on differences in their activity and tractive power demand. Thus, the aggregated energy rates (e.g., KJ/mile) calculated by MOVES will differ by regulatory class.

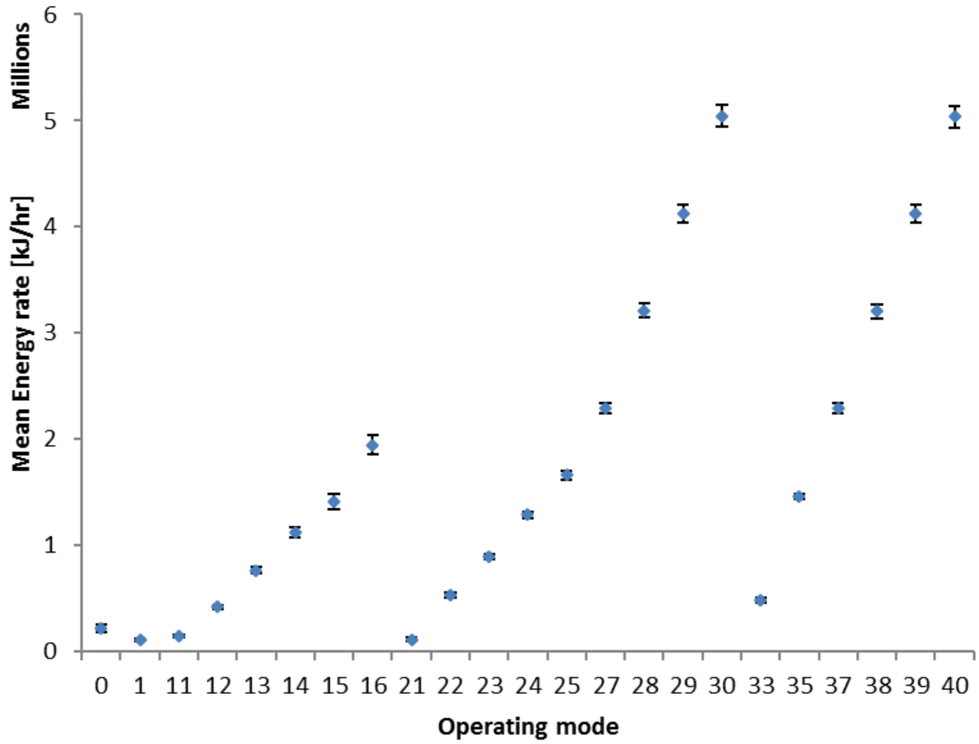


Figure 2-26. Diesel running exhaust energy rates for LHD≤14K, LHD45, MHD, HHD, and Urban Buses for 1960-2013 model years. Error bars represent the 95 percent confidence interval of the mean

2.1.4.3 LHD≤10K, LHD≤14K, LHD45, MHD, Urban Bus, and HHD Energy Rates for Model Years 2014-2050

The energy rates for 2014 through 2018 model years reflect the impact of the Medium- and Heavy-Duty Greenhouse Gas (GHG) Phase 1 Rule.**Error! Bookmark not defined.** The heavy-duty greenhouse gas program begins with 2014 model year and increases in stringency through 2018. MOVES201X also includes an update for the Medium and Heavy-Duty GHG Phase 2 rule.[48] The Phase 2 program begins in 2018 model year for trailers and in 2021 for the other categories, while phasing 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 in MOVES)
- Heavy-duty pickups and vans (3/4 and 1 ton trucks and vans)
- Vocational trucks (buses, refuse trucks, motorhomes, single-unit trucks)

The programs set separate standards for engines and vehicles and ensures improvements in both. It also sets separate standards for fuel consumption, CO_2, N_2O, CH_4 and HFCs.[f]

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

In MOVES, the improved fuel consumption from the HD GHG Rules is implemented in two ways. First, the running, start, and extended idle rates for total energy consumption are reduced. Second, the truck weights and road load coefficients are updated to reflect the lower vehicle weights, lower resistance tires, and improved aerodynamics of the vehicle chassis. The discussion of the vehicle weights and road load coefficients is included in the Population and Activity Report.[5]

The revised running, start, and extended idle rates for total energy consumption are drawn from the HD GHG rulemaking modeling.[48,49] The estimated reductions for heavy-duty diesel vehicles from the HD GHG Phase 1 rule, for running, start, and extended idle rates, are shown in Table 2-20. These reductions are generally for the 2014 through 2020 model years, and reflect the improvements expected from improved energy efficiency in the powertrain. The reductions from the baseline, representing MY 2013, were applied to the appropriate regulatory classes and model years in the MOVES emissionRate table.

Table 2-20 Estimated Reductions in Diesel Engine Energy Consumption Rates from the HD GHG Phase 1 Program

GVWR Class	Fuel	Model Years	Reduction from MY 2013 Energy Rates
HHD (8a-8b)	Diesel	2014-2016	3%
		2017	6%
LHD(4-5) and MHD (6-7)	Diesel	2014-2016	5%
		2017-2020	9%

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 (Class 7 and 8 trucks in regClassID 46 and 47) under the default MOVES framework, it was necessary to create a new EmissionRateAdjustment table with sourceTypeID as another primary key. The EmissionRateAdjustment table enabled MOVES to model the final standards for vocational vehicles and tractor-trailers simultaneously. The EmissionRateAdjustment table includes the following data fields, many shared with the EmissionRate table:

- polProcessID (primary key)
- sourceTypeID (primary key)
- regClassID (primary key)
- fuelTypeID (primary key)
- beginModelYearID (primary key)
- endModelYearID (primary key)
- emissionRateAdjustment
- dataSourceID

Table 2-21 includes the energy rate reductions stored in the EmissionRateAdjustment table which are applied to the running rates in MOVES201X for MY 2020 and later heavy-duty diesel vehicles.

Table 2-21: Estimated Reductions in Diesel Engine Energy Consumption Rates due to the HD GHG Phase 2 Program

Vehicle Type	Fuel	Model years	Reduction from MY 2017 Energy Rates
Long-haul Tractor-Trailers	Diesel	2018-2020	1.0%
		2021-2023	7.9%
		2024-2026	12.4%
		2027+	16.3%
Short-haul Tractor-Trailers	Diesel	2018-2020	0.6%
		2021-2023	7.4%
		2024-2026	11.9%
		2027+	15.0%
Vocational	Diesel & CNG	2021-2023	7.8%
		2024-2026	12.3%
		2027+	16.0%
Urban Buses	Diesel & CNG	2021-2023	7.0%
		2024-2026	11.8%
		2027+	14.4%

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. Table 2-22 describes the expected changes in CO_2 emissions due to improved engine and vehicle technologies due to the HD GHG Phase 1 program. Similarly, Table 2-23 shows the projected improvements in CO_2 emissions due to the HD GHG Phase 2 program. Since nearly all HD pickup trucks and vans will be certified on a chassis dynamometer, the CO_2 reductions for these vehicles are not separated by engine and road load reduction components, but represented as total vehicle CO_2 reductions. 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. The energy consumption rates for LHD≤10K and LHD≤14K were lowered by the percentages shown in Table 2-22 and Table 2-23 for the corresponding model years.

Table 2-22 Estimated Total Vehicle Reductions in Energy Consumption Rates for HD Diesel and Gasoline Pickup Trucks and Vans due to the HD GHG Phase 1 Program

GVWR class	Fuel	Model years	Reduction from MY 2013 Energy Rates
LHD 2b-3	Gasoline	2014	1.5%
		2015	2%
		2016	4%
		2017	6%
		2018-2020	10%
	Diesel	2014	2.3%
		2015	3%
		2016	6%
		2017	9%
		2018-2020	15%

Table 2-23 Estimated Total Vehicle Reductions in Energy Consumption Rates for HD Diesel and Gasoline Pickup Trucks and Vans due to the HD GHG Phase 2 Program

GVWR class	Fuel	Model years	Reduction from MY 2020 Emission Rates
LHD 2b-3	Gasoline and Diesel	2021	2.50%
		2022	4.94%
		2023	7.31%
		2024	9.63%
		2025	11.89%
		2026	14.09%
		2027+	16.24%

Figure 2-37 displays the average energy consumption (across all running operating modes) for LHD≤10K diesel vehicles across model years 1970 through 2030. The rates show the impact of the Phase 1 and 2 Medium and Heavy- Duty Greenhouse Gas Rules. After the phase-in of the Phase 2 rule, the energy rates are constant going forward from 2027 to 2060.

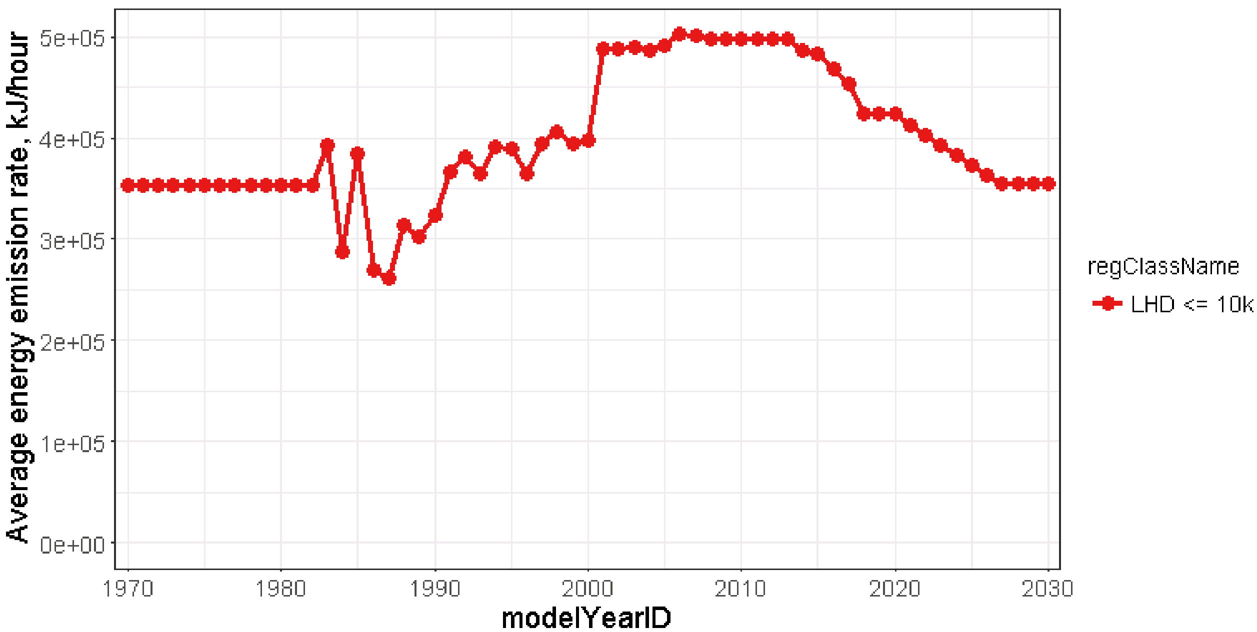


Figure 2-27. Average Energy Consumption Rates for LHD≤10K diesel vehicles across all running operating modes[g]

Figure 2-38 displays the relative reductions in energy consumption for all heavy-duty vehicles from Phase 1 and Phase 2 rules. Energy rates for regClassID 40 are identical for MY 1960-2013. Similarly, regClassIDs 41 through 48 (which are grouped together) have identical energy rates for MY 1960-2013. For MY 2013 (which is the baseline for Phase 1 reductions), the average energy rate across all running OpModes is 498,357 kJ/hr and 1,804,140 kJ/hr for regClassID 40 and regClassIDs 41–48, respectively. Thus, while the Phase 1 relative reductions for regClassIDs 40 and 41 are the same for MY 2014-2017, their absolute energy rates and reductions are different since they start with different energy rates in MY 2013. In Phase 1, regClassID 47 and 48 are treated as same. In Phase 2, regClassID 47 and 48 are separated and regClassID 47 is further separated in to vocational (“voc”), tractor-trailer short-haul (“short-haul”) and tractor-trailer long-haul (“long-haul”). A somewhat similar separation occurs for regClassIDs 42 and 46. The energy rates for a given vehicle type are constant from MY 2027 and beyond.

[g] Note, this figure displays a straight average across all operating modes, and thus emphasizes the energy used in the operating modes with highest energy consumption. At run time MOVES actually computes emissions based on an operating mode distribution determined by VMT allocation by roadtype and speed as well as sourcetype mass. See the MOVES Vehicle Population and Activity report[5] for more information on operating mode distributions.[h] Problems in testing caused that data from only one of the APU systems could be used. Additionally, the PM composition measurements (EC/PM fraction) was collected on tests with errors in the exhaust flow measurement issues. The PM emission rates were determined invalid for these tests, and the measurements were excluded and repeated, but the PM composition measurements from these tests were considered valid, and were not repeated.

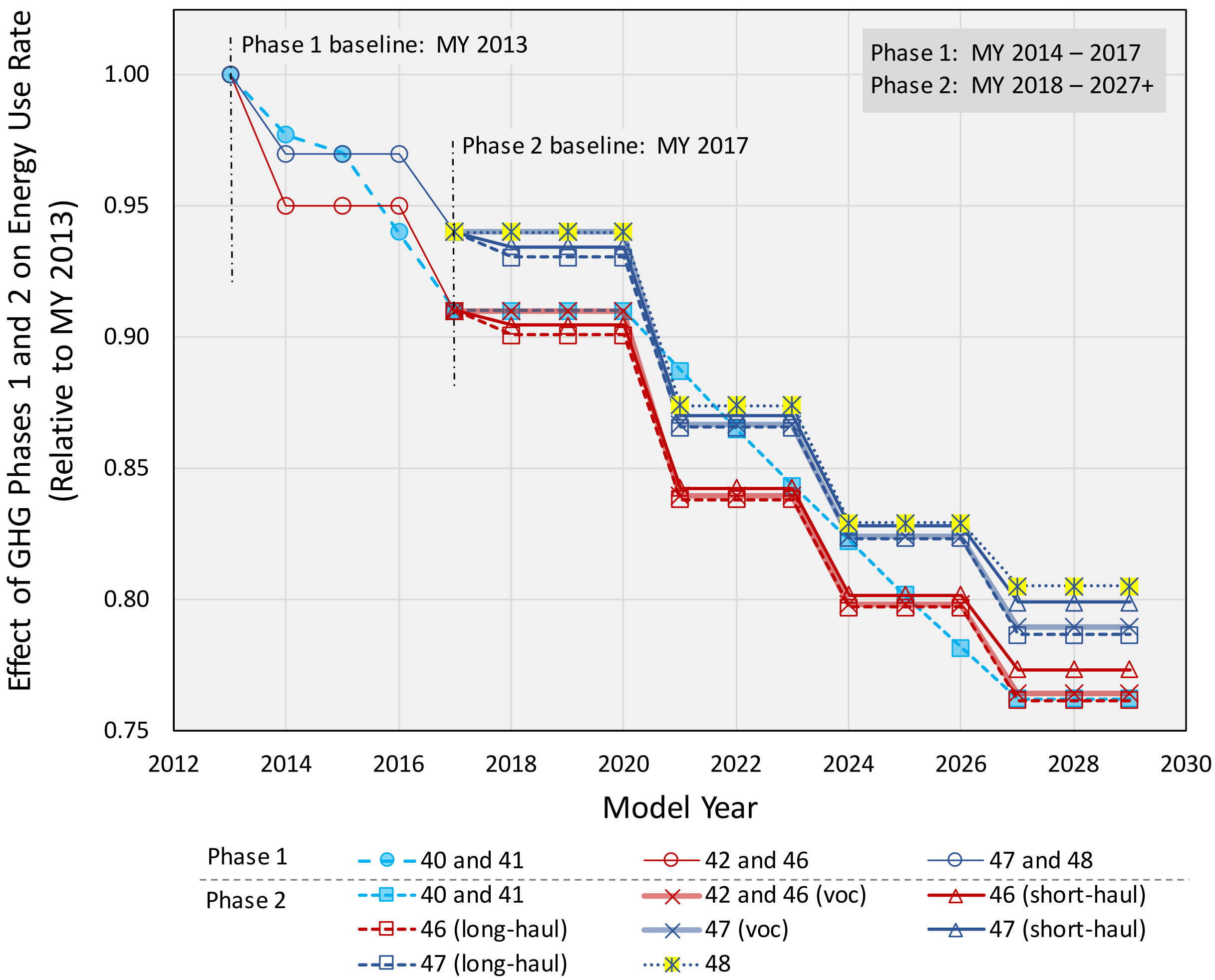


Figure 2-28. HD GHG Phase 1 and Phase 2 rule reductions in energy consumption rates for LHD≤10K (40), LHD≤14K (41), LHD45 (42), MHD (46), HHD (47), and Urban Bus (48) diesel vehicles

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. That is, we use the difference in emissions between a test cycle with a cold start and the same test cycle with a hot start. We define eight intermediate 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 emission rate document[9]. The impact of ambient temperature on cold starts is discussed in the Emission Adjustments MOVES report[50].

2.2.1 ***HC, CO, and NO_X***

The pre-2010 model year emission are discussed in Section 2.2.1.1 and 2010+ model year emission rates are discussed in Sections 2.2.1.2 and 2.2.1.3.

2.2.1.1 Pre-2010 Model Year

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 the same dynamometer cycle, except that Bag 1 starts with a cold start, and Bag 3 begins with a hot start. A similar approach was applied for LHD vehicles tested on the FTP and ST01 cycles, which also have separate bags containing 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 HC, CO, and NO_X are shown in Table 2-24.

Table 2-24. Average Start Emissions Increases for pre-2010 Model Year Light Heavy-Duty Diesel Vehicles (g) for Regulatory Class LHD≤10K, LHD≤14K, and LHD45 (regClassIDs 40, 41, and 42)

	HC	CO	NO_X
Cold start emission increase in grams	0.13	1.38	1.68

For HHD and MHD trucks, data were unavailable. To provide at least a minimal amount of information, we measured emissions from a 2007 Cummins ISB 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 2-39. The biggest drop in emission rate through 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 HC.

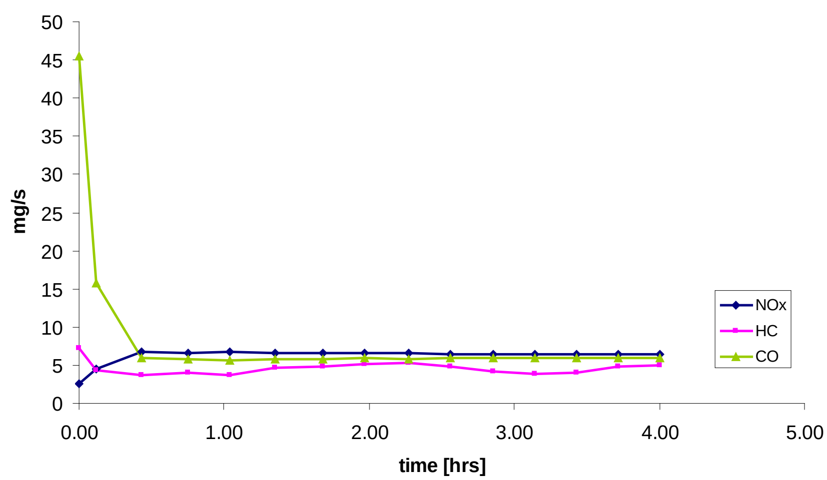


Figure 2-29. Trends in the Stabilization of Idle Emissions from a Diesel Engine Following a Cold Start (from a 2007 Cummins ISB Measured on an Engine Dynamometer)

We calculated the area under each trend 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 remaining portion of the test, or the warm idle portion. The difference between cold start and warm idle is in Table 2-25. The measured HC increment is zero. The NO_X increment is negative since cold start emissions are lower than warm idle emissions.

Table 2-25. Cold-start Emissions Increases in Grams on the 2007 Cummins ISB

HC	CO	NO_X
0.0	16.0	-2.3

We also considered NO_X data from University of Tennessee[51], 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 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 2-26 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 2-26. 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.

HC	CO	NO_X
0.0	16.0	0.0

As discussed in the Emission Adjustments Report[50], MOVES applies an additive adjustment to HC cold-start emissions to the diesel start emissions for ambient temperatures below 72 F. Thus, despite a pre-2010 baseline HC start emission rate of zero, MOVES estimates positive HC start emissions from heavy-duty diesel vehicles at ambient temperatures below 72 F. No temperature adjustments are applied to CO, PM, or NO_X diesel start emissions.

2.2.1.2 Model Year 2010 and Later Update for MOVES201X

The cold start emissions for 2010 model year and later LHD, MHD, and HHD diesel engines have been updated for MOVES201X based on new data. 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 (40 CFR Part 86, Appendix I.f.2). 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 MOVES201X update, includes the following engine families from 2016 and 2017 model years shown in Table 2-27.

Table 2-27: Engine Data Analyzed to Revise 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 2-24.

$$\begin{aligned}&Grams\ per\ Start\\ &\quad = [Cold\ FTP\ Emission\ Results\ (g/(hp-hr))\\ &\quad - Hot\ FTP\ Emission\ Results(g/(hp-hr))]\\ &\quad * FTP\ Cycle\ Work\ (hp-hr)\end{aligned}$$ **Equation 2-24**

However, 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, but is required to convert the FTP emission results in grams per horsepower-hour into grams. Furthermore, the 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. 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 2-40, the FTP cycle work is approximately linear with 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 0.0599 times the Rated Power (hp) plus 4.4297.

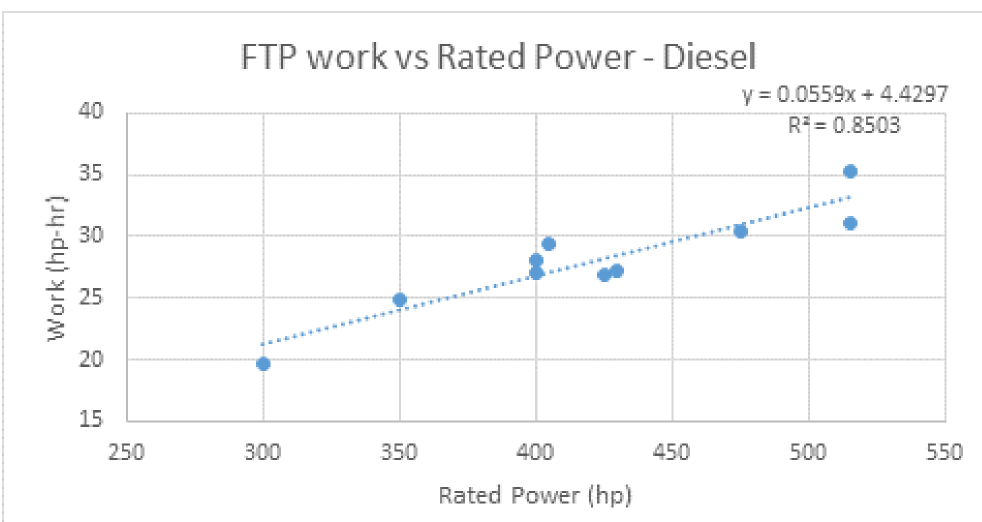


Figure 2-30: Relationship between HD Diesel Engine Rated Power and FTP Cycle Work

The analysis of cold and hot start FTP emissions data from eleven HHD diesel engines determined that the grams per start for HC, CO, NO_X, and PM2.5. The average and standard deviation of the HC, CO, and NO_X emission levels of the eleven engines are shown in Table 2-28. The engines included MY2016 and MY2017, ranged in displacement between 7.7 and 14.9 liters, and ranged in rated power between 260 and 605 HP. The new default cold start emissions values for MOVES201X are the mean values shown in the table. The HC and NO_X cold start emissions for HHD diesel engines are increasing with this update, compared to what is currently in MOVES2014, while the CO emissions are decreasing.

Table 2-28: Cold Start Emissions for MY2010 and Later Heavy Heavy-Duty Diesel Engines

Grams per Start	HC	CO	NO_X
Mean	0.08	6.6	8.4
Standard Deviation of Data	0.1	5.6	1.7

Six MHD diesel engines were used to determine the HC, CO, and NO_X grams emitted per start. The average and standard deviation of the emissions from the six engines are shown in Table 2-29. The engines included MY2016 and MY2017, ranged in displacement between 5.1 and 8.9 liters, and ranged in rated power between 230 and 380 HP. The new default values for MOVES201X are the mean values shown in the table. Similar to the HHD engines, the HC and NO_X cold start emissions for the MHD diesel engines are increasing with this update, compared to what is currently in MOVES2014, while the CO emissions are decreasing.

Table 2-29 Cold Start Emissions for MY2010 and Later Medium Heavy-Duty Diesel Engines

Grams per Start	HC	CO	NO_X
Mean	0.20	2.5	6.4
Standard Deviation of Data	0.2	2.7	1.8

Analysis of five LHD diesel engines determined that the grams per start for HC, CO, and NO_X are the values shown in Table 2-30. The engines included MY2016 and MY2017, ranged in displacement between 3.0 and 6.7 liters, and ranged in rated power between 161 and 330 HP. The new default values for MOVES201X are the mean values. The CO and NO_X cold start emissions are increasing with this update for the LHD diesel engines, compared to what is currently in MOVES2014, while the HC emissions are lower.

Table 2-30 Cold Start Emissions for MY2010 and Later Light Heavy-Duty Diesel Engines (regClassID=42)

Grams per Start	HC	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 HC, CO, and NO_X emission rates from the 2016MY and 2017MY engines to 2010MY and newer engines. The latest tier of HD diesel emission standards completed phase-in in 2010MY and the aftertreatment systems on these engines are similar and generally include both a diesel particulate filter and selective catalytic reduction system.

2.2.1.3 Incorporation of Tier 3 Standards for Light Heavy-Duty Diesel

The Tier 3 exhaust emission standards affect light heavy-duty diesel vehicles in the LHD≤10K and LHD≤14K categories (regClassID = 40, 41, respectively). Reductions are applied to rates for NO_X only starting in MY2018 and culminating in MY2021. No reductions are applied to HC and CO rates.

For NO_X, reductions for start emissions are applied as previously described for running emissions in Section 2.1.1.4.5. Examples of rates during the phase-in period are shown in Figure 2-41. Note that start rates are identical for the two regulatory classes.

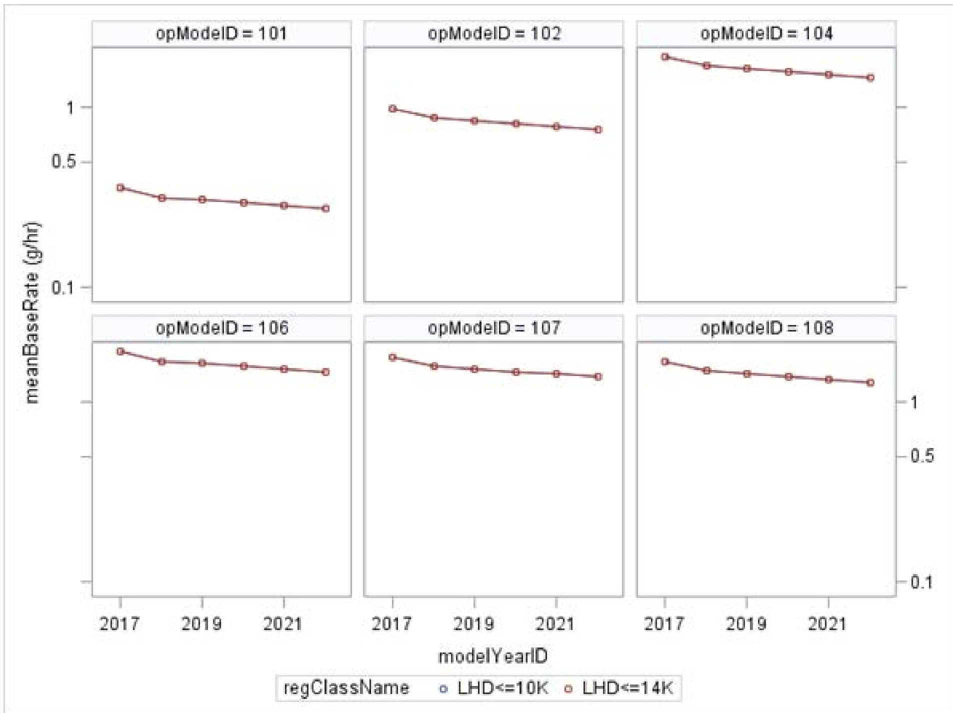


Figure 2-31. NO_X: Start emission rates in selected operating modes vs. model year for the LHD≤10K and LHD≤14K regulatory classes (LOGARITHMIC SCALE)

2.2.2 Particulate Matter

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 was 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 MY2004. 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 0.10985 grams. The data are shown here:

Cold start FTP average = *1.9314 g $PM_{2.5}$*
Warm start FTP average = *1.8215 g $PM_{2.5}$*
Cold start – warm start = *0.1099 g $PM_{2.5}$*

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 0.01099 g. The value is the same for all heavy-duty diesel regulatory class vehicles.

As introduced in Section 2.1.2.2.8, 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 starts rates by applying the 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 pre-2007 trucks. 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[41].

The cold start emissions for 2010 model year and later LHD, MHD, and HHD diesel engines have been updated for MOVES201X 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 2-31.

Table 2-31: Cold Start PM2.5 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] The value for the light heavy-duty diesel PM emission rate in MOVES201X will not be zero, as indicated by the test data. Instead, the emission rate will be represented by the medium heavy-duty diesel emission rate because of the overlap in engines and aftertreatment systems between the two categories.

We are applying the new cold start PM emission rates from the model year 2016 and 2017 engines to MY 2010 and newer engines because the PM standards are the same and the MY 2010 and later engines generally include both a diesel particulate filter and selective catalytic reduction.

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.

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

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 2-32 describes the different start-related operating modes in MOVES as a function of soak time. These modes are not related to the operating modes defined in Table 1-4 which are for running exhaust emissions.

Table 2-32. 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

The soak fractions we used for HC, CO, and NO_X for MY 2009 and older HD diesel vehicles are illustrated in Figure 2-42 below. Due to limited data, we applied the same soak fractions that we applied to 1996+ MY light-duty gasoline vehicle as documented in the light-duty emission rate report[9]. The soak fractions are taken from the non-catalyst soak fractions derived in a CARB report[52] and reproduced in a MOBILE6 report.[53]

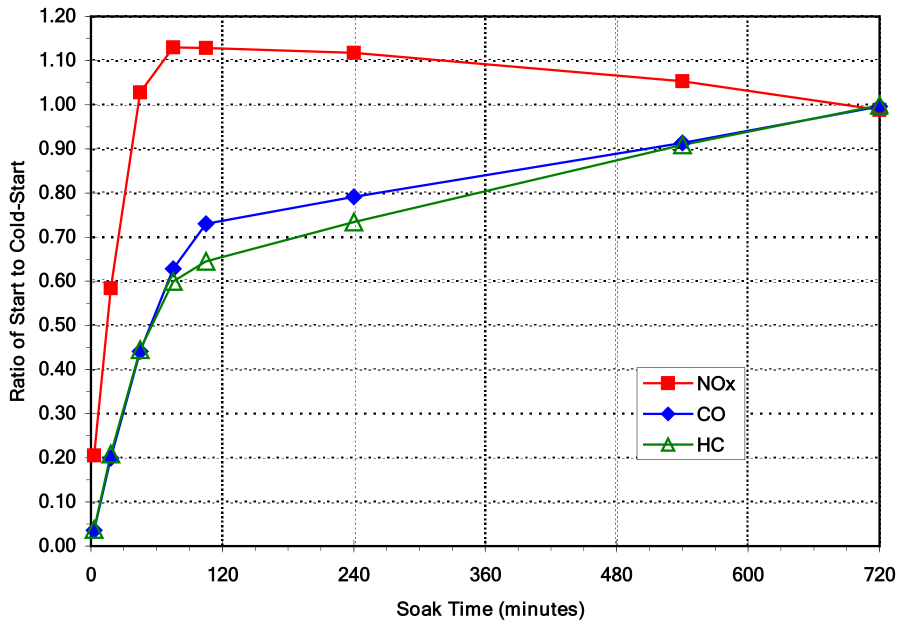


Figure 2-32. Soak Fractions Applied to Cold-Start Emissions (opModeID = 108) to Estimate Emissions for shorter Soak Periods (operating modes 101-107). This figure is reproduced from the Light-Duty Emissions Report[9]

For light heavy-duty vehicles (regulatory classes LHD≤10K, LHD≤14K, and LHD45), the soak distributions apply to the cold starts for HC, CO and NO_X. For medium and heavy heavy-duty vehicles (regulatory classes MHD, HHD, and Urban Bus) only the CO soak fractions are applied to the cold-start emissions, because the base cold start HC and NO_X emission rates for medium and heavy heavy-duty emission rates are zero. The start emission rates used for 2009 MY and older heavy-duty vehicles, derived from applying the soak fractions are displayed in Table 2-33 for HC, CO, and NO_X.

Table 2-33. Heavy-Duty diesel HC, CO, and NO_X Start emissions (g/start) by operating mode for 2009MY and older vehicles and all ages in MOVES

	HC		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 regClassIDs 40, 41, and 42
[2] Other HD refers to the medium heavy-duty, heavy heavy-duty, and urban bus regulatory classes (46, 47, 48)

The PM start rates by operating mode are given in Table 2-34 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 2-34. Particulate Matter Start Emission Rates by Operating Mode (soak fraction) for all HD Diesel vehicles through MY 2009 (regClassID 40 through 48)

Operating Mode	$PM_{2.5}$ (grams per start) 1960-2006 MY	$PM_{2.5}$ (grams per start) 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 new test programs were conducted to revise the 2010 MY and later soak curves for heavy-duty diesel vehicles in MOVES201X. 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 was tested on a heavy-duty chassis.[54] 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 2-43. 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 Table 2-32. At least two repeats were conducted for each soak period. The emission measurements included dilute gaseous measurements and triplicate particulate matter filters.

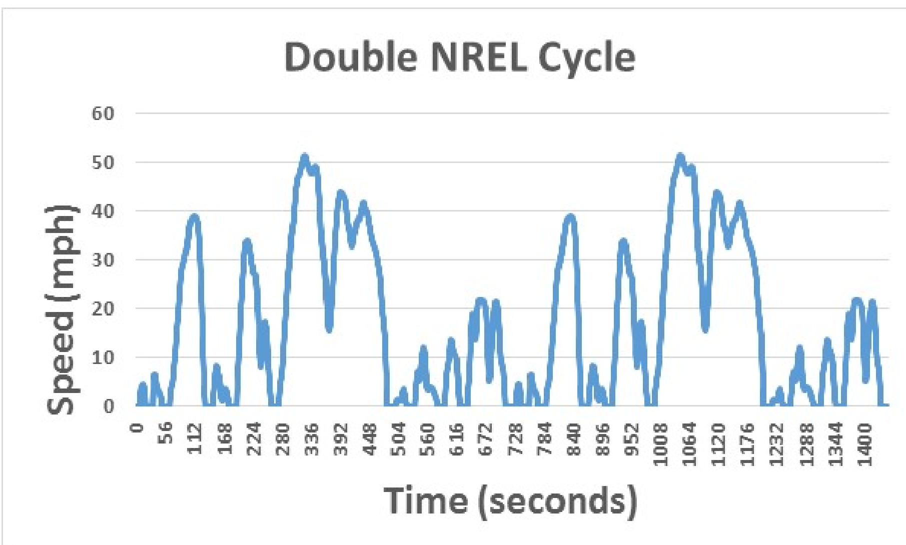


Figure 2-33 National Renewable Energy Laboratory's Heavy-Duty Vocational Transient Cycle

The NO_X, CO, HC, and PM emission results in terms of grams or mg per mile from the tests over a range of soak periods are shown in Figure 2-44 through Figure 2-47.

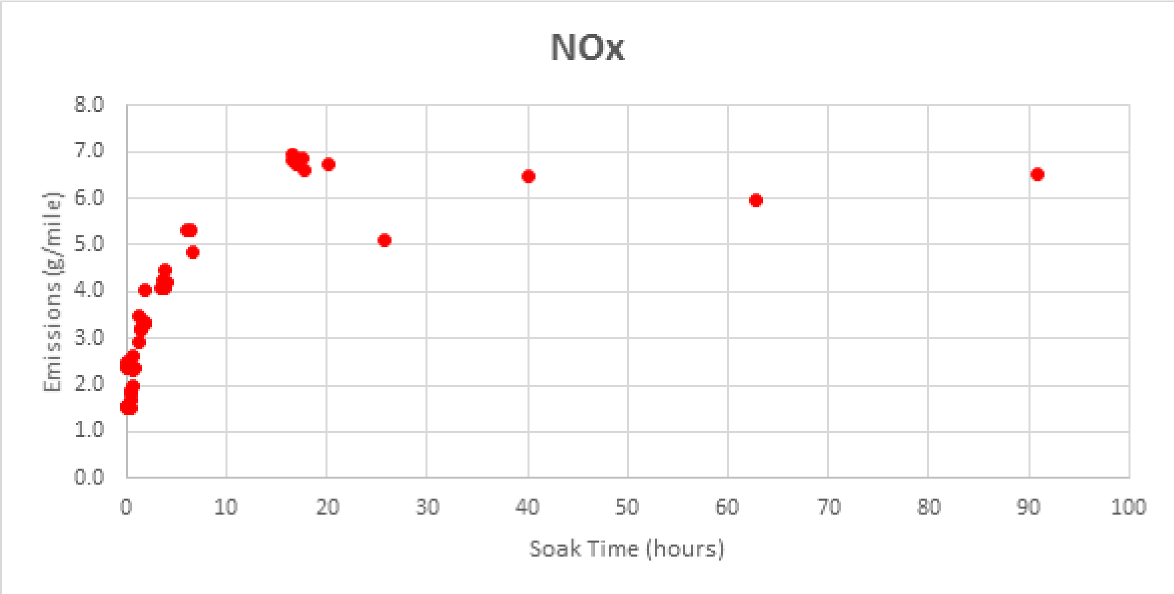


Figure 2-34 MY 2015 Heavy-Duty Vehicle NO_X Emissions by Soak Time

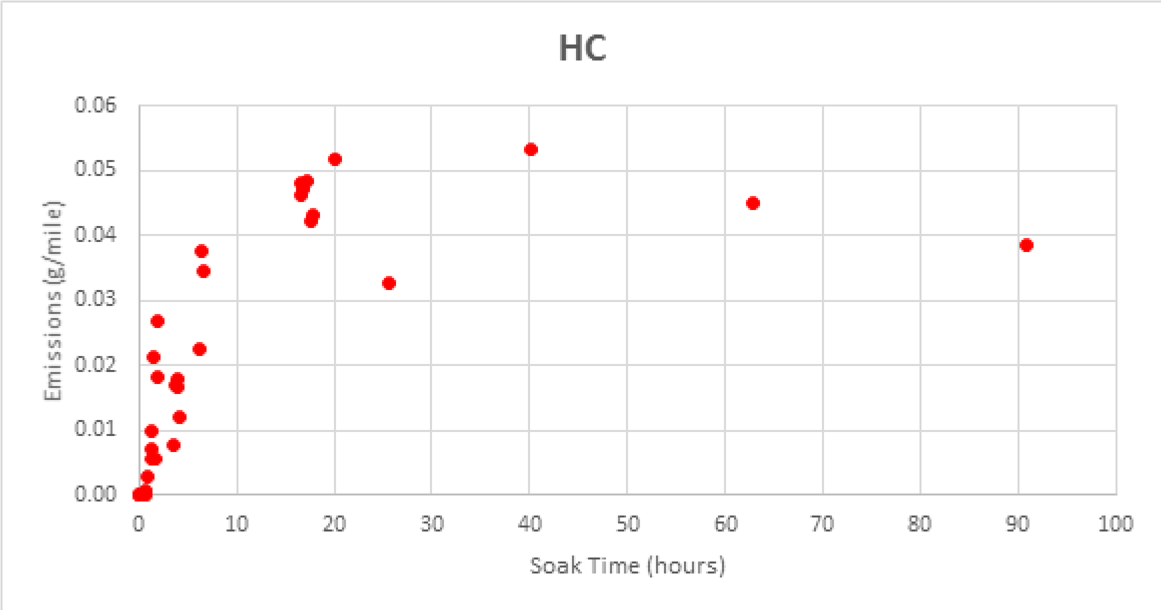


Figure 2-35 MY 2015 Heavy-Duty Vehicle HC Emissions by Soak Time

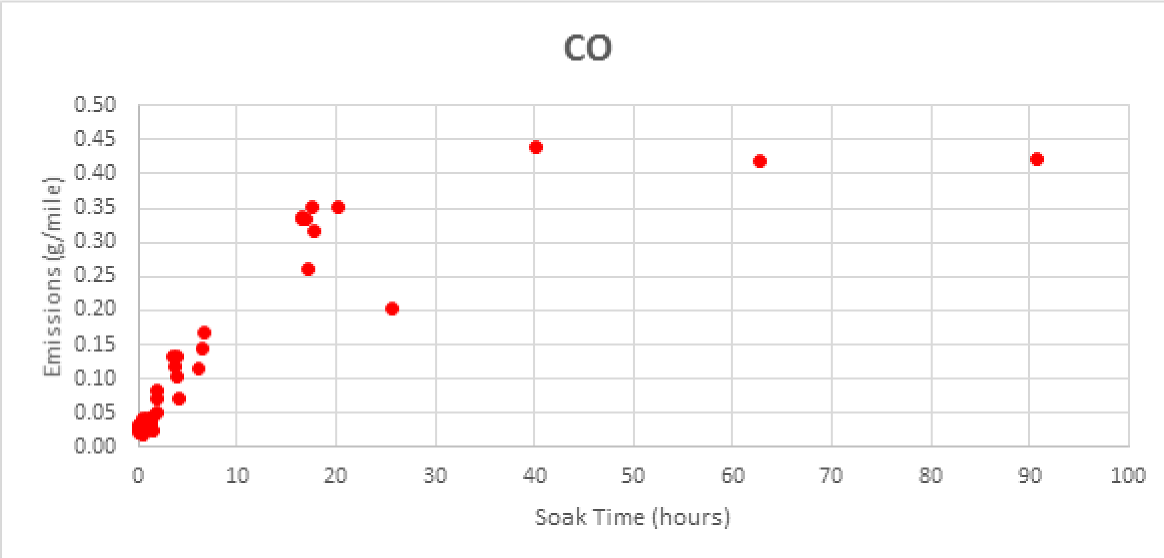


Figure 2-36 MY 2015 Heavy-Duty Vehicle CO Emissions by Soak Time

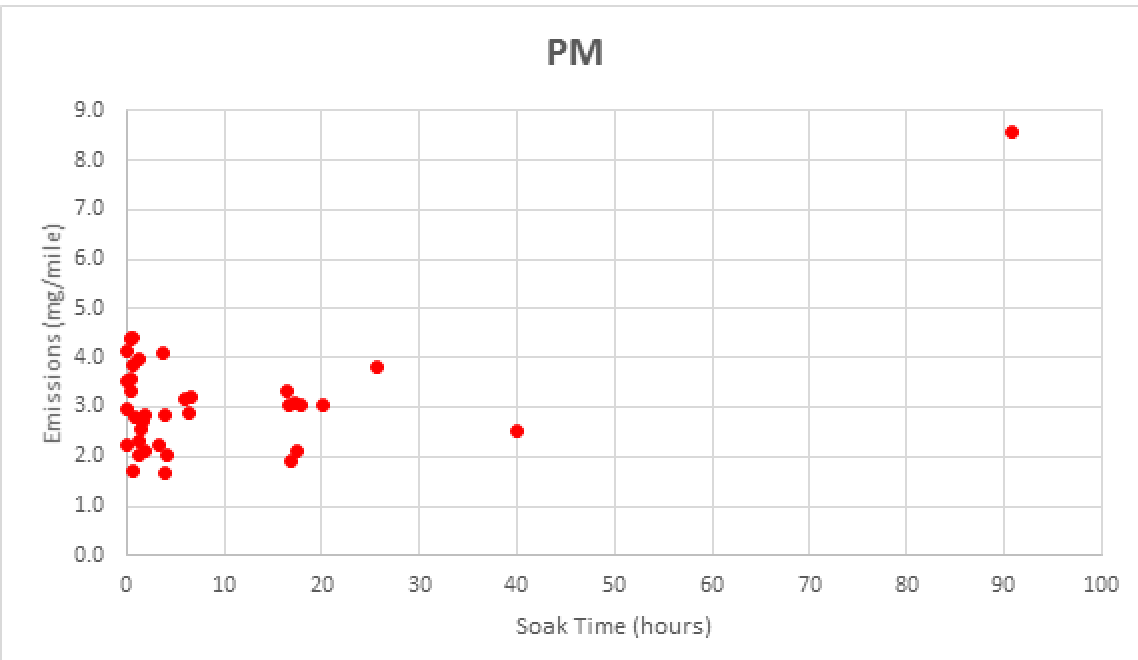


Figure 2-37 MY 2015 Heavy-Duty Vehicle PM Emissions by Soak Time

In addition to the chassis testing, onroad testing was conducted using a portable emissions measurement system (PEMS).[55] 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 then was driven through the soak route. A typical vehicle speed profile from the route is shown in Figure 2-48. The cycle consisted of approximately 700 seconds of driving in a neighborhood/urban environment over approximately 2.7 miles.

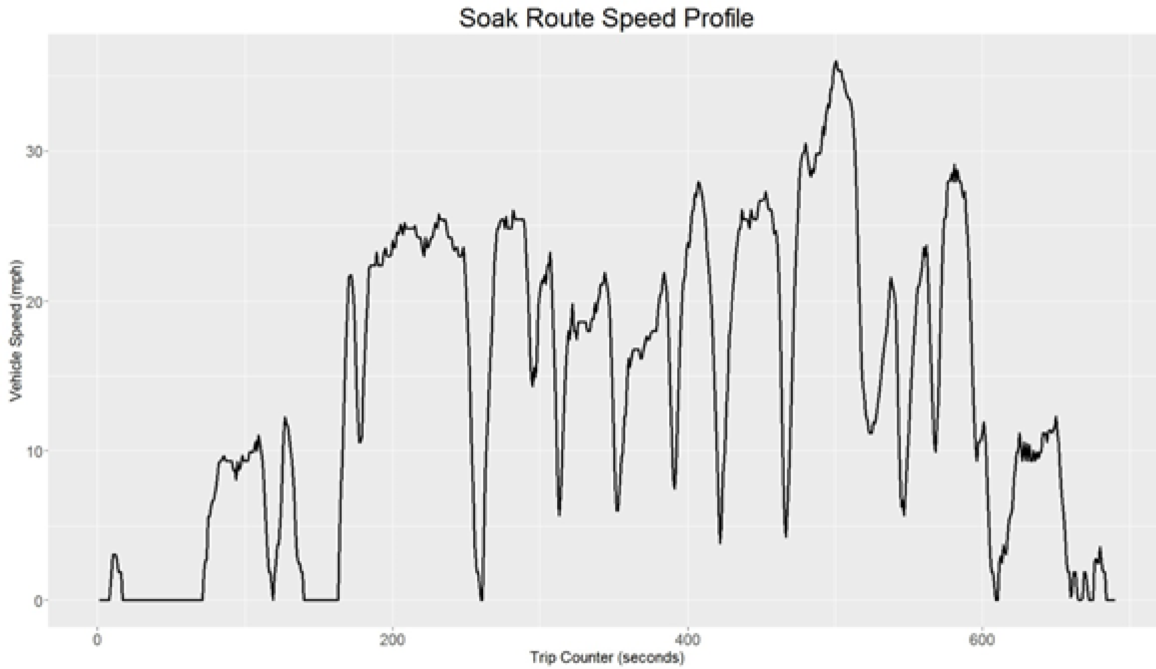


Figure 2-38 Onroad Soak Drive Route

The emission results, in terms of total emissions over the route, from the onroad tests are shown in Figure 2-49 through Figure 2-51.

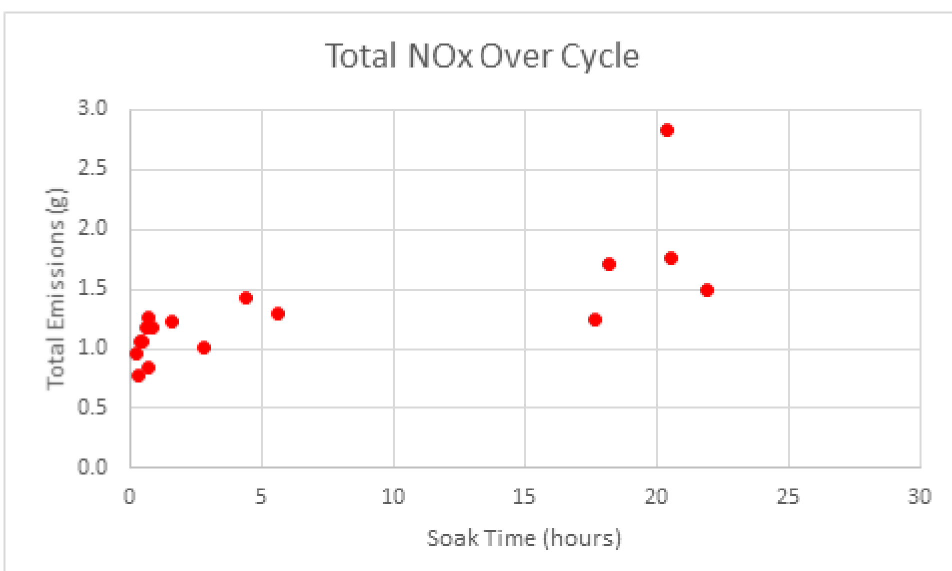


Figure 2-39 MY 2016 Heavy-Duty Vehicle NO_X Emissions by Soak Time

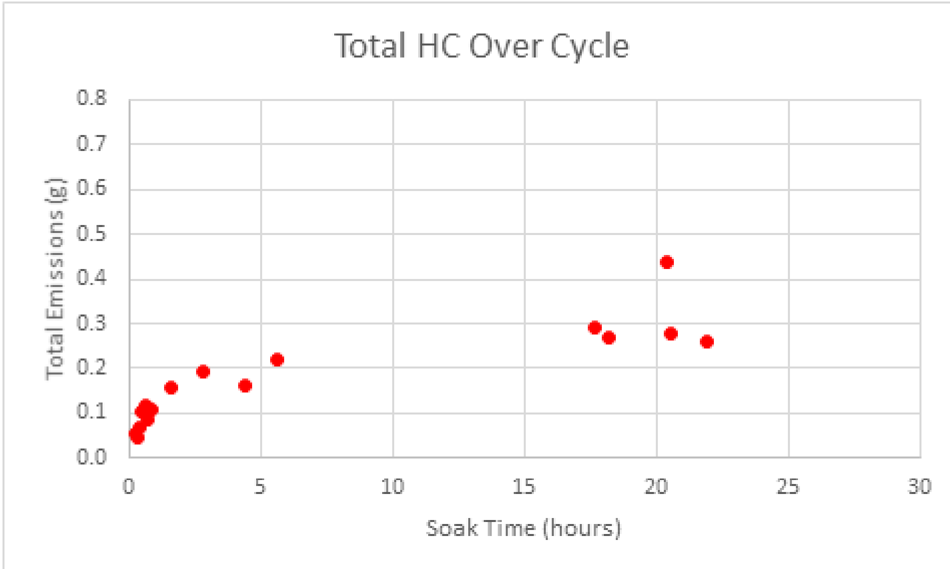


Figure 2-40 MY 2016 Heavy-Duty Vehicle HC Emissions by Soak Time

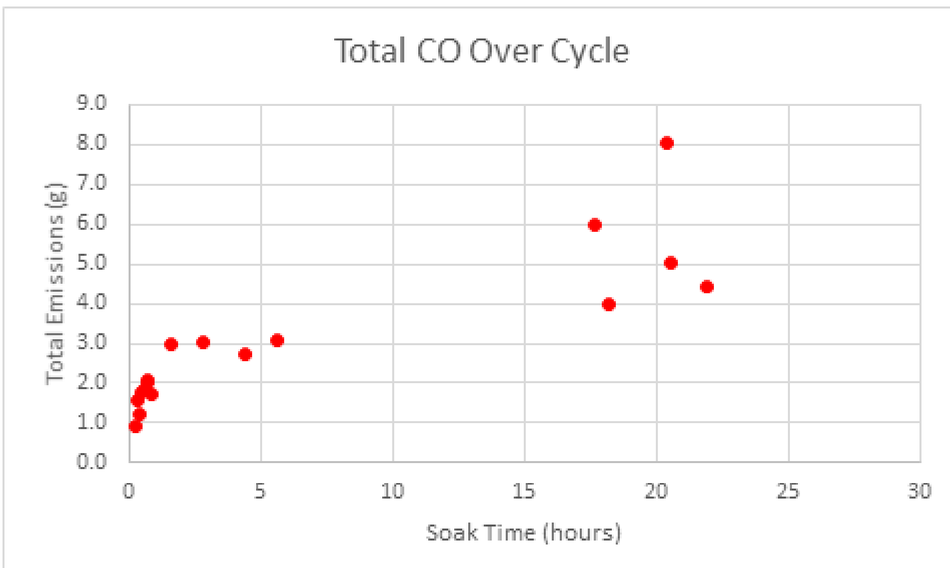


Figure 2-41 MY 2016 Heavy-Duty Vehicle CO Emissions by Soak Time

The soak emission 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 emission (NO_X, HC, CO) for each vehicle. Then the start emissions for each soak period were determined by subtracting the average total emissions from 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 OpMode 101 and 102 soak times. In other words, soak fraction for OpMode 102 was multiplied by the ratio of 3 minutes divided by 18 minutes (the midpoint times of OpMode 101 and 102). The NO_X, CO, and HC soak period ratio results for each vehicle are shown below in Figure 2-52.

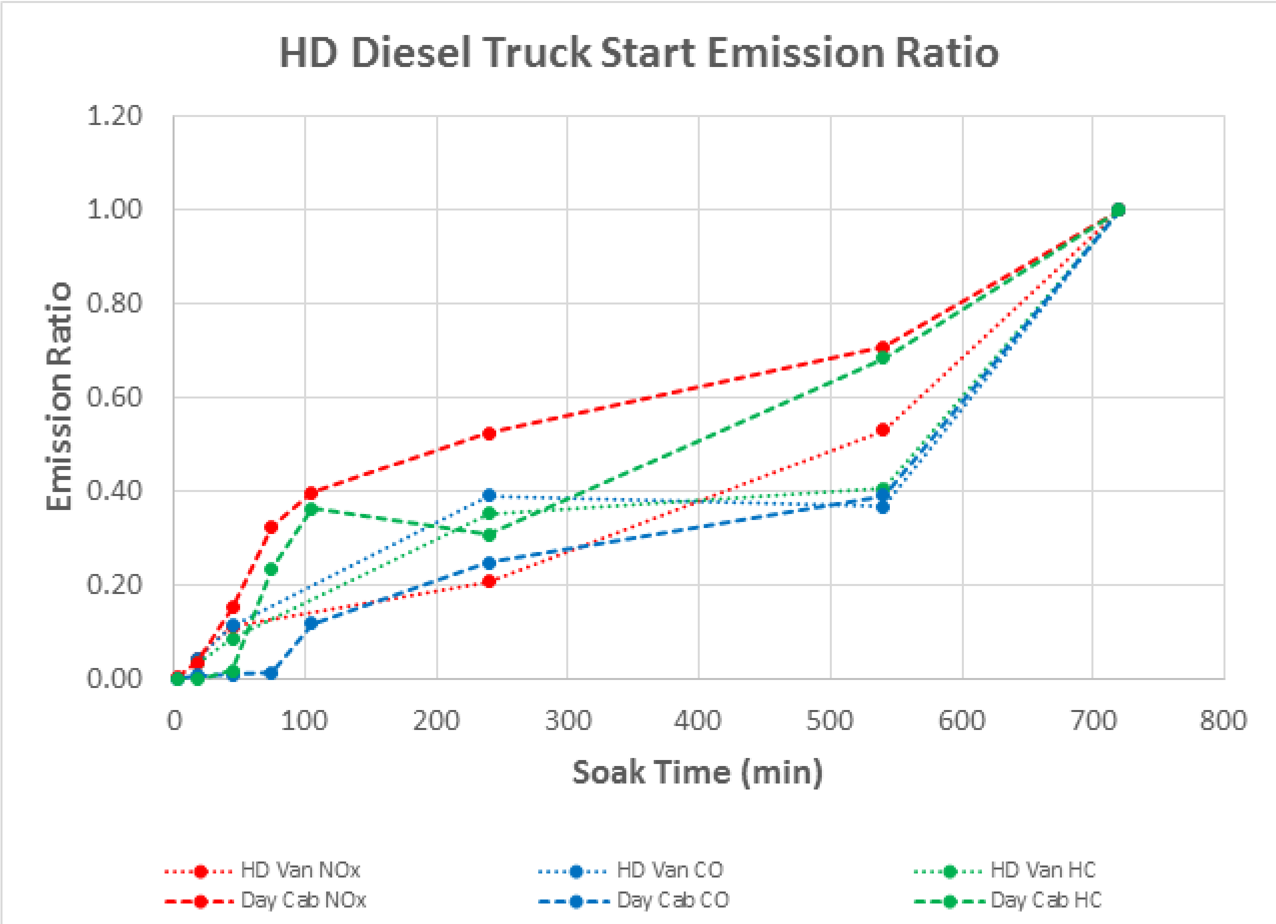


Figure 2-42 Soak Curves from a MY 2015 HD Day-Cab and a MY 2016 HD Van

The 2010 MY and later heavy-duty diesel soak ratios for MOVES201X were determined based on averaging the results from the two trucks. The resulting soak fractions are shown in Table 2-35. The soak fractions are applied to all heavy-duty diesel regulatory classes.

Table 2-35 HD Diesel Engine Soak Ratios for MY 2010 and Newer

Operating Mode	Description	NO_X	CO	HC
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

The PM start rates by operating mode are given in Table 2-36 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). This approach is consistent with the approach taken for MY 2009 and older vehicles, as described in Section 1. We did not revise the approach because we obtained PM data for only one of the trucks and it showed mixed results. The PM start rates for MY 2010 and newer vehicles are updated in MOVES201X using the same linear interpolation methodology, but based on the new cold start data for Operating Mode 108.

Table 2-36 Particulate Matter Start Emission Rates by Operating Mode (soak fraction) for all MY 2010 and newer HD vehicles (regClassID 40 through 48)

Operating Mode	$PM_{2.5}$ (grams per start) Reg Class 47 and 48	$PM_{2.5}$ (grams per start) Reg Class 46	$PM_{2.5}$ (grams per start) Reg Class 40-42
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 emission adjustments report discusses the impact of ambient temperature on cold start emission rates (opModeID 108).[50] The ambient temperature effects in MOVES model the impact ambient temperature has on cooling the engine and aftertreatment system on vehicle emissions. The temperature effect is 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.

However, because the HC 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 applied the same soak fractions described in Section 2.2.3 for pre-2007 and 2010+ trucks to obtain cold start temperature adjustments for opModeID 101 through 107. The additive cold start adjustment for HC emission factors are displayed in Table 2-37, along with the soak fractions applied. These additive HC starts are applied to all diesel sources in MOVES, including light-duty diesel (regulatory class 20 and 30). There are currently no diesel temperature effects in MOVES for PM, CO, and NO_X.

Table 2-37 HC Diesel Start Temperature Adjustment by opModeID

	pre-2010		2010+	
opModeID	Start Temp Adjustment	Soak fraction	Start Temp Adjustment	Soak fraction
101	-0.0153×(Temp - 75)	0.38	0×(Temp - 75)	0
102	-0.0152×(Temp - 75)	0.37	-0.0008×(Temp - 75)	0.02
103	-0.0180×(Temp - 75)	0.44	-0.002×(Temp - 75)	0.05
104	-0.0201×(Temp - 75)	0.5	-0.0097×(Temp - 75)	0.24
105	-0.0211×(Temp - 75)	0.52	-0.0146×(Temp - 75)	0.36
106	-0.0254×(Temp - 75)	0.62	-0.0134×(Temp - 75)	0.33
107	-0.0349×(Temp - 75)	0.86	-0.0223×(Temp - 75)	0.55
108	-0.0406×(Temp - 75)	1	-0.0406×(Temp - 75)	1

2.2.4 Start Energy Rates

The MOVES start energy rates for the heavy-duty diesel regulatory classes are shown in Figure 2-53. The energy start rates were developed for MOVES2004[56], and updated in MOVES2010 as documented in the MOVES2010a energy updates report.[46] As shown, there is more detail in the pre-2000 emission rates. The spike in fuel economy at 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 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 2-20 and Table 2-22. It is worth noting that unlike the Phase 1 HD standards, the technologies projected for meeting the HD Phase 2 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).

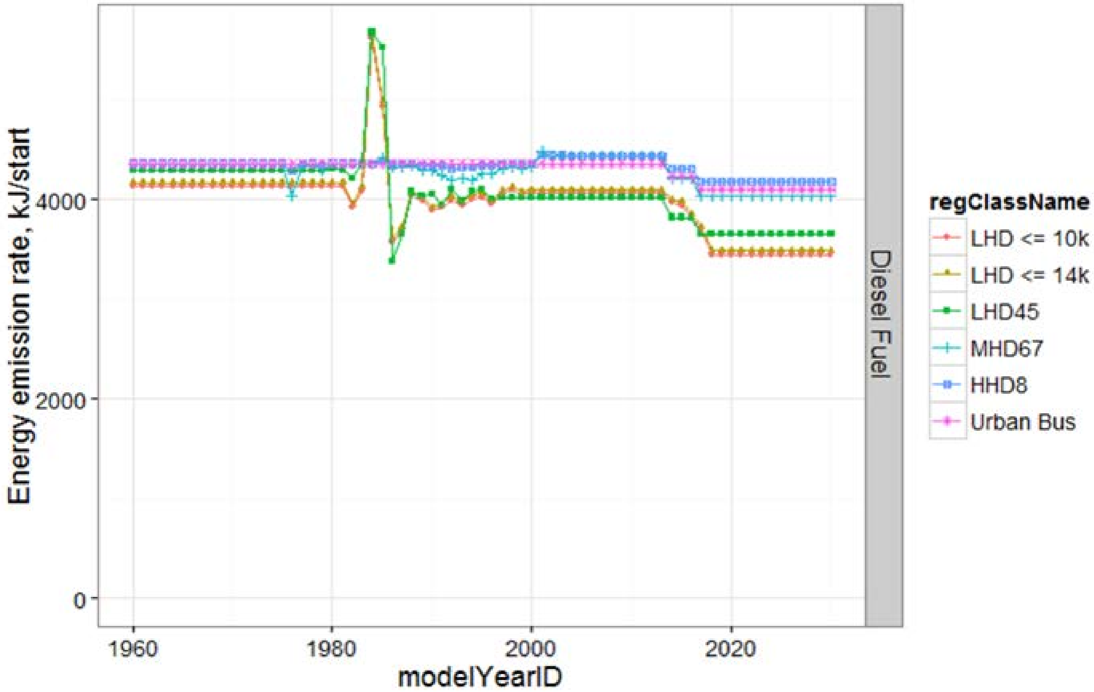


Figure 2-43. Heavy-Duty Energy Cold Start Energy Rates (opMode 108) by Model Year and Regulatory Class

The start energy rates are adjusted in MOVES for increased fuel consumption required to start a vehicle at cold ambient temperatures. The temperature effects are documented in the MOVES2004 Energy Report.[56] Additionally, the energy consumption is reduced for starts that occur when the vehicles are soaking for a short period of time. The soak fractions used to reduce the energy consumption emission rates at cold start are provided in Table 2-38. These fractions are used for all model years and regulatory classes of diesel vehicles. These fractions are used for all model years and regulatory classes of diesel vehicles.

Table 2-38. Fraction of energy consumed at start of varying soak lengths compared to the energy consumed at a full cold start (operating mode 108)

Operating Mode	Description	Fraction of energy consumption compared to 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

One of the reasons that energy rates for heavy-duty starts has not been updated is the relatively small contribution the starts have on the energy inventory. Table 2-39 displays the relative contribution of total energy consumption estimated from a national run of MOVES for calendar year 2011, using MOVES2014. As shown, the estimated energy consumed due to starts is minor in comparison to the energy use of running activity.

Table 2-39. Relative contribution of total energy consumption from each pollutant process by regulatory class for Heavy-Duty diesel vehicles in calendar year 2011

processID	processName	LHD≤10K	LHD≤14K	LHD45	MHD	HHD	Urban Bus
1	Running Exhaust	97.4%	99.2%	99.3%	98.1%	95.1%	99.7%
2	Start Exhaust	2.6%	0.8%	0.7%	0.6%	0.1%	0.3%
90	Extended Idle Exhaust				1.3%	4.7%	
91	Auxiliary Power Exhaust				0.01%	0.04%	

2.3 Extended Idling Exhaust Emissions

In the MOVES model, extended idling is idle operation characterized by idle periods more than an hour in duration, typically overnight, including higher engine speed settings and extensive use of accessories by the vehicle operator. Extended idling most often occurs during long layovers between trips 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."[57]

Accessory use during idle increases the load on the engine. Additionally, idling for extended periods allows the vehicle's exhaust emission aftertreatment systems to cool down, which has the potential to reduce their effectiveness. As a result, extended idle is treated as a separate emission process in MOVES.

Extended idling does not include vehicle idle operation that occurs during normal road operation, such as idling at a traffic signal or 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, diesel long-haul combination trucks (sourceTypeID 62) are only associated with diesel MHD (regClassID 46) and HHD (regClassID 47) regulatory classes, and are the only source type assumed to have significant extended idling activity. As a result, no other source types or regulatory classes are assigned extended idling emission rates in MOVES.

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). The emission rates for Auxiliary Power Units (APUs) are discussed in Section 2.4. For each range of years, MOVES applies data representative of accessory use and high idle engine speed to calculate extended idle emission rates.

2.3.1 Pre-2007 Extended Idle Emissions

The MOVES extended idling emission rates were derived from data collected in several distinct test programs. The references outlined in this section contain 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.[58]. Ten of the trucks were Class 8 heavy-duty axle semi-tractors, one was a Class 7 truck, and one of the vehicles was a school bus. The model year ranged from 1990 through 1998. A typical Denver area wintertime diesel fuel (NFRAQS) 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.).[59] The model years ranged from 1985 through 2001. The vehicles were put through a battery of tests including a variety of discretionary and non-discretionary idling conditions.

Testing was conducted on 42 diesel trucks in parallel with roadside smoke opacity testing in California (Lambert)[60]. All tests were conducted by the California Air Resources Board (CARB) at a rest area near Tulare, California in April 2002. Data collected during this study were included in the data provided by IdleAire Technologies (below) that was used in the analysis.

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.)[61]. Not all trucks were tested under all conditions. Only results from the testing in Tennessee and New York are described in the IdleAire report. The Tulare, California, data are described in the Clean Air Study cited above. 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.[62]

The National Cooperative Highway Research Program (NCHRP)[63] obtained the idling portion of continuous sampling during transient testing was used 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.)[64]. 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)[65]. 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.)[66]. 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)[51].

EPA used the data sources referenced above to estimate mean emission rates for particulate matter (PM), oxides of nitrogen (NO_X), hydrocarbons (HC), carbon monoxide (CO) and carbon dioxide (CO_2). The data was grouped by truck and bus and by idle speed and accessory usage to develop emission rates more 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.

The use of accessories (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 pollutant processes in MOVES assume both accessory use and engine idle speeds set higher than used for "curb" (non-discretionary) idling.

Data from these studies were obtained from 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.

The idle emission rates for heavy duty diesel trucks prior to the 1990 model year are based on the analysis of the 18 trucks from 1975-1990 model years used in the CRC E-55/59 study and one 1985 truck from the Lim study. These data represent a curb idle condition. To estimate the elevated NO_X emission rates characteristic of higher engine speed and accessory loading of extended idle, data from the 1991-2006 trucks were used.

As summarized in the tables of Appendix C, 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 pre-1990 model year curb idle rate to get the calculated pre-1990

NO_X emission rate with high engine sped and A/C. A similar strategy was applied to the HC, CO, and CO_2 emission rates for pre-1990 model years.

As mentioned above, an NREL 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.[67] In a 2004 UC-Davis survey, respondents' average engine idle speed was 866 rpm, with small peaks around 650 and 1000 rpm.[68] Only 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 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.[69] Additionally, Hoekzema cited similar studies representing 764 trucks that averaged engine speeds of 886 rpm during extended idle.

While many engine manufacturers recommend using high idle when idling for long periods, Hoekzema and Lutsey et al. reported far fewer followed those recommendations in their studies. Previously, MOVES emission rates were calculated assuming all extended idling occurred at a high idle condition. For MOVES201X, the amount of high idle was reduced from 100 percent to 33 percent to better match the references noted above. Using the data summarized in Appendix D, an adjusted emission rate was 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. Extended idling measurements have large variability due to low engine loads.

The NO_X, HC, CO, and PM emission rates from this data analysis are representative of diesel HHD trucks (regClassID 47). Previously, we calculated the MHD (regClassID 46) extended idle emission rates as half of the corresponding HHD emission rates. However, a 2009 study by Khan et al. found that MHD and HHD trucks had similar emission rates during extended idle.[70] Consequently, MOVES201X applies the same extended idle emissions rates to regClassID 46 and regClassID 47, as shown in Table 2-40.

MOVES stores PM emission rates according to elemental carbon (EC) and NonECPM, but the data sources used to calculate extended idle emission rates reported total PM. As mentioned in Section 2.1.2.2.8, an EC/PM fraction of 46.4 percent is applied for idle operating mode (opModeID 1), and we also apply it to extended idle. The resulting EC and NonECPM rates are also shown in Table 2-40.

Table 2-40. Extended idle emission rates (g/hour) in MOVES by pollutant for regClassID 46 and regClassID 47 based on the pre-2007 MY data analysis (g/hour)

Model Year Groups	NO_X	THC	CO	PM	EC	Non-ECPM
Pre-1990	69.3	49.8	50.8	5.39	2.50	2.89
1990-2006	136	25.6	55.0	2.48	1.15	1.33

2.3.2 2007+ Extended Idle Emission Rates

The extended idle emission rates for model year 2007 and later heavy-duty tractor trailers (sourceTypeID 62, regClassID 46 and 47) in MOVES were updated using two data sets which conducted in-use extended idling data collected on vehicles in these model year ranges. The Texas Transportation Institute (TTI) tested extended idle emission from 15 heavy-duty diesel tractors ranging from model year 2005 to 2012.[71] The California Air Resources Board (ARB)[72] tested five tractors (engine model years 2007 and 2010), that were also included in this analysis. 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 2-41. The last three columns in Table 2-41 are taken from the California Executive Order certification database.[73] 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.[74] In these cases, the family emission limit for which the vehicle was certified is reported in Table 2-41. 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 2-41 indicates if 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 2-41. Information for the Heavy-Duty Diesel Tractors Used to Update the 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 tested in 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. Several tests and idling conditions were measured by TTI, including idling after different soak lengths and 'high idle' for engines capable of idling with an engine speed approximately 400 rpm higher than their standard idle speed. 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 2-42), but were not commanded to be in the high idle state. We decided not to use the 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 winter and summer conditions of the test were deemed to be more extreme cases for extended idle emissions, because they did not include any tests at moderate ambient temperatures, and the tests did contain some high idle emissions. Two of the trucks high idle during the winter stabilized tests due to automatic engine control strategies.
3) The emissions impact of 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 high idle emission rates.

For these reasons, the summer and winter stabilized conditions were deemed to be our best estimate of real-world extended emissions. The 'stabilized' idle emission rates (g/hr) for the winter and summer conditions, are reported in Figure 2-54 through Figure 2-58.

Table 2-42. Ambient Test Conditions for the TTI Extended Idle Tests

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

The five trucks tested by ARB were tested on a chassis dynamometer on the ARB HHDDT 4-mode cycle, they reported 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 from 10-20 minutes.[75] 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.

To develop the revised extended idle emission rates for MOVES, we averaged the emission rate from each of the tests, within model year ranges that represent engine and aftertreatment technology groups that have 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 was weighted significantly towards the TTI tests. This was appropriate, because the TTI data are more representative of real-world extended idle conditions, and provide a higher estimate of emissions, which we believe is more representative of in-use emissions.

The individual test results and the average emission rates by model year group are presented in the following figures. Within each figure, the tests are distinguished according to test condition. The ‘hot’ and ‘cold’ conditions represent the tests from the TTI test program, and the ‘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 directly used the average of the extended idle emission rates in MOVES, with no increase in emissions to account for deterioration of the engines or emission control systems. We did not observe strong effects of the emission control in the extended idle emission rates for these pollutants and we believe, 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 in the discussion of the THC and $PM_{2.5}$ emission rates.

Figure 2-54 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 > 1000 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. We used the conversion factor of 0.0736 g CO_2/KJ and 10,045 g CO_2/gallon from B5 (5 percent biodiesel blend) highway diesel reported from the MOVES GHG and Energy Report.[76]

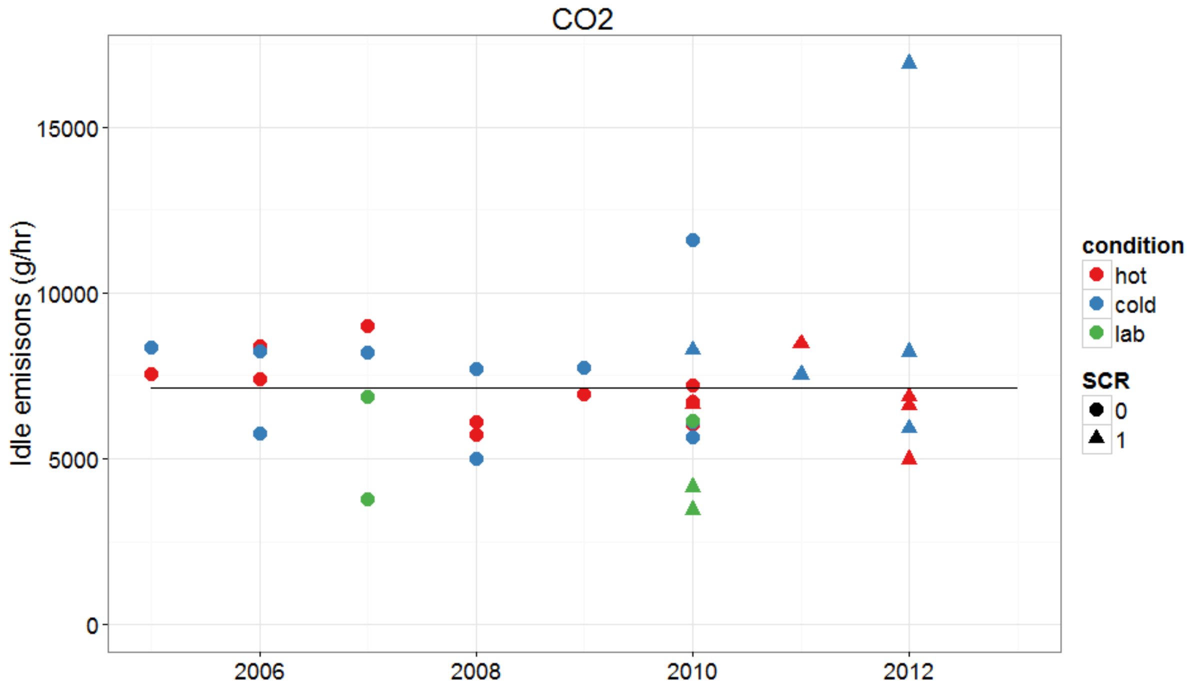


Figure 2-44. CO_2 Emission Rates from the TTI and ARB Programs by Engine Model Year, and Average Emission Rate (line) Based on All the Data. Within Condition, “hot” refers to the summer conditions from the TTI tests, “cold” refers to the winter conditions from TTI, and “lab” refers to the laboratory 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 2-55 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. Similar to CO_2, a single average emission rate is calculated for all the tests results.

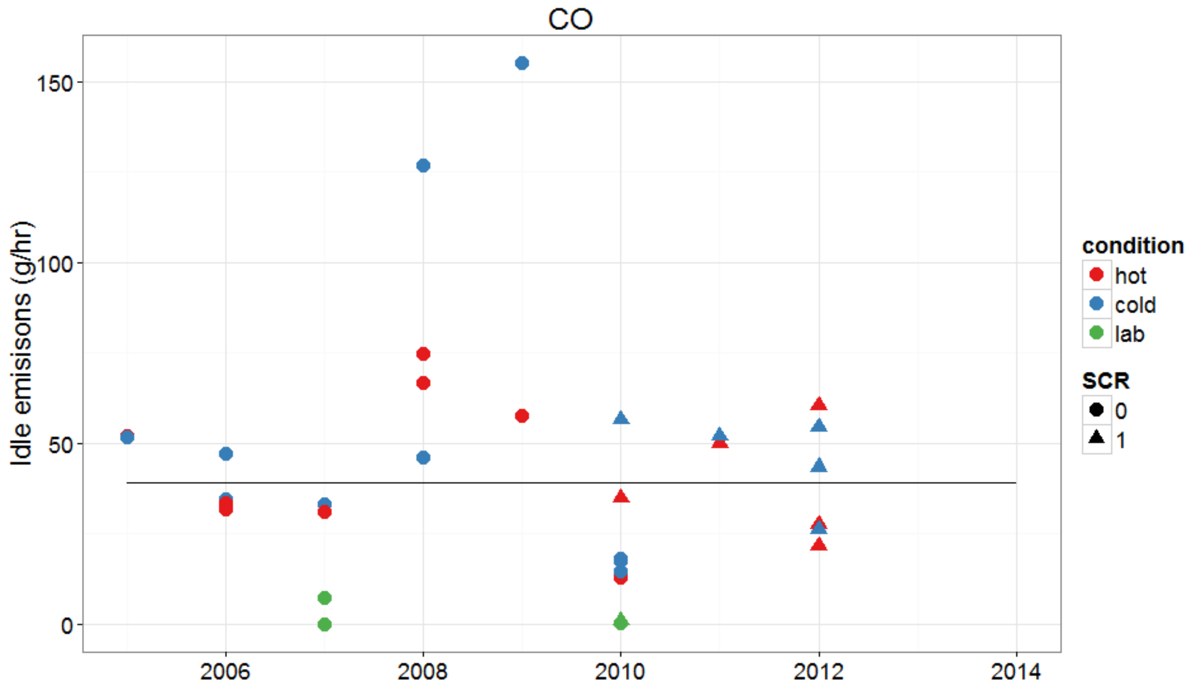


Figure 2-45. CO Emission Rates from the TTI and ARB Programs by Engine Model Year, and Average Emission Rate (line) Based on All the Data

Figure 2-56 displays the NO_X individual test results. We initially expected the data would show a decrease in the extended idle emission rates beginning in 2008 to account for the California Clean Idle Certification (all the 2008 and later trucks were clean-idle certified). However, no reduction was observed. We also expected we would 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 and later model years) as shown below.

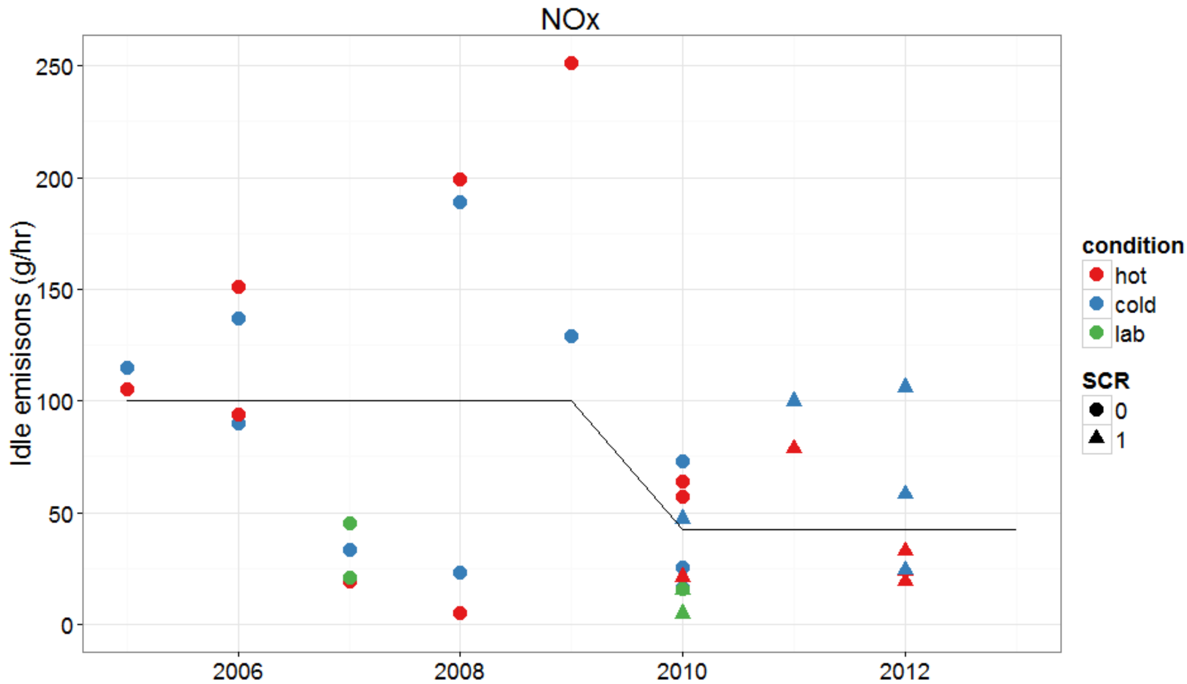


Figure 2-46. NO_X Emission Rates from the TTI and ARB Programs by Engine Model Year, and Average Emission Rates for 2005-2009 and the 2010-2012 Engine Model Years (lines)

Figure 2-57 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 represents a combination of DPF and non-DPF equipped trucks. The 2010-2012 represents DPF equipped trucks, with some penetration of SCR equipped trucks. Although, we did not test any 2013 and later model year engines, we calculated an average emission rate for the 2013+ model year group, by averaging the rates of all the SCR equipped trucks in the data set. Model year 2013 was chosen as the first year for these rates, 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.[77]

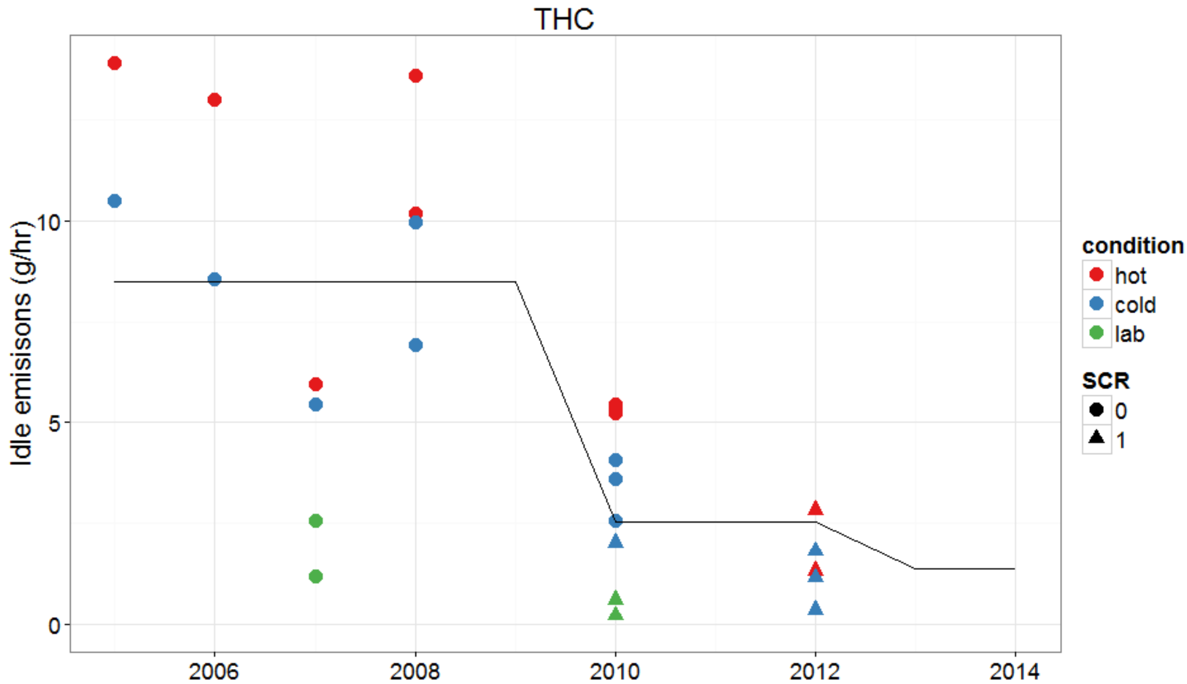


Figure 2-47. THC Emission Rates from the TTI and ARB Programs by Engine Model Year, and Average Emission Rates for 2005-2009, 2010-2012, and 2013 + (SCR only) Engine Model Years (lines)

Figure 2-58 displays the $PM_{2.5}$ individual test results. The ARB tests reported zero emission or "Not Reported due to PM collection failure" for the 5 ARB tests, and thus, the ARB data were not used to develop the PM extended idle emission rates. Like the THC results, the use of an SCR-equipped engine had a significant impact on the $PM_{2.5}$ emissions. Additionally, 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). As for THC, we used the results from the 2010 and later SCR equipped trucks to calculate the 2013 and later model year group emission rate.

$PM_{2.5}$ emission rates in MOVES are composed of elemental carbon (EC) and non-elemental carbon PM (nonEC). The TTI study did not include estimate of the EC emission rates. We used the EC/PM fractions from the sources listed in Table 2-43 to estimate the EC and PM emission rates and the results are shown in Table 2-43.

Table 2-43. Baseline elemental carbon to PM2.5 fraction assumed for extended idling

Model Year Group	EC/PM	Source
Pre-2007	0.26	MOVES2014 Extended Idling[79]
2007-2009	0.10	ACES Phase I[75]
2010+	0.16	ACES Phase II[78]

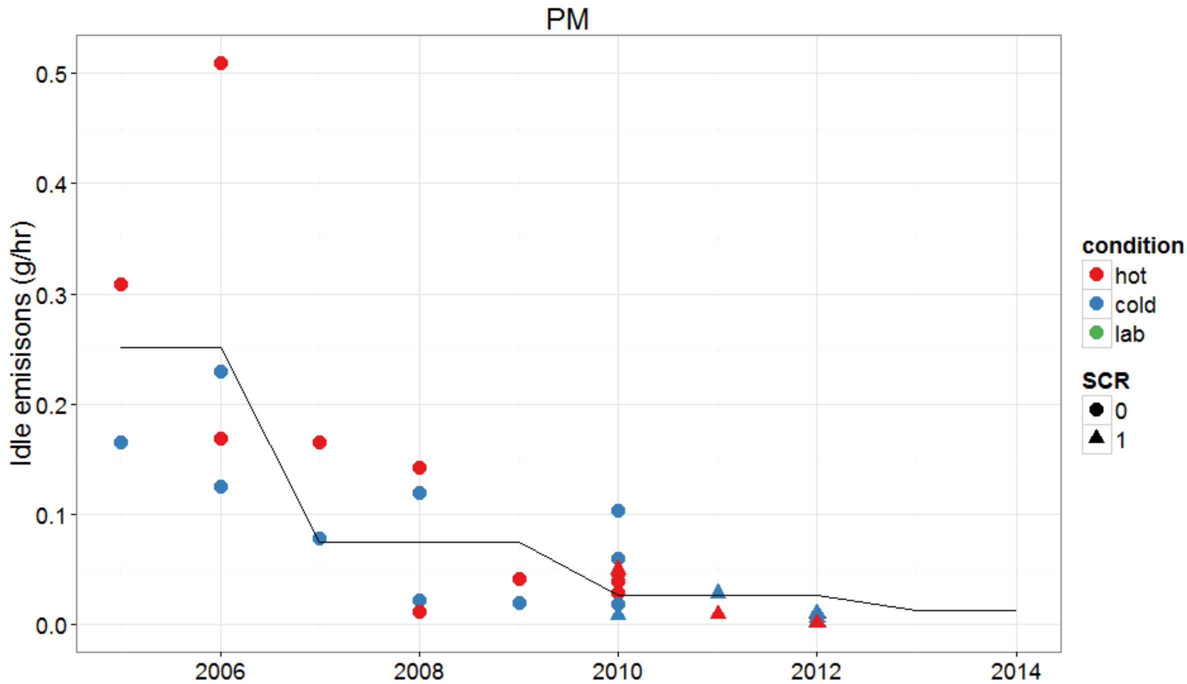


Figure 2-48. $PM_{2.5}$ Emission Rates from the TTI Program by Engine Model Year, and average Emission Rates Using for 2005-2006, 2007-2009, 2010-2012, and 2013 + (SCR only) Engine Model Years (lines)

As shown in the figures above, the THC and $PM_{2.5}$ emission showed the largest reductions in extended idle emissions with newer model year vehicles. We believe that the reductions are due to the continued effectiveness of the diesel particulate filter even under 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 of $PM_{2.5}$. To do so, 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 2-44. 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 2-44. References Used to Support In-Use DPF Failure Rate Assumption

Study	Relevant Information
US EPA (2014)[79]	7% of 2007+ trucks in MOVES are assumed to either have a PM filter leak or have the PM filter disabled.
Preble et al. (2015)[80]	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)[81]	3% of 2007+ trucks at Port of LA PM emissions 3× the standard. 9% of 2008+ trucks at Cottonwood site have PM emissions 3× the standard
CARB (2015)[82]	35% to 4% of trucks submitted warranty claims related to the PM filter between 2007 and 2011
CARB (2015)[82]	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)[81] and Preble et al. (2015)[80] 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 2-45. 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 2-45. Baseline and deteriorated THC and PM 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. 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.[83] MOVES projects that the mean life-time miles traveled of a long-haul combination trucks is 1,530,000 miles, and that the deteriorated emission rate is representative of this phase-of the engine life. 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 2-46. As shown, the MOVES EC/PM emission rates for MY 2007+ trucks are slightly higher than the 'Baseline' EC/PM fractions in Table 2-45, 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 2-46. Emission Rates Calculated from Weighting the 'Baseline' and 'Deteriorated' Emission Rates from Table 2-45 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

Table 2-47 shows the updated MOVES extended idle emission rates for HD GHG Phase 2 Final Rule National Inventory. 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. In MOVES, extended idling is modeled only for long-haul combination trucks, which consist of heavy heavy-duty (HHD) diesel and medium heavy-duty (MHD) diesel engines. We did not analyze extended idle emission rates from MHD trucks. We populated the MHD extended idle emission rates with the same emission rates derived for HHD emission rates for two reasons. First, for simplicity since MOVES estimates that 5 percent of long-haul combination trucks in the US are MHD trucks, thus they are a minor contributor to the emissions from extended idling trucks. Second, Khan *et al.* 2009[84] 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. Without any extended idling data on 2007 and later model year trucks, we felt it was most defensible to keep the MHD emission rates the same as the HHD emission rates.

Table 2-47. Extended Idle Emission Rates for 2007 and Later Model Year Heavy-Duty Vehicles in MOVES

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

2.3.3 Summary of Extended Idle Emission Rates

Extended idle emission rates were updated for all model years, as described in Sections 2.3.1 and 2.3.2. Figure 2-59 through Figure 2-62 illustrate the extended idle emission rates in MOVES201X for regClassIDs 46 and 47.

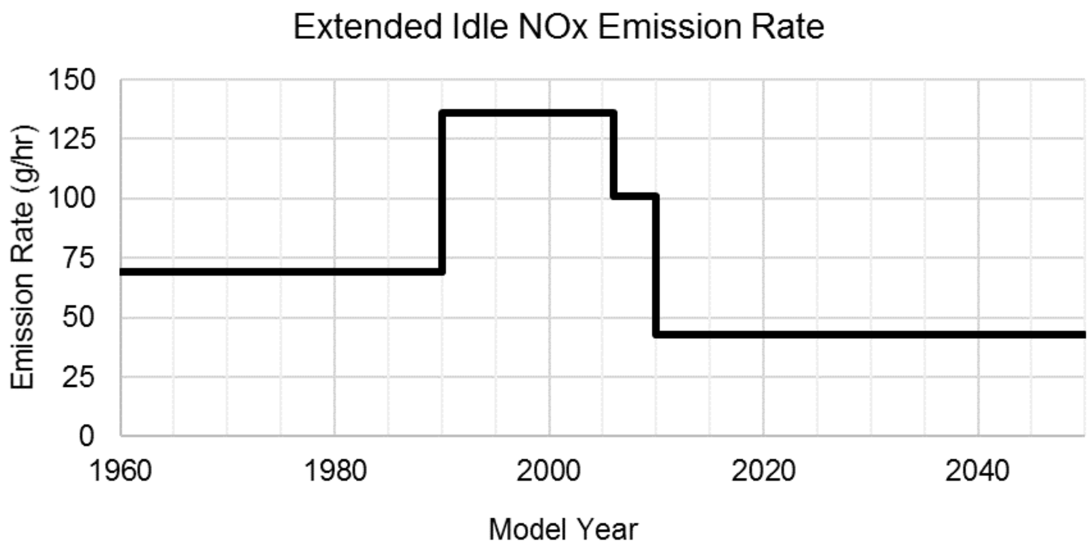


Figure 2-49 Extended Idle NO_X Emission Rates for regClassIDs 46 and 47

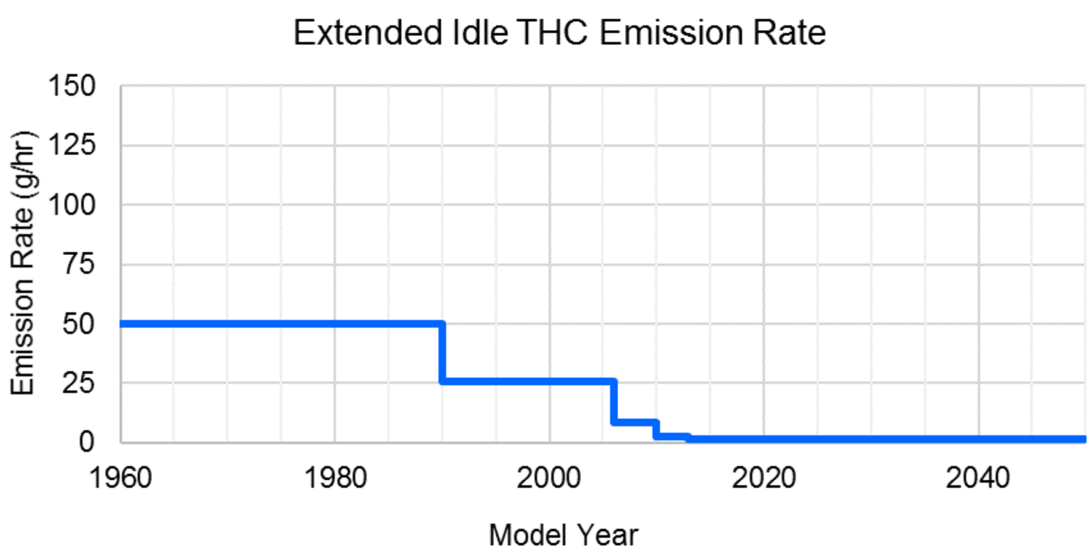


Figure 2-50 Extended Idle THC Emission Rates for regClassIDs 46 and 47

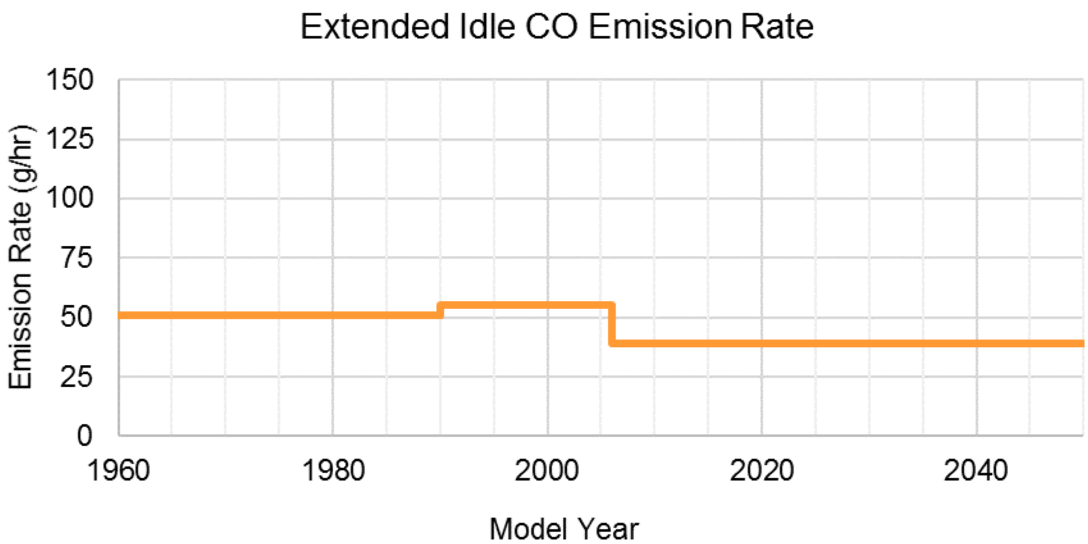


Figure 2-51 Extended Idle CO Emission Rates for regClassIDs 46 and 47

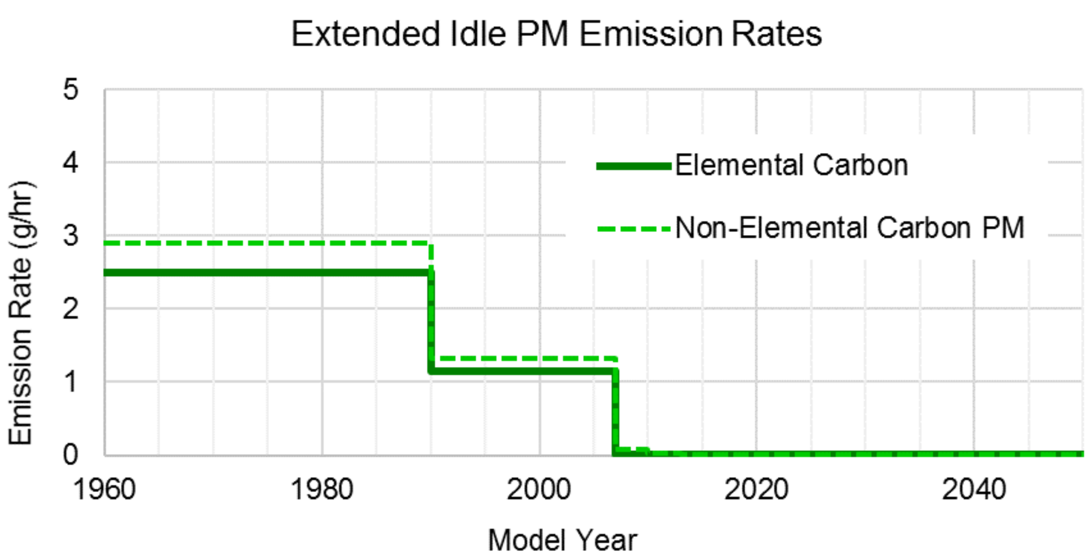


Figure 2-52 Extended Idle PM Emission Rates for regClassIDs 46 and 47

2.3.4 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[56], and are displayed in Figure 2-63. The extended idle energy consumption rates are the same for both regulatory class MHD67 and HHD diesel vehicles. The extended idle energy rates for 2007+ trucks were estimated using the CO_2 emission rates presented in Table 2-47, and are also plotted in Figure 2-63. The extended idle energy consumption rates are the same for both regulatory class MHD67 and HHD diesel vehicles.

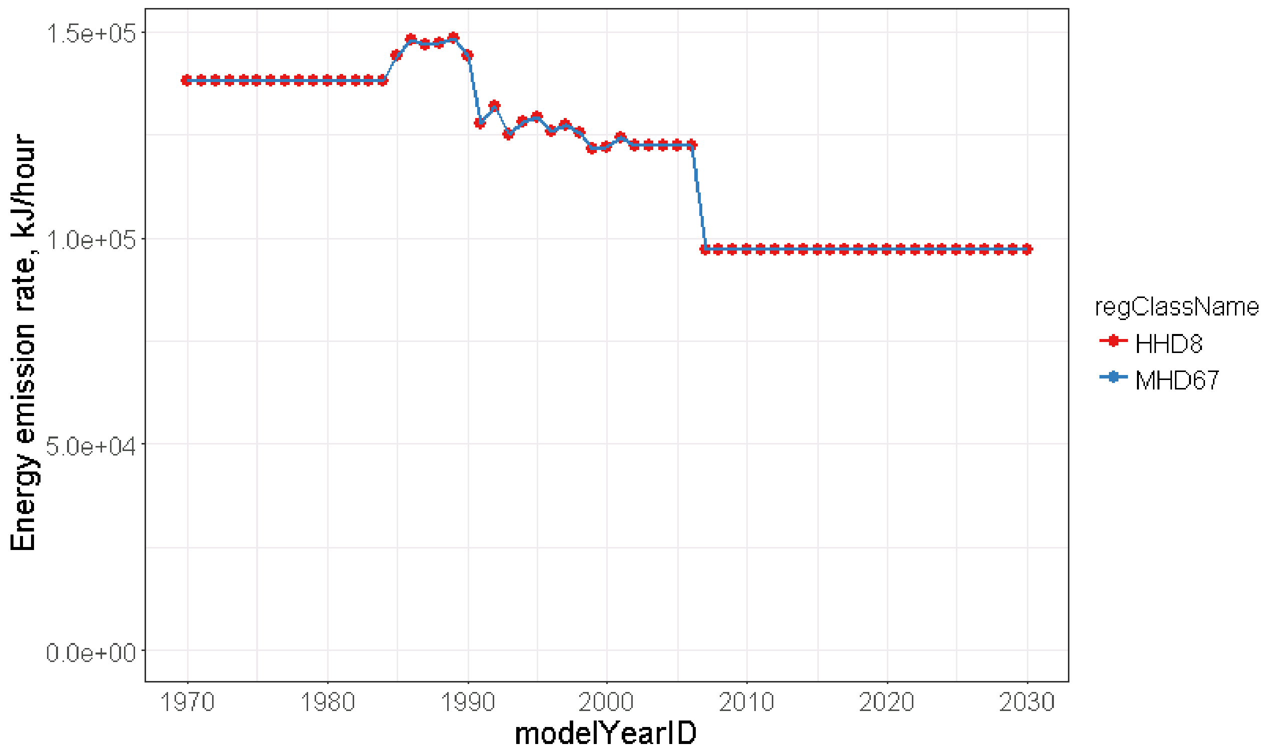


Figure 2-53. Extended Idle Energy Emission Rates for HHD and MHD Diesel Trucks

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 extended idling activity, which are the heavy-duty regulatory classes (MHD and HHD) within the combination truck source types. The projected use of APUs during extended idling due to the HD GHG Phase 2 program, shown below in Table 2-48, were used to revise the “hotellingactivitydistribution” table in MOVES201X.[48] Users can update the fraction of hotelling activity spent in extended idling, APU usage, and engine off activity as discussed in the MOVES2014 User Guide.[85]

Table 2-48: 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%

For MOVES201X, the APU emission rates have been updated to reflect new standards, data, and analysis. The MOVES APU emission rates were updated for the final rulemaking based on two studies that measured in-use APU emission rates. The Texas Transportation Institute (TTI, 2014)[86] tested two diesel APU systems with and without diesel particulate filters for the US EPA, within the TTI environmental chamber at 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.[91,h]

The second study used to update APU emission rates was by Frey and Kuo (2009)[87], who tested two APU systems (APU ID 2 and 3) that both were 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 rate 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 emission rates obtained from the previous two studies. TTI 2012[88] 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[89] 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[87] 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 as comparative data sets.

Table 2-49. 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[86]
2	Kubota Z482	2006	0.48	10.9/8.1	Tier 2	Frey and Kuo 2009[87]
3	Kubota Z482	2006	0.48	10.9/8.1	Tier 2	Frey and Kuo 2009
4	Confidential Information					TTI 2012[88]
5	Confidential Information					TTI 2012
6	Kubota Z482					Storey *et al.* 2003[89]

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

Table 2-50 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, fuel consumption is 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 criteria emissions (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 in the criteria emissions between the hot and cold conditions.

Table 2-50. 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 (℉)	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℃ (50-68℉)

Because the only notable trend in the APU emissions data was the large decrease in PM emission rates with the use of a DPF, for developing baseline MOVES emission rates, we used 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 2-51.

Table 2-51. 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 2-53.

We applied an EC/PM fraction derived from the PM composition measurements made on APU ID 1 as reported in Appendix B. For each test, we calculated the EC/TC ratio, and then averaged the EC/TC ratio across all cold and hot tests, separately for the DPF and the non-DPF tests as shown in Table 2-52. We assumed that 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 2-53.

Table 2-52. Average EC/TC Ratio for APU ID 1 without and with a Diesel Particulate Filter

	EC/TC ratio
APU 1 non-DPF	0.138
APU 1 DPF	0.073

Table 2-53. Fleet-Average Non-DPF Equipped APU Emission Rates in HDGHG2 FRM Nat. Inv

CO_2 (g/hr)	CO (g/hr)	NO_X (g/hr)	THC (g/hr)	PM (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 in 2018 and 2024 (beyond the Tier 4 nonroad standards).[i] 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 2-54.[90]

[i] See 40 CFR 1037.106(g).

Table 2-54: Nonroad Tier 2, Nonroad (8≤KW<19) Tier 4, and HD GHG Phase 2 Emission Standards

Emission Standard	CO g/kW-hr (g/hp-hr)	NMHC + NO_X g/kW-hr (g/hp-hr)	PM g/kW-hr (g/hp-hr)
Tier 2 2005-2007	6.6 (4.9)	7.5 (5.6)	0.8 (0.6)
Tier 4 2008-2017	6.6 (4.9)	7.5 (5.6)	0.40 (0.30)
APU 2018-2023			0.15 (0.11)
APU 2024+			0.02 (0.01)

We developed the future 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.[91]

We anticipate that the APU manufacturers will meet the 2018 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, and when we observed a decrease in PM emissions between the 2012 and 2013 certified APU engines, there was an accompanying 25 percent increase in NO_X emissions. Thus, we conservatively estimated a slight NO_X disbenefit in obtaining a lower PM standard. We estimated the in-use APU NO_X emissions for 2018-2023 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 2018 standard, and estimated the emissions will not change in 2018 for these pollutants.

To achieve the 2024 APU PM standard, 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 2-50), which is similar to the extended idle PM emission rate for 2013+ trucks (Table 2-47) 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 extended idle 2013+ extended idle PM emission rate for the APU emission PM emission rate for 2024 and later model years (Table 2-47). We used the EC/PM split measured from the DPF-equipped APU (Table 2-52) 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 2010-2017 model year group. The emission standard adjusted APU emission rates by model year group are shown in Table 2-55.

Table 2-55 APU Emission Rates in MOVES201X with APU PM Controls in the HD GHG Phase 2 Program

Model Year	CO_2 (g/hr)	CO (g/hr)	NO_X (g/hr)	THC (g/hr)	PM (g/hr)	EC (g/hr)	NonEC (g/hr)	EC/PM	Fuel (gal/hr)
2010-2017[1]	3510	10.0	15.6	1.3	0.96	0.13	0.83	0.14	0.35
2018-2023	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 2010-2017 APU emission rate.

3 Heavy-Duty Gasoline Emissions

The discussion of heavy-duty gasoline vehicles first includes discussion of the running exhaust emissions (Section 3.1), followed by start emissions (Section 3.2).

3.1 Running Exhaust Emissions

3.1.1 HC, CO, and NO_X

3.1.1.1 Data and Analysis for 1960-2007 Model Year Trucks

As gasoline-fueled vehicles are a small percentage of the heavy-duty vehicle fleet, the amount of data available for analysis was small. We relied on four medium heavy duty gasoline trucks from the CRC E-55 program and historical data from EPA's Mobile Source Observation Database (MSOD)[92], 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, HC, and CO analysis, the chassis vehicle speed and acceleration, coupled with the average weight for each regulatory class, were used to calculate STP (Equation

1-2). To supplement the data available, we examined certification data as a guide to developing model year groups for analysis. Figure 3-1 shows averages of certification results by model year.

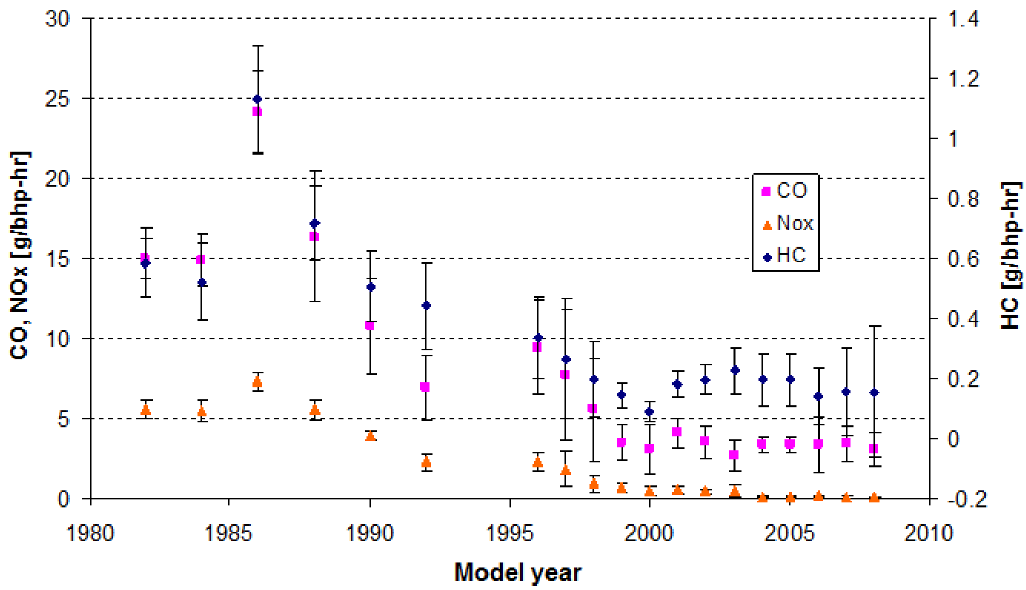


Figure 3-1. Brake-Specific Certification Emission Rates by Model Year for Heavy-Duty Gasoline Engines

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 sparseness of data, we used only the two age groups listed in Table 3-1. We also did not classify by regulatory class since there was not sufficient data to estimate emission rates by separate regulatory classes. The derivation of the model year 2008 and later emission rates are discussed in Sections 3.1.1.3 and 3.1.1.4.

3.1.1.2 Emission Rates for Regulatory Class LHD ≤10K (regClassID 40)

The emission rates were initially analyzed by binning the emission rates using the STP with a fixed mass factor of 2.06, to bring the emission rates into VSP-equivalent space, used for modeling emissions for regulatory class LHD≤10K. Figure 3-2 shows all three pollutants vs. operating mode for the LHD≤10K. In general, emissions follow the expected trend with 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.

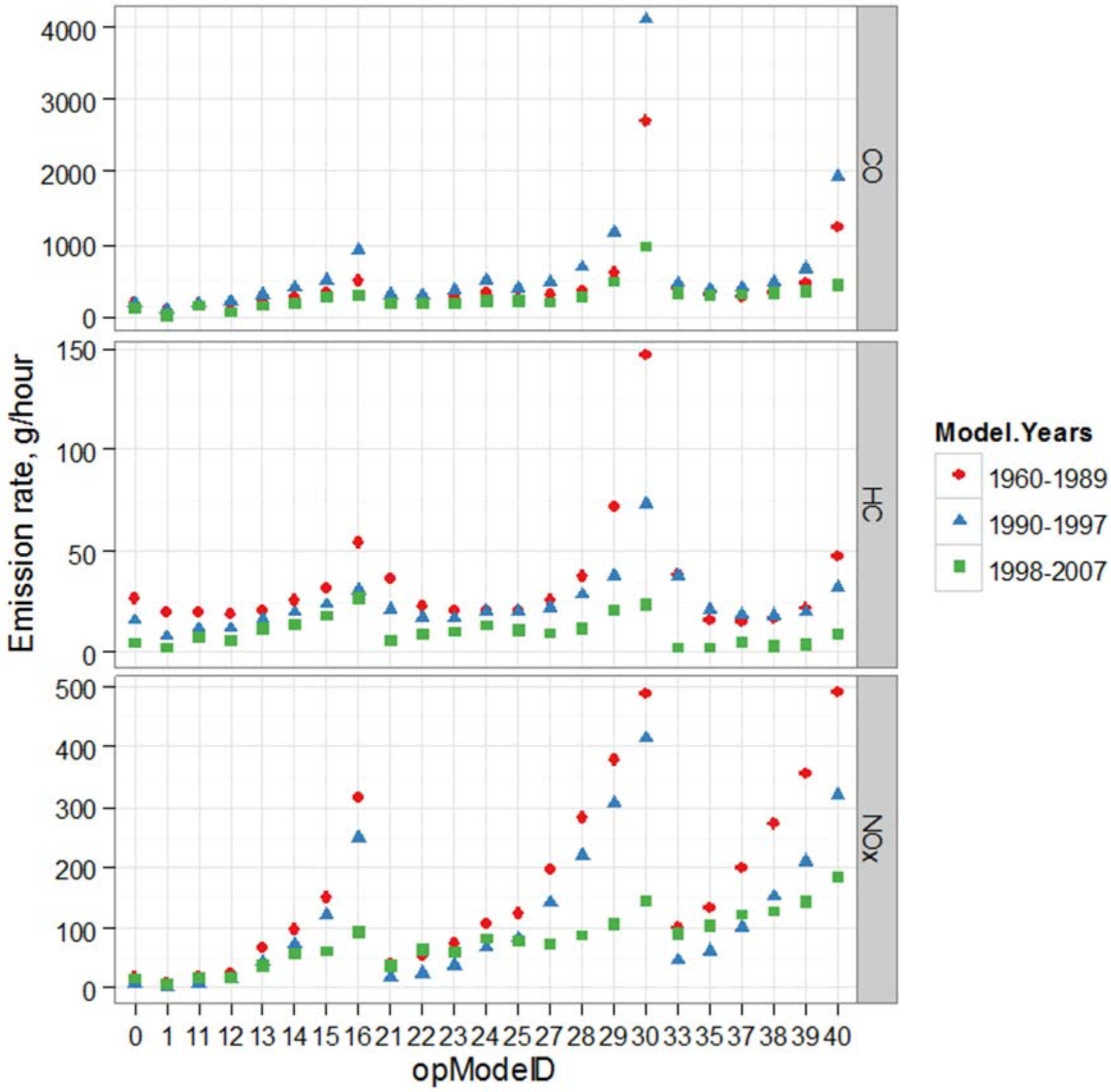


Figure 3-2. Emission Rates by Operating Mode for MY Groups 1960-1989, 1990-1997, and 1998-2007 at Age 0-3 Years for Regulatory Class LHD ≤ 10K

Figure 3-3 shows the emissions trends by age 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.

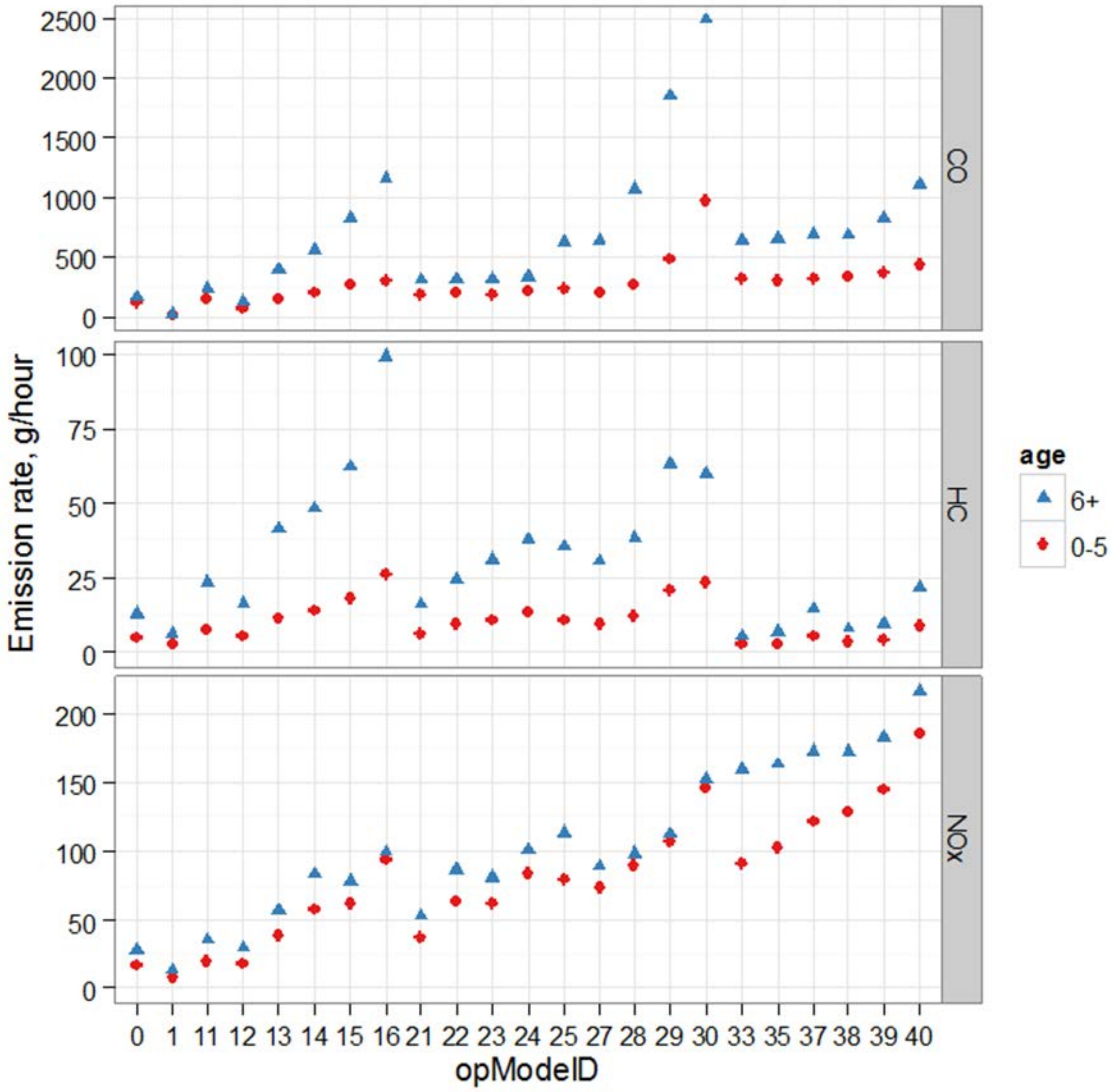


Figure 3-3. Emission Rates by Operating Mode and Age Group for MY 1998-2007 Vehicles in Regulatory Class LHD ≤10K

Table 3-2 displays the multiplicative age effects by operating mode for Regulatory Class LHD≤10K 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 HC, 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 to develop the multiplicative age effects due to the limited data set. The relative age effects were derived for each OpModeID defined using Scaled Tractive Power with the $f_{scale} = 2.06$, to be consistent with LHD≤10K (regClassID 40).

Table 3-2. Relative Age Effect on Emission Rates between Age 6+ and Age 0-5 for LHD≤10K Gasoline Vehicles in Model Years 1960-2007

OpModeID	HC	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

3.1.1.3 Emission Rates for RegClass 40 for 2008 through 2017 Model Years

In MOVES2014, we introduced a new regulatory class, LHD≤10K (regClassID 40) that applies to LHD2b trucks that are classified as passenger or light-commercial trucks. Regulatory class LHD≤14K (regClassID 41) also contains LHD2b trucks, but only vehicles that are classified as single-unit trucks. The distinction was made in MOVES2014 because passenger and light-commercial trucks assign operating modes using VSP, and MOVES assigns STP-based operating modes to single-unit trucks. In previous versions of MOVES (2010b and earlier), regulatory class LHD2b3 (Previously RegClasID 41) was used to model all Class 2b and 3 trucks.

Most of the analysis conducted in this section was conducted assuming that there would be a single regulatory class to represent all Class 2b and 3 trucks (LHD2b3). We thus used the term LHD2b3 trucks to refer to trucks in both regulatory class LHD≤10K (regClassID 40) and LHD≤14K (regClassID 41). However, we used the data in this section only to update the emission rates for regulatory class LHD≤10K (regClassID 40). Emission rates for regulatory class LHDLHD≤14K (regClassID 41) for 2008+ vehicles are discussed in the following section.

3.1.1.3.1 Comparison of LHD2b3 Emission Rates in MOVES2010 with Relevant Emission Standards

Gasoline vehicles in MOVES2010 regulatory class LHD2b3 are a mixture of engine certified heavy-duty vehicles, chassis certified heavy-duty vehicles, and medium duty passenger vehicles (MDPVs). Each group has a separate set of regulations governing their emissions. These emission standards are summarized below (Table 3-3).[j]

Table 3-3. Useful Life FTP Standards from the Tier 2[93] and 2007 Heavy-Duty Highway[94] Rules

	MDPV (Tier 2 Bin 5)	**8.5k – 10K (Class 2B)**	**10K-14K (Class 3)**	**Engine Certified[k]**
Units	g/mile	g/mile	g/mile	g/bhp-hr
Fully Phased in MY	2009	2009	2009	2010
HC	0.09 NMOG	0.195 NMHC	0.230 NMHC	0.14 NMHC
CO	4.2	7.3	8.1	14.4
NO_X	0.07	0.2	0.4	0.2

The relative proportions of the vehicles within the MOVES2010 LHD2b3 regulatory class vary each year depending on demand. Consequently, we estimated proportions based on recent model year data and engineering judgment. MOBILE6 documentation from 2003 indicates that MDPVs were approximately 16 percent of the gasoline 8,500 to 10,000 truck class.[95] In MOVES2014, we project that MDPVs are 15 percent of total MOVES LHD2b3 regulatory class in MYs 2008 and later. The MOBILE6 document also states that more than 95 percent of class 2B trucks are chassis certified.[95] Thus, we estimate that 5 percent of all vehicles in the LHD2b3 regulatory class are engine certified. Based on analysis from the recent medium and heavy-duty greenhouse gas rulemaking, we assume that sales of 2B class trucks vehicles were triple that of 3 class trucks.[96] This is roughly consistent with recent model year sales totals.[97] Combining these assumptions, we get the sales fractions shown below (Table 3-4).

Table 3-4. Population Percentage of LHD2b3 Trucks

	% of Reg Class
MDPV	15%
Class 2B	60%
Class 3	20%
Engine Certified	5%

To generate an aggregate FTP standard for LHD2b3 regulatory class, we weighted the individual certification standards shown in Table 3-3 using the proportions shown in Table 3-4.[l] While the model produces estimates of onroad emissions rather than certification emissions, the weighted certification standard is a useful benchmark for the modeled rates (Table 3-5).[m]

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[j] This mixture of vehicles was not explicitly considered during the development of MOVES2010.
[l] The engine standard was converted to a g/mile standard using a factor of 1.2 as described in the MOBILE6 report
[l] The engine standard was converted to a g/mile standard using a factor of 1.2 as described in the MOBILE6 report
[m] Several simplifications were made in calculating this aggregate useful life FTP. The distinction between NMHC and NMOG was ignored in calculating the aggregate FTP, and would have yielded only minor variation in the aggregate certification standard. The engine standard was also converted to a chassis equivalent as discussed above.

Table 3-5. Aggregate Useful Life FTP Standard for LHD2b3 trucks

	g/mile
NMOG	0.18
CO	7.49
NO_X	0.22

As a benchmark, we compared the calculated aggregate FTP standard to an FTP calculated using the emission rates in the MOVES2010a database. The Physical Emission Rate Estimator (PERE),[35] modified to produce Scaled Tractive Power (STP) distributions, was used to generate the operating mode mix of a LHD2b3 regulatory class vehicle on the Federal Test Procedure drive cycle. For the STP modification, we changed the vehicle weight in PERE to match the Light-Commercial Truck source type (sourceTypeID 32) in MOVES (2.06 Tons). We incorporated emission rates from the MOVES database for the age 0-3 group, and added in a cold start (operating mode 108) and a hot start (operating mode 102) from the MOVES database. The modified version of PERE produced the operating mode distribution shown in Table 3-6.

Table 3-6. Operating Mode Bin Distribution for a Light-Commercial truck on the Federal Test Procedure (FTP)

OpModeID	N	%	OpModeID	N	%
0	160	12%	**25**	41	3%
1	258	19%	**27**	49	4%
11	94	7%	**28**	17	1%
12	68	5%	**29**	13	1%
13	70	5%	**30**	15	1%
14	36	3%	**33**	13	1%
15	48	3%	**35**	12	1%
16	141	10%	**37**	13	1%
21	68	5%	**38**	17	1%
22	44	3%	**39**	15	1%
23	97	7%	**40**	6	0%
24	77	6%			
			Total	1372	100%

Using this operating mode distribution, we constructed a simulated FTP out of four components (bag 1/3 running,[n] cold start, hot start, and bag 2 running). We constructed bag 1 (cold start + bag 1 running) and bag 3 (hot start + bag 3 running) and weighted the resulting components together according to the FTP formula,[o] and compared the 2008 and later rates in MOVES to the aggregate standard calculated above (Table 3-7). MOVES2010a estimates at age 0-3 were two to ten times larger than the standard, which indicates that the average vehicle HD gas vehicle in MOVES2010a is modeled as significantly out of compliance with the relevant emission standards.

[n] Bag 1 and Bag 3 are considered to have the same emission rate.

[o] FTP =((Bag 1 + Bag 2)*0.43+ (Bag 3+ Bag 2)*0.57)/ 7.45

Table 3-7. Comparison between MOVES DB FTP and Aggregate FTP for LHD2b3 trucks

	MOVES2010 FTP for LHD2b3 Trucks (g/mile)	LHD2b3 Aggregate FTP Standard (g/mile)	Ratio – MOVES to Aggregate Standard
NMOG	0.36	0.18	1.93
CO	14.54	7.49	1.94
NO_X	2.04	0.22	9.28

3.1.1.3.2 Validation against In-Use Verification Program Data

We compared the In-Use Verification Program (IUVP) data for MYs 2004-2008 vehicles (estimated test weights of 7,500 pounds to 10,000 pounds) to the MOVES2010 emission rates.[p] We evaluated whether vehicles during these MYGS were achieving the standard, or if alternate methods were being used for compliance. While the IUVP data is not fully representative of the in-use fleet, it provides a reasonable snap-shot. Without weighting for sales or accounting for the standards applicable to each vehicle, we calculate average ratios of test value to the aggregate standard (Table 3-8) of 0.42 (NMOG) and 0.23 (NO_X). These ratios indicate that vehicles typically comply with the standard, with a significant amount of headroom. The distribution of the data is shown in Figure 3-4.

Table 3-8. Average Compliance Margin and Headroom for LHD2b3 Trucks

	Average	Average
	Ratio Certification FTP/Aggregate Standard	Headroom
NMOG	0.42	0.58
NO_X	0.23	0.77

[p] While this population of vehicles is not identical, these test weights significantly overlap with these GVWR classes.

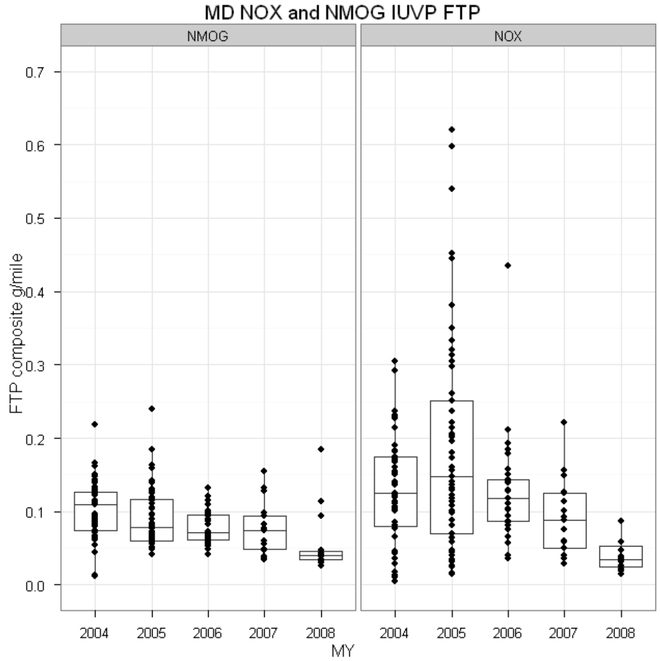

Figure 3-4. Distribution of IUVP FTP Tests for LHD2b3 Trucks

The emission rates in MOVES include all vehicles, and consequently represent a broader sample than the IUVP data. As a result, we expect that the onroad vehicles would have higher emission rates than vehicles in the IUVP program.[q] However, the emission rates represented by MOVES2010 are higher than those that would be expected from vehicles compliant with the standards in place in MY 2008 and later.

3.1.1.3.3 Emission Rates

We updated the HC/CO/NO_X emission rates for regulatory Class LHD≤10K (regClassID 40) vehicles in 2008 and later MYs in MOVES2014.

In conducting this analysis, we lacked any modal data on regulatory class LHD≤10K (regClassID 40) vehicles. As such, we conducted the analysis using a method that we have used repeatedly on the light-duty side, which is ratioing the modal emission profile by the difference in standards.[9] By MY 2008, the medium duty vehicles are nearing the emission levels of Tier 2 Bin 8 vehicles. Consequently, we relied on the analysis of in-use Tier 2 Bin 8 vehicles conducted for the light-duty vehicle emission rates.[9] Because we are basing the emission rates on light-duty emission rates (which are also VSP-based), the emission rate update is limited to regulatory class LHD≤10K (regClassID 40) vehicles.

[q] Even in the absence of emission equipment deterioration, tampering and mal-maintenance will increase the emissions from an onroad vehicle.

We scaled the modal data from Tier 2 Bin 8 vehicles by the ratio of FTP standards[r] so that the rates would be consistent with the higher emission rates of regulatory class LHD≤10K (regClassID 40) vehicles, as shown in Table 3-9.

Table 3-9. Aggregate LHD2b3 Standard Ratios against Bin 8 Modal Rates

	Aggregate LHD2b3 FTP standard	Bin 8 FTP standard	Aggregate/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 converted this ratio into a "split" ratio, where the running rates increased twice as much as the start rates, but the same overall emissions were simulated on the FTP. 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 running and start, which were applied to the light-duty Tier 2 Bin 8 vehicle emission rates are shown in Table 3-10.

Table 3-10. Ratio Applied to Light-Duty Tier 2 Bin 8 Emission Rates to Estimate Regulatory Class LHD≤10K (regClassID 40) Emission Rates for 2008-2017 MY

	HC	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 2009 and later regulatory class LHD≤10K (regClassID 40) 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 3-11.

Table 3-11. Multiplicative Age Effect used for Running Emissions for Regulatory Class LHD≤10K (regClassID 40) 2008+ Model Years

ageGroupID	HC	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

[r] The aggregate FTP standards used include both Class 2b and 3 trucks. However, the ratio is only applied to develop updated regulatory class LHD≤10K (regClassID 40) emission rates (which only contain 2b trucks). The LHD2b3 aggregate emission factors are 2 percent, 28 percent, and 25 percent higher than aggregate emission factors based on 2b trucks only for NMOG, CO, and NOx. However, as discussed later, the final emission rates are still below the aggregate standard. So, we believe using the LHD2b3 aggregate standard is appropriate.

After applying the above mentioned steps (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 scaled to be higher than MY 2006 regulatory class LHD≤10K (regClassID 40) rates. This essentially capped the emission rates, such that none of the operating mode, or age–specific emission rates for 2009 and later model year vehicles are higher than the 2007 and earlier model year emission rates.

This final step capped emission rates in the highest operating modes, as shown in Figure 3-5. For HC, 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. shows the regulatory class LHD≤10K (regClassID 40) model year 2008-2017 emission rates for CO, HC, and NO_X. Emission rates that exhibit the start-step deterioration trend are the emission rates that were capped with the pre-2007 emission rates. Even with the capped emission rates, the regulatory class LHD≤10K (regClassID 40) emission rates are higher than the Light-Duty Trucks (regClassID 30) emission rates with a few exceptions. The few exceptions are some of the age-dependent HC and or CO emission rates in operating modes 1, 30, 38, 39, and 40. However, the majority of emission rates are significantly higher in regulatory class LHD≤10K than regulatory class Light-Duty Trucks and when used in MOVES, the simulated FTP emission rates are significantly higher for regulatory class LHD≤10K vehicles.

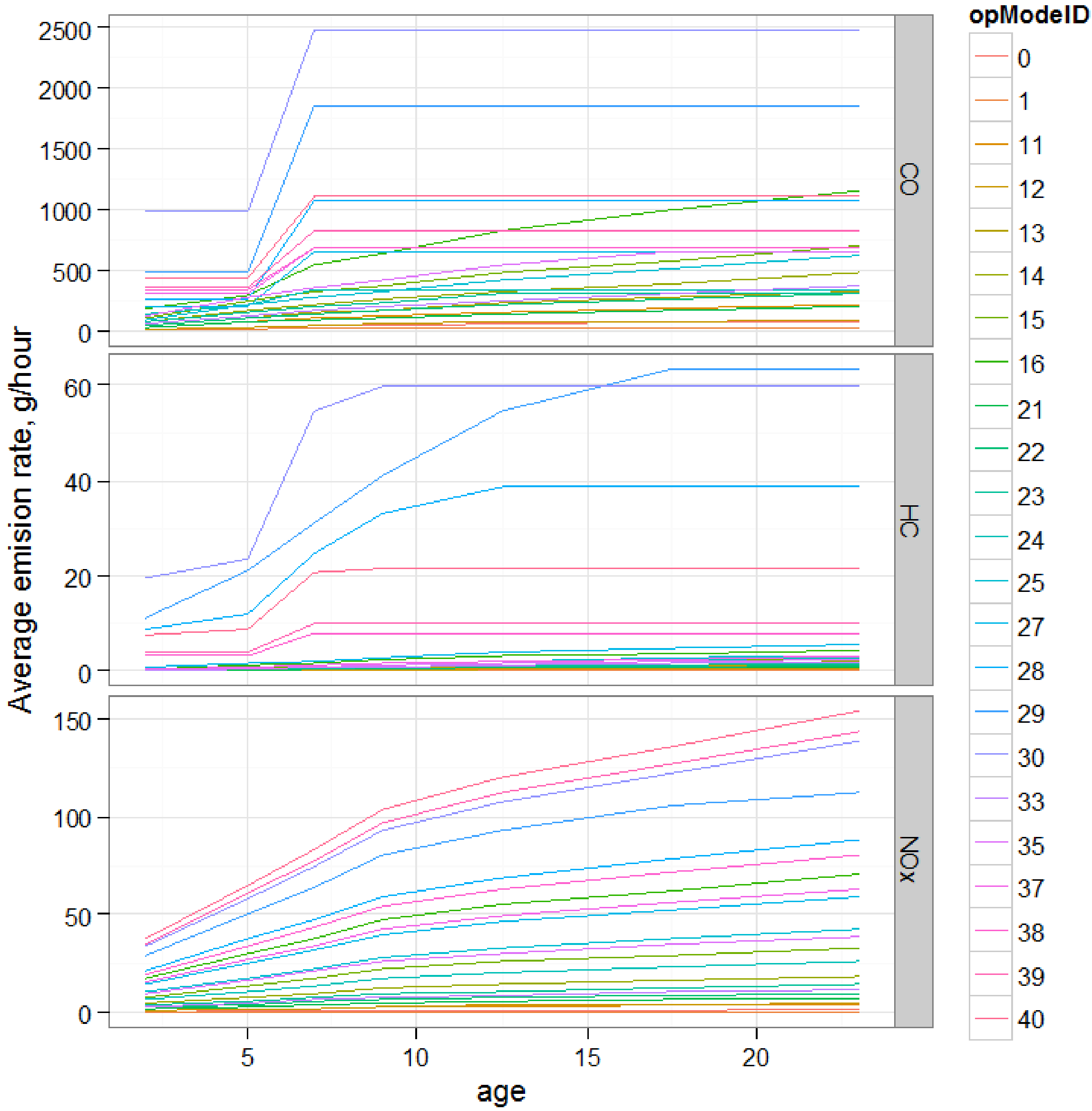

Figure 3-5. Age Effects for CO, HC, and NO_X Emission Rates for Regulatory Class LHD≤10K (regClassID 40) Vehicles in Running Operating Modes for MY 2008-2017

After calculating new regulatory class LHD≤10K (regClassID 40) emission rates, we used the emission rates to simulate an FTP cycle, as shown in Table 3-12. We compared these emission rates to the calculated aggregate standard. The calculated headroom for NO_X is less than that shown in the IUVP data, and the calculated headroom for NMOG is greater than that shown in the IUVP data (Table 3-8). For NO_X, this difference is more significant. However, as stated above, the IUVP data is not fully representative of in-use vehicles. By contrast, the Tier 2 Bin 8 rates are based on extensive I/M testing, and are considered more representative of the entire fleet.

Table 3-12. Ratio of Final Rates against Standards

	Simulated LHD≤10K regulatory class 2008+ FTP (g/mile)	Aggregate 2010+ LHD2b3 FTP Standard (g/mile)	Simulated FTP emissions/ Aggregate FTP Standard
NMOG	0.06	0.18	33%
CO	3.08	7.49	41%
NO_X	0.18	0.22	84%

In terms of the phase-in, we assumed that the regulatory class LHD≤10K (regClassID 40) rates phase in at a rate of 50 percent in MY2008 and considered fully phased in MY2009. The MY2008 running emission rates are interpolated values between the 2007 and 2009 emission rates by operating mode and age group.

3.1.1.4 Running Emission Rates for Regulatory Class LHD≤10K (regClassID 40) Vehicles for 2018 and later

The Tier 3 program will affect not only light-duty vehicles (below 8,500 pounds GVWR), but also chassis-certified vehicles between 8,500 and 14,000 pounds GVWR. This class of vehicles is referred to "light heavy-duty" or "medium-duty" vehicles. This regulatory class comprises several classes of vehicles, including Class 2b and Class 3 trucks, medium-duty passenger vehicles (MDPV) and engine-certified trucks. However, the latter two groups of vehicles are not regulated under the medium-duty standards described here. However, for completeness, they are reflected in the emission rates.

During the phase-in period, we assumed that Class 2b and 3 vehicles would be certified to four standard levels. Composite FTP values for these standard levels are shown in Table 3-13. Phase-in fractions for each standard level are also shown in Table 3-14. The phase-in fractions were applied to the FTP values to calculate weighted average FTP values for these two truck classes for each model year during the phase-in, as shown in Table 3-15.

In addition to the 2b and 3 vehicles regulated under Tier 3, light heavy-duty vehicles also include MDPV and engine-certified vehicles. Composite FTP values were estimated for these classes as well. The levels for MDPV were assumed to be equivalent to Tier 2 Bin 8 vehicles in 2017 and to light-duty vehicles in 2022 (30 mg/mi). Interim values were calculated for each model year during the phase-in by assuming a linear decrease over each year between the initial and final values. The FTP values for the engine-certified vehicles were assumed to be unaffected by the Tier 3 standards and to therefore remain constant throughout. The projected averaged FTP values for these two vehicle classes are also shown in Table 3-15.

Finally, weighted average values for all four vehicle classes were calculated as shown in Equation 3-1. Note that the weights assigned to each vehicle class are equivalent to those previously shown in Table 3-4. Values of the weighted means by model year are shown in Table 3-15.

$$FTP_{\text{weighted}} = 0.8\left(0.75\ \text{FTP}_{2b} + 0.25\ \text{FTP}_{3}\right) + 0.05\ \text{FTP}_{\text{Engine-certified}} + 0.15\ \text{FTP}_{\text{MDPV}} \qquad \textbf{Equation 3-1}$$

Table 3-13. Composite FTP NMOG+NO_X Standards for Class 2b and 3 Vehicles (mg/mi)

Vehicle Class	LEV	ULEV34	ULEV25	SULEV17
2b	395	340	250	170
3	630	570	400	230

Table 3-14. Phase-in Fractions by Standard Level for Class 2b and 3 Vehicles

Model Year	LEV	ULEV34	ULEV25	SULEV17
2017	0.10	0.50	0.40	0.0
2018	0.0	0.40	0.50	0.10
2019	0.0	0.30	0.40	0.30
2020	0.0	0.20	0.30	0.50
2021	0.0	0.10	0.20	0.70
2022	0.0	0.0	0.10	0.90

Table 3-15. Projected FTP Composite Values for Four Vehicle Classes (mg/mi), plus Weighted Means, for 2017 (pre-Tier 3) and 2022 (Full Phase-in of Tier 3)

Model Year	Vehicle Class				Weighted Mean
	2b	3	MDPV	Engine-Certified	
2017					400
2022	178	247	30	408	181

If we take the initial value before onset of the phase-in (400 mg/mi) and the final value when the phase-in is complete (181 mg/mi), and treat these two values as references, we can calculate the phase-in fractions that correspond to the weighted means in each intervening model year from 2018 to 2021 inclusive, as shown in Equation 3-2. Resulting phase-in fractions so calculated are shown in Table 3-16.

$$\mathbf{FTP}_{weighted} = 181 f_{T3} + 400(1 - f_{T3}) \qquad \textbf{Equation 3-2}$$

Table 3-16. Phase-in Fractions Applied to Rates in Model Years 2018 and Later to Represent Partial and Full Tier-3 control

Model Year	f_{T3}	$1 - f_{T3}$
2017	0.00	1.00
2018	0.49	0.51
2019	0.62	0.38
2020	0.75	0.25
2021	0.87	0.13
2022[1]	1.00	0.00

[1]Also applicable to model years 2022 and later.

To calculate modal emission rates in MY2018 and later, we applied the fractions shown in Table 3-16 above to sets of modal rates representing MY 2017 and MY2022.

The rates for MY2017 were extracting from a previous version of the MOVES database used in analyses supporting the Tier-3 Rulemaking, and represented existing rates prior to the adoption of Tier-3 standards.[s] The rates for MY2022 were estimated as equivalent to light-duty rates, assuming a fleet composition of 10 percent Bin 8 and 90 percent Bin 5 standards. These rates were designed to represent full Tier-3 control.

Thus, starting with these subsets of rates for MY2017 and MY2022, the calculation shown in Equation 4-2 was performed for all rates across all operating modes and ageGroups. Resulting rates for HC, CO and NO_X are shown in Figure 3-6, Figure 3-7, and Figure 3-8 respectively.

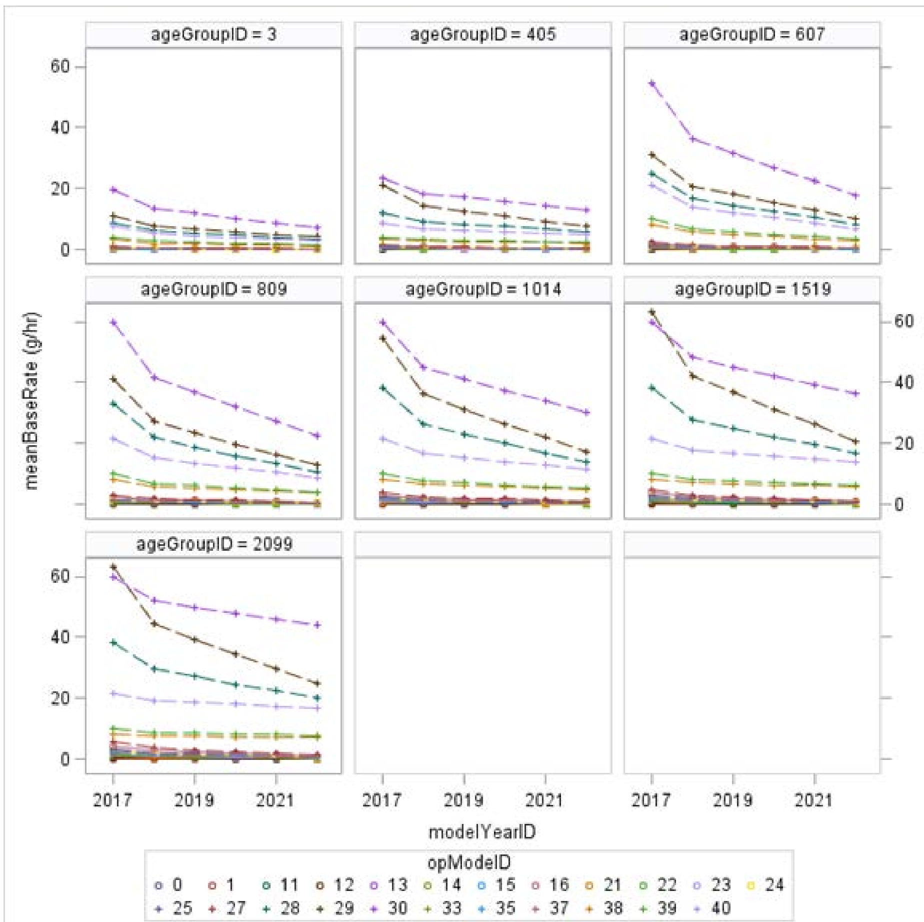

Figure 3-6. THC: Running-Exhaust Emission Rates for Vehicles in the LHD≤10K Regulatory Class (regClassID 40), during the Tier-3 Phase-in

[s] The database version used was MOVESt3DB20110331.

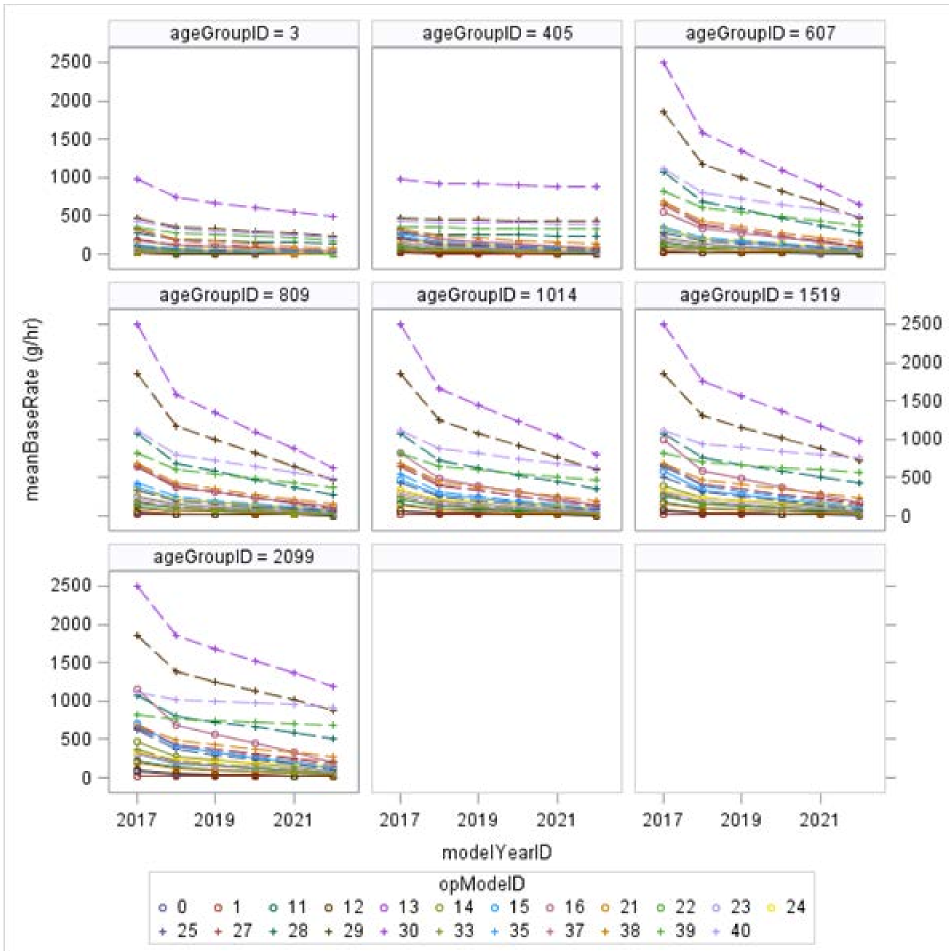

Figure 3-7. CO: Running-Exhaust Emission Rates for Vehicles in the LHD≤10K Regulatory Class (regClassID 40), during the Tier-3 Phase-in

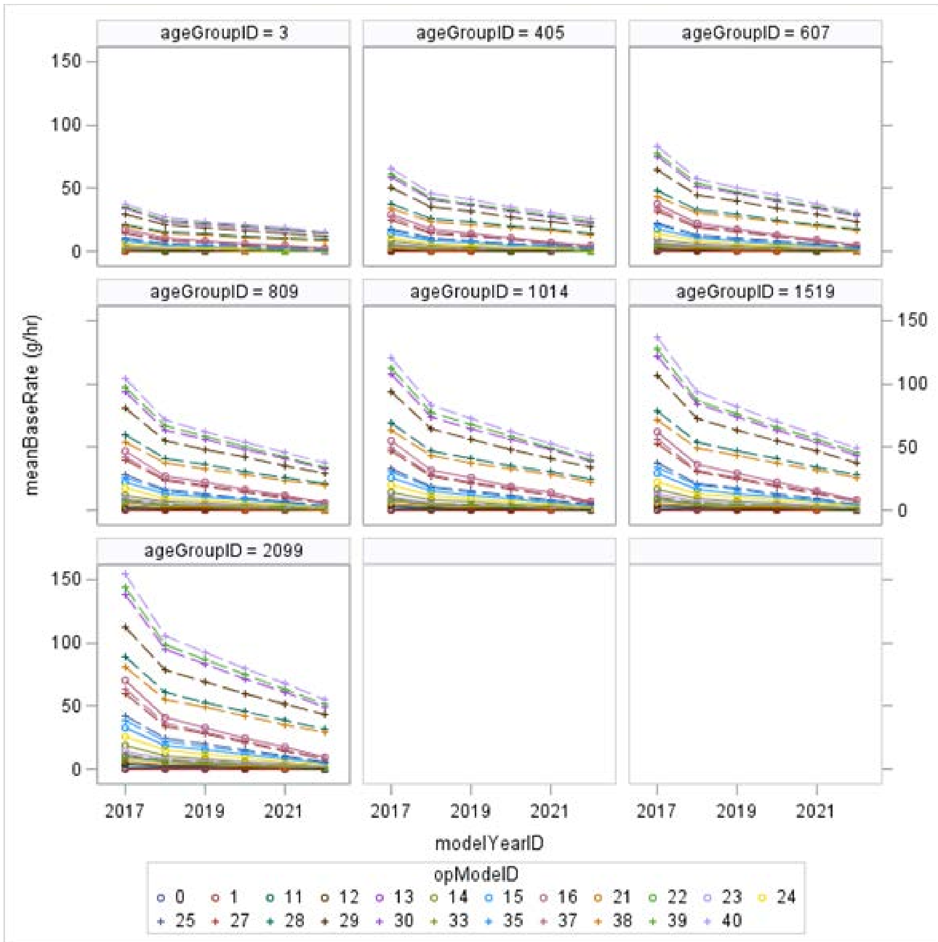

Figure 3-8. NO_X: Running-Exhaust Emission Rates for Vehicles in the LHD≤10K Regulatory Class (regClassID 40), during the Tier-3 Phase-in

Figure 3-9 summarizes the decreasing trend in emissions from the analysis documented in this chapter, showing the average emission rates (across all operating modes) for CO, HC, and NO_X for the 1980 to 2007 model years for LHD≤10K vehicles. Note that the 1980 rates are used for all model years 1960-1980, and the 2030 rates are used for all model years beyond 2030.

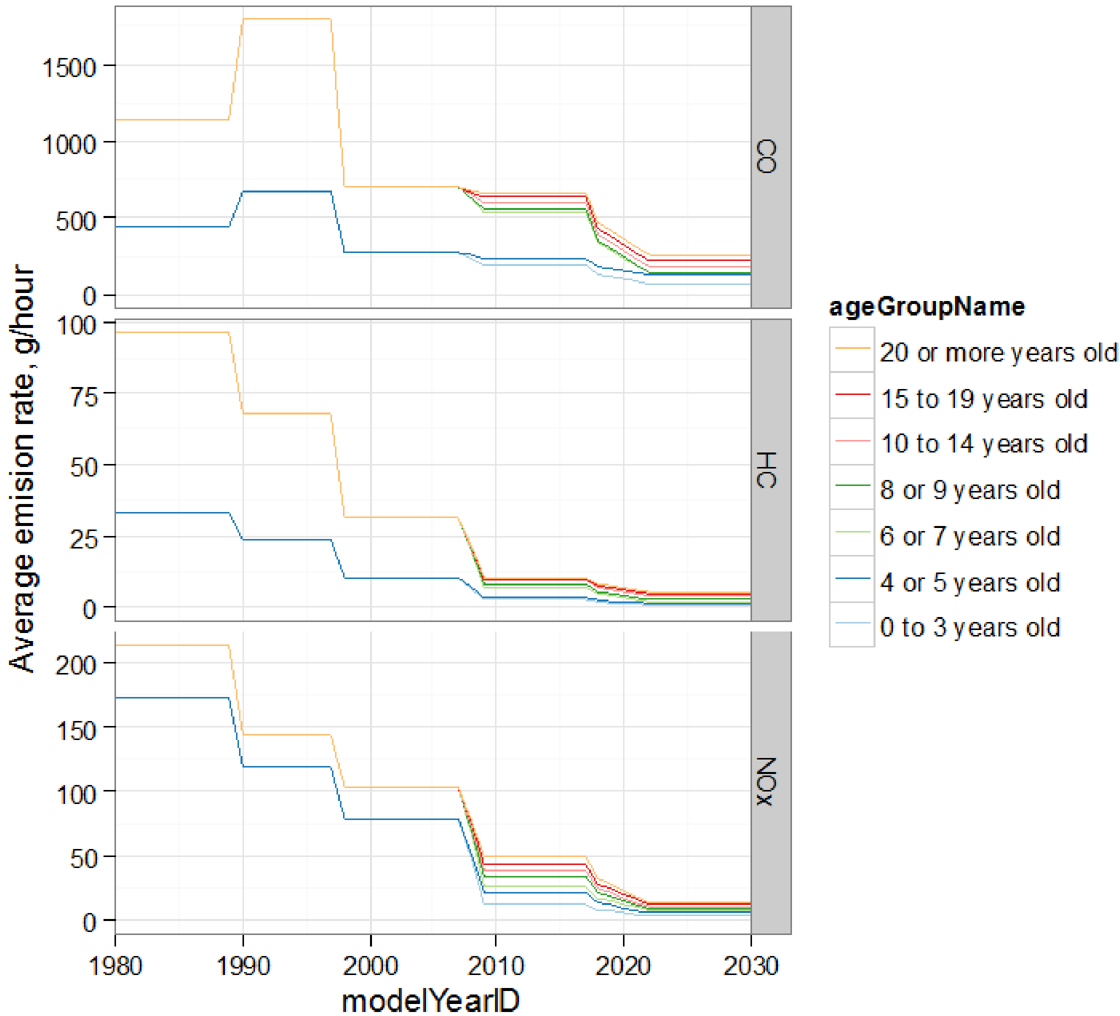

Figure 3-9. Average Emission Rate (across all Operating Modes) for Regulatory Class LHD≤10K (regClassID 40) Trucks for CO, HC, and NO_X. The 1960-2007 emission rates only differ according to two broad age groups (0-5) and (6+). For 2008 and later emission rates, the emissions differ according to the age groups shown in the legend.

3.1.1.5 Running Emission Rates for Regulatory Class LHD≤14K, LHD45, and MHD, and HHD for 1960-2007 Model Years

Emission rates are equivalent across all the heavy-duty gasoline regulatory classes: LHD≤14, LHD45, MHD, and HHD. Like the regulatory class LHD≤10K rates described above, the heavy-duty gasoline rates are based on emissions data from the mix of LHD2b3 and MHD vehicles outlined in Table 4-1. The same model year groups are used to classify the emission rates: 1960-1989, 1990-1997, and 1998-2007. Also, we use the same relative increase in emission rates for the age effect. The only difference from the analysis of regulatory class LHD≤10K emission rates is that the regulatory class LHD≤14K, LHD45, MHD, and HHD emission rates were analyzed using STP operating modes with a fixed mass factor of 17.1. Sample emission rates for HC, CO, and NO_X for the 1994 MY Group are presented in Figure 3-10 for these source types.

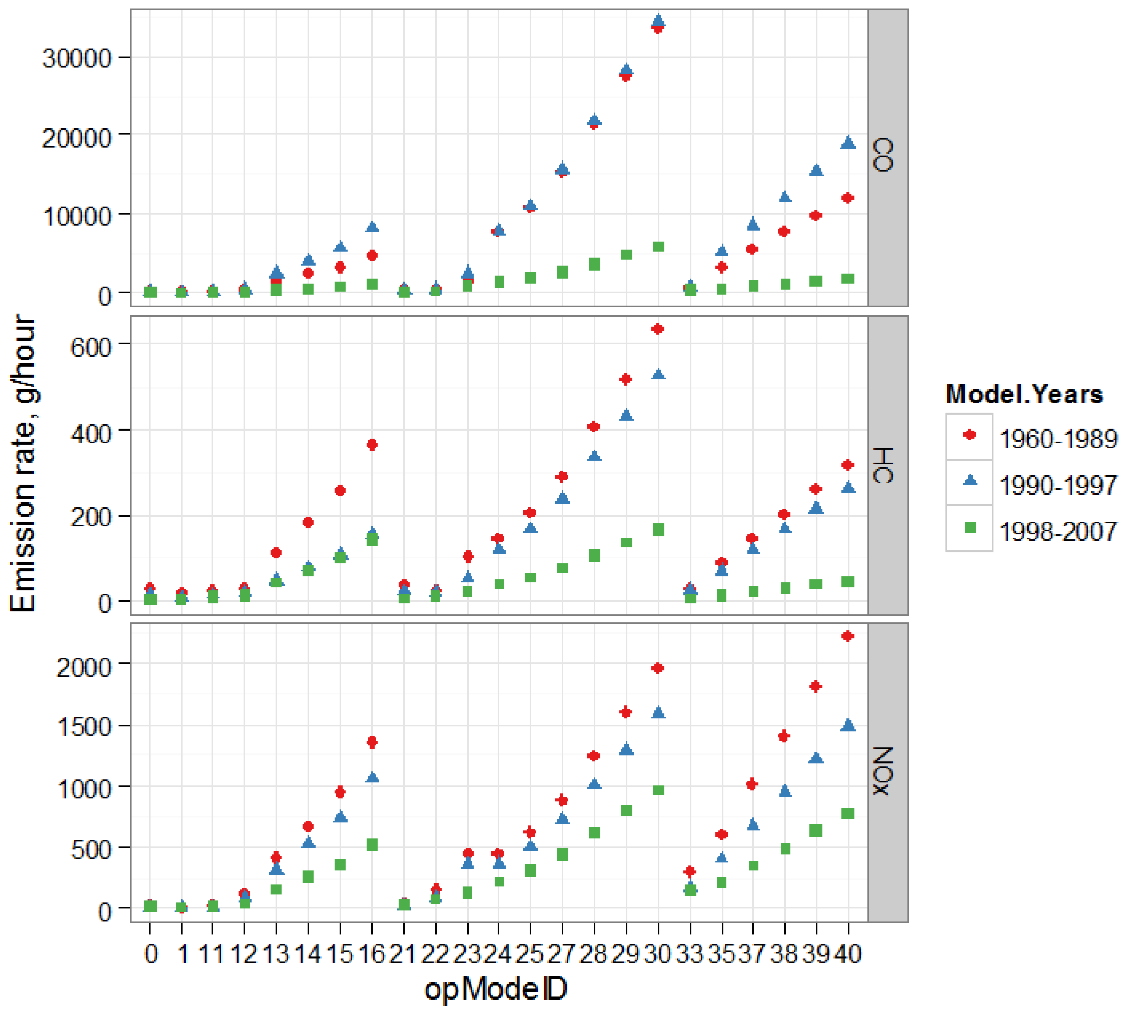

Figure 3-10. Emission Rates by STP Operating Mode for MY 1994 at age 0-3 years for Regulatory Classes LHD < 14K, LHD45, MHD, and HHD

Table 3-17 displays the multiplicative age effects by operating mode for LHD<14K, LHD45, MHD, and HHD gasoline vehicles. While these age effects were derived from the same data as those for the LHD≤10K vehicles, these heavy-duty age effects are slightly different for these vehicles, 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≤10K age effects. Also, because the vehicles tested were LHD2b/3 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 3-17 Relative Age Effect on Emission Rates between Age 6+ and Age 0-5 for LHD<14K, LHD45, MHD, and HHD Gasoline Vehicles in All Model Years 1960-2050

OpModeID	HC	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 3-11 displays the resulting emission rates by operating mode bin and age group for the LHD<14K, LHD45, MHD, and HHD gasoline vehicles, which were calculated by applying the multiplicative age effects in Table 3-17.

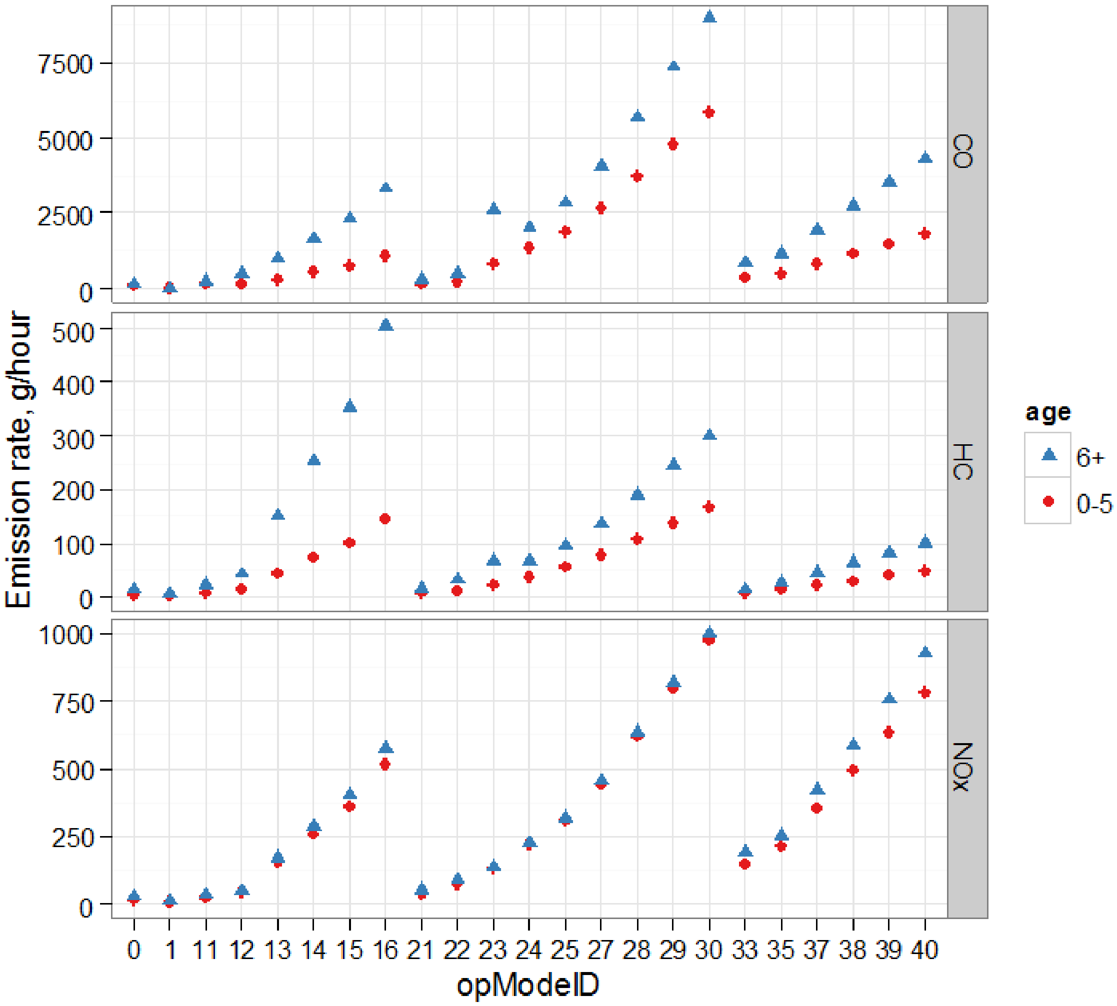

Figure 3-11. Emission Rates by Operating Mode and Age Group for MY 1998-2007 Vehicles in Regulatory Class LHD ≤14K, LHD45, MHD, and HHD Gasoline Vehicles

3.1.1.6 Running Emission Rates for Regulatory Class LHD≤14 K, LHD45, and MHD, and HHD for 2008 and Later Model Years

Of the onroad heavy-duty vehicles GVW class 4 and above, a relatively small fraction are powered by gasoline: about 15 percent are gasoline, as opposed to 85 percent diesel.[t] The gasoline percentage decreases as the GVW class increases. Since these vehicles are a small portion of the fleet, there is relatively little data on these vehicles, and we did not update the 2008 and later model year emission rates from MOVES2010.[98] The 2008 and later model years are modeled with a 70 percent reduction in the running rates starting in MY 2008, which is consistent with the emission standard reduction with the "Heavy-Duty 2007 Rule".[99] The 2008 and later 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, as shown in Figure 3-14. The analysis of regulatory class LHD≤10K (regClassID 40) emission rates for 2008 and later model years is based on light-duty truck VSP-based emission rates. We did not have load-based data on class 2b and 3 trucks to derive STP-based emission rates specific for regulatory class LHD≤14K (regClassID 41) trucks. As such, we estimate regulatory class LHD≤14K trucks for 2008 -2017, using the relatively simple 70 percent reduction from the 1998-2007 baseline.

3.1.1.7 Running Emission Rates for Regulatory Class LHD≤14K for 2018 and Later Model Years

As discussed earlier, regulatory class LHD≤14K (regClassID 41) includes Class 2b and 3 trucks; as such, the Tier 3 Vehicle Emission standards apply to 2b portion of this category. Rates for vehicles in this regulatory class were developed in the same way as those for the LHD≤10K regulatory class, as described in Section 3.1.1.4.

However, for these two classes, the rates for running operation differ in that those for regulatory class LHD≤10K (regClassID 40) are based on STP with a fixed mass factor of 2.06, whereas those for regulatory class LHD≤14K (regClassID 41) are based on STP with the same fixed mass factor (17.1) used for the other heavy-duty regulatory classes.

For these two sets of rates, the absolute values of the running rates differ but the relative reductions representing Tier 3 control in each model year are applied in the same proportions. These patterns are shown in Figure 3-12 and Figure 3-13 which show rates for regulatory classes LHD≤10K and LHD≤14K in selected operating modes for running emissions. Note that the results are shown on logarithmic scales, and that the parallelism in the trends indicates that the proportional reductions are identical for both the LHD≤10K (regClassID 40) and the LHD≤14K (regClassID 41) rates. Figure 3-14 displays the emission rates across all model years for LHD≤14K, LHD45, MHD and HHD (regClassIDs 41,42,46 and 47). Only LHD≤14K shows a decrease in emission rates in the 2018-2021 model year time frame.

[t] Negligible portions are run on other fuels. The figures are aggregated from data supplied by Polk.

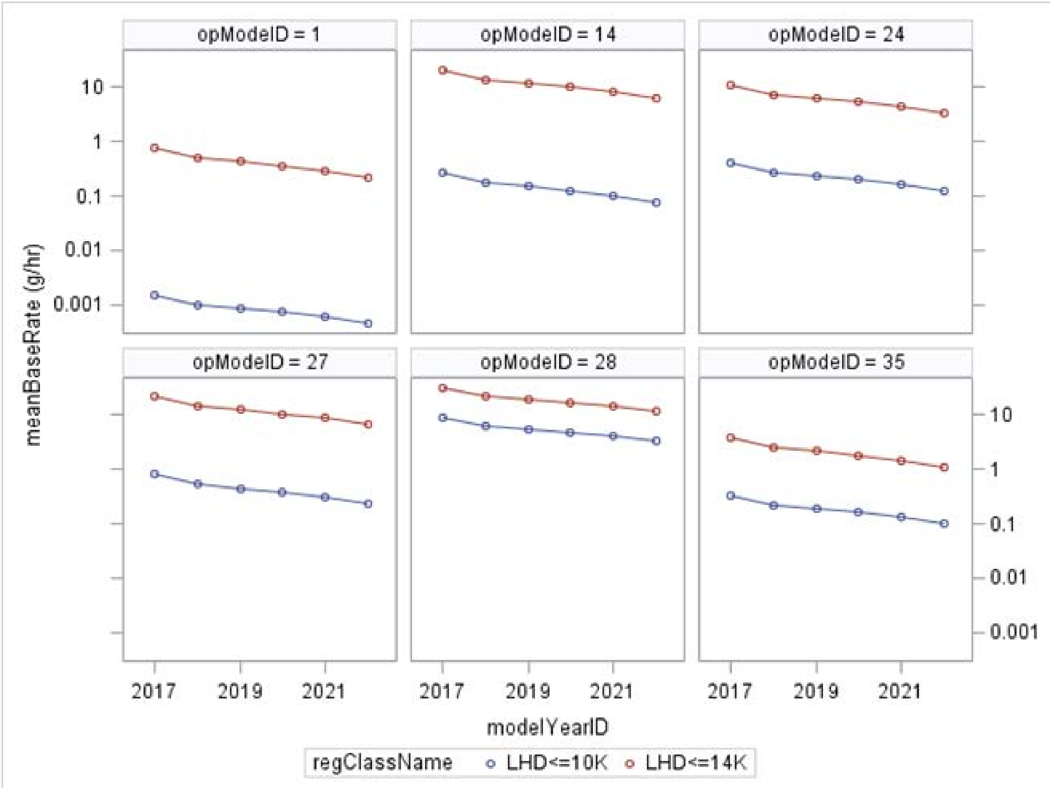

Figure 3-12. THC Emission Rates vs. Model Year for Regulatory Classes LHD≤10K and LHD≤14K, Showing Selected Operating Modes for the Running-Exhaust Process (Note the Logarithmic Scale)

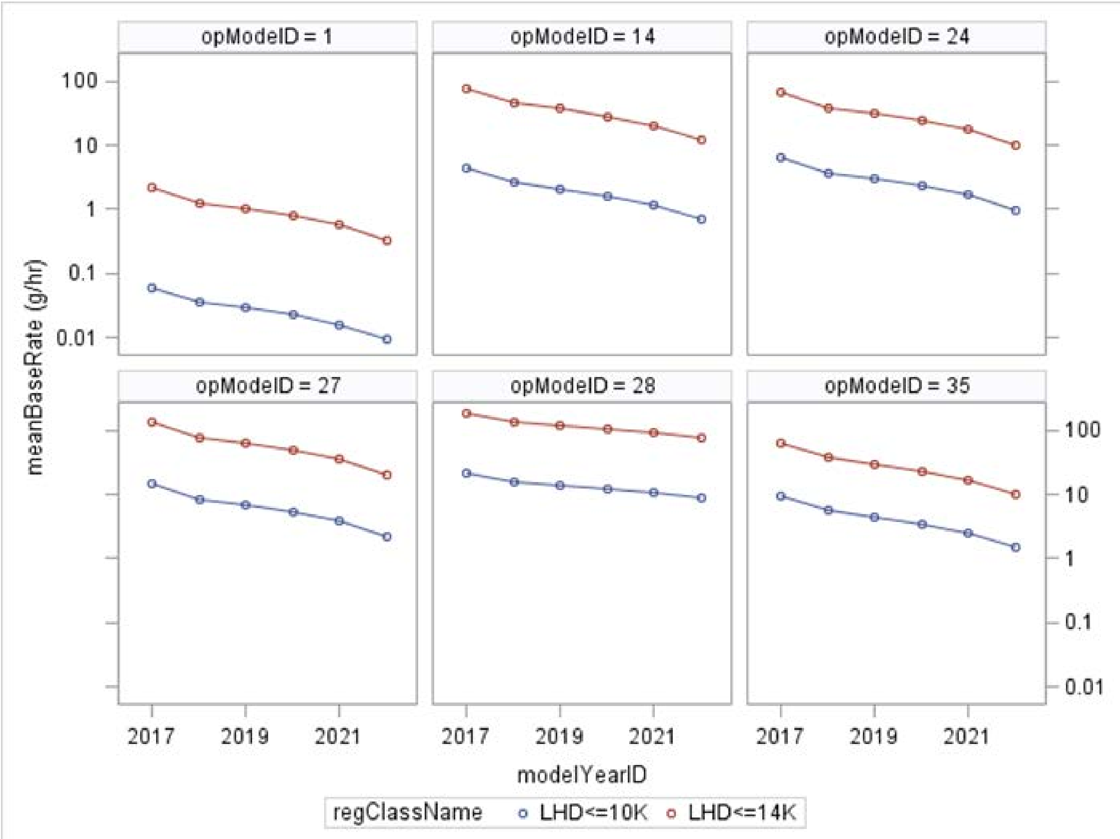

Figure 3-13. NO_X Emission Rates vs. Model Year for Regulatory Classes LHD≤10K and LHD≤14K, Showing Selected Operating Modes for the Running Exhaust Process (Note the Logarithmic Scale)

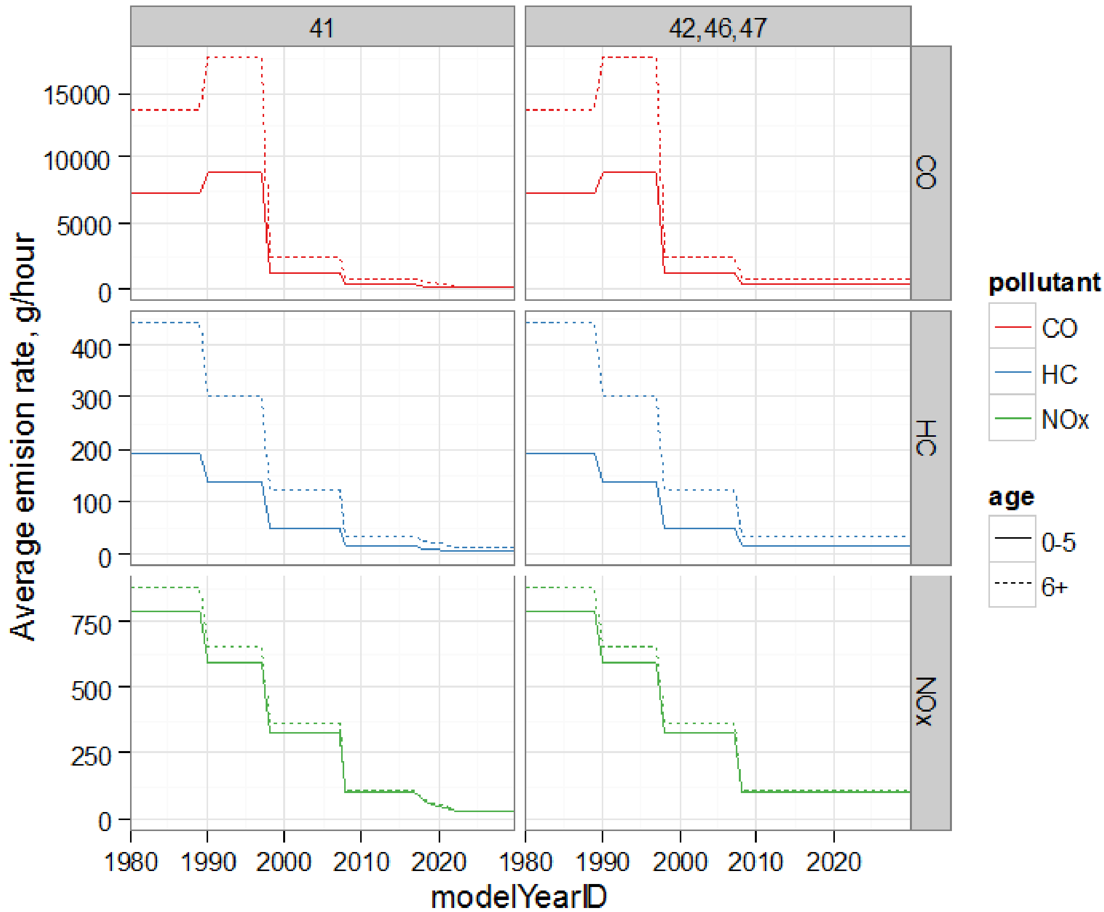

Figure 3-14. Average Emission Rate (Across All Operating Modes) for Regulatory Class LHD≤14K, LHD45, MHD and HHD (regClassIDs 41,42,46 and 47) for CO, HC, and NO_X. Emission Rates for 1960-1989, and 2022 – 2050 are Constant.

3.1.2 Particulate Matter

Unfortunately, the available $PM_{2.5}$ emission data from heavy-duty gasoline trucks were too sparse to develop the detailed emission rates for which the MOVES model is designed at the time of analysis. As a result, only a very limited analysis could be done. EPA will likely revisit and update these emission rates when sufficient additional data on $PM_{2.5}$ emissions from heavy-duty gasoline vehicles become available.

In MOVES, the heavy-duty gas $PM_{2.5}$ emission rates are calculated by multiplying the MOVES2010 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 are made beyond 2003, because the HD 2007 Rule PM standards are not expected to change in-use emissions for medium and heavy-duty gasoline vehicles, and the Tier 3 program is not expected to impact the PM emissions of heavy-duty gasoline vehicles. As presented in the next section, the MOVES PM rates for 2008+ vehicles is based on UDDS results of 2.7 mg/mile, while the standard for 2008+ spark-ignition vehicles is 20 mg/mile[99].

3.1.2.1 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 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 3-18.

Table 3-18. 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 only 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

3.1.2.2 Emission Rates for Regulatory Class LHD≤10K

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.

To make the comparisons appropriate, the simulated light-duty UDDS results were matched to the results from the four heavy-duty gas trucks in the sample. This comparison meant that the 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 older light-duty gas truck group using MOVES2010b are 38.84 mg/mi $_{2.5}$(Ignoring sulfate emissions which are on the order of 1×10^{-4} mg/mile for low sulfur fuels), This value leads to the computation of the ratio: $\frac{65.22 \frac{mg}{mile}}{38.84 \frac{mg}{mile}} = 1.679$.

The simulated $PM_{2.5}$ UDDS emission rates for the newer light-duty gas truck group are 4.687 mg/mi using MOVES2010b. Ignoring sulfate emissions, which are in the order of 1×10^{-5} mg/mile for low sulfur fuels, this value leads to the computation of the ratio: $\frac{2.71 \frac{mg}{mile}}{4.687 \frac{mg}{mile}} = 0.578$.

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 was intuitively inconsistent, 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:

$$Ratio_{final} = Ratio_{older} WtFrac + Ratio_{newer}(1 - WtFrac)$$
$$= 1.679\times0.75 + 0.578\times0.25 = 1.40$$

Equation 3-3

We then multiplied this final ratio of 1.40 by the light-duty gasoline truck PM rates to calculate the input emission rates for heavy-duty gasoline PM rates. This approach works for regulatory class LHD ≤ 40 (regClassID 40) because the emission rates for both regulatory class LDT and LHD≤10K are normalized to vehicle mass (or VSP-based emission rates).

As documented in the light-duty report,[9] the PM emission rates for light-duty vehicles were revised in MOVES2014 and MOVES201X. These revisions including accounting for the Tier 3 light-duty program, incorporating newer data from port-fueled injection vehicles and gasoline direct injection vehicles (GDI). This analysis used the light-duty truck PM emission rates from MOVES2010b PM emission rates to derive the 1.4 ratio, and the subsequent heavy-duty gasoline PM emission rates. We have not updated the heavy-duty PM emission rates is due to limited data regarding heavy-duty PM rates and uncertainty regarding the expected penetration of gasoline direct injection technology in heavy-duty gasoline vehicles. Additionally, the Tier 3 standards are not anticipated to cause reductions in heavy-duty gasoline PM.

3.1.2.3 Emission Rates for Regulatory Class LHD≤14 K, LHD45, MHD, and HHD

For the larger heavy-duty gasoline emission rates, the emission rates are STP-based with a fixed mass factor of 17.1. Unlike the gaseous emission rates, we do not have sec/sec emission rates associated with power output that would enable us to calculate a 17.1 metric ton STP-based PM emission rates directly.

We used an indirect approach to derive STP-based PM emission rates from the emission rates derived for the LHD ≤ 10K regulatory class. We assume that the relationship of HC between STP and VSP based emission rates is a reasonable surrogate to map PM emission rates to STP-based emission rates. To do so, we first calculated the emission rate ratio for HC emissions for each operating mode between regulatory class LHD≤14K (regClassID 41) and LHD≤10K (regClassID 40). We then multiplied this ratio to the PM emission rates in regulatory class LHD≤10K (regClassID 40) to obtain STP-based PM emission rates in the heavier regulatory classes (RegClass IDs 41, 42, 46 and 47). An example of the regulatory class LHD≤10K PM emission rates, STP/VSP HC ratios, and the calculated STP-based $PM_{2.5}$ emission rates are displayed in Table 3-19. No reductions are made for future years, because the 2007 HD rule is not anticipated to cause reductions in heavy-duty gasoline PM emissions.

Table 3-19. Derivation of STP-based PM Emission Rates from VSP-based Rates using the Ratio of HC VSP to STP Emission Rates as a Surrogate, Using Model Year 2001 as an Example

opModeID	regClassID 40 EC emission rates (mg/hr)	HC STP to VSP Ratio	regClassID 41, 42, 46, 47 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

3.1.3 Energy Consumption

3.1.3.1 LHD≤10K Energy Rates for Model Years 1960-2013

The energy rates for LHD≤10K gasoline pre-2007 energy rates are unchanged from the rates for the LHD2b3 regulatory class in MOVES2010a. In MOVES2010a, the energy rates for this regulatory class, 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[46].

3.1.3.2 LHD≤10K Energy Rates for Model Years 2014-2060

For model years 2014 through 2020, lower energy consumption rates for LHD≤10K vehicles are expected due to the Phase 1 Medium and Heavy-Duty Greenhouse Gas Rule, as discussed in more detail in Section 2.1.4.3. The CO_2 emission reductions for gasoline 2b trucks in Table 3-21 were applied to the 2013 model year energy consumption rates in each running operating mode bin to derive 2014 through 2020 energy consumption rates. The energy rates were also updated for MOVES201X to reflect the projected CO_2 emission reductions from the Heavy-Duty GHG Phase 2 Rule. The reductions outlined in Table 3-22 were applied to the 2020 model year energy consumption rates in each running operating mode to derive the 2021 model and later rates. displays the average energy consumption (across all running operating modes) for model years 1970 through 2030. The rates are constant between 1960 to 1973, and from 2027 to 2060.

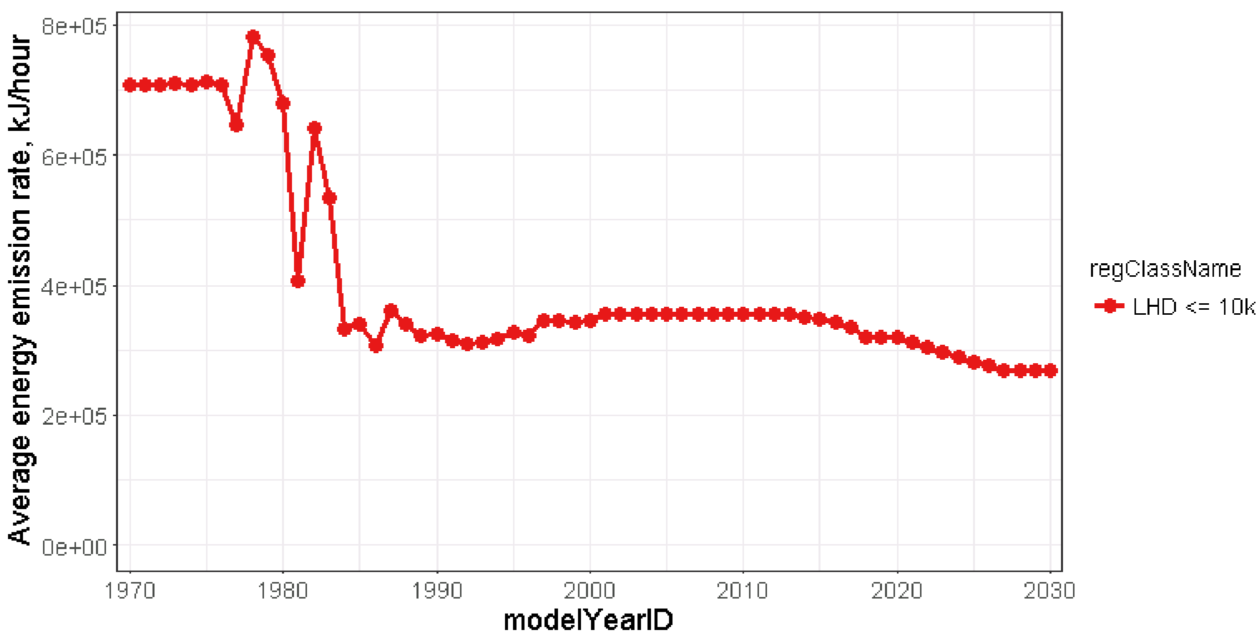

Figure 3-15. Average Energy Consumption Rates for LHD≤10K Gasoline Vehicles Across All Running Operating Modes[u]

[u] Note, this figure displays a straight average across all operating modes, and thus emphasizes the energy used in the operating modes with highest energy consumption. At run time MOVES actually computes emissions based on an operating mode distribution determined by VMT allocation by roadtype and speed as well as sourcetype mass. See the MOVES Vehicle Population and Activity report[5] for more information on operating mode distributions.

3.1.3.3 Energy Rates for LHD≤14K (Model Years 1960-2013), LHD45, MHD, and HHD (Model Years 1960-2015)

The data used to develop energy rates for heavy-duty gasoline vehicles, within LHD≤14K, LHD45, MHD, and HHD regulatory classes, is the same data set as we used to develop the HC, CO, and NO_X exhaust emission rates. Similar to the diesel running exhaust energy rates, we made no distinction in rates by model year (within the 1960-2013 range for LHD≤14K and within the 1960-2015 range for the other heavy-duty regulatory classes), 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 1-2. Figure 3-16 summarizes the gasoline running exhaust energy rates stored in MOVES for the STP-based regulatory classes (LHD= <14K, MHD, and HHD).

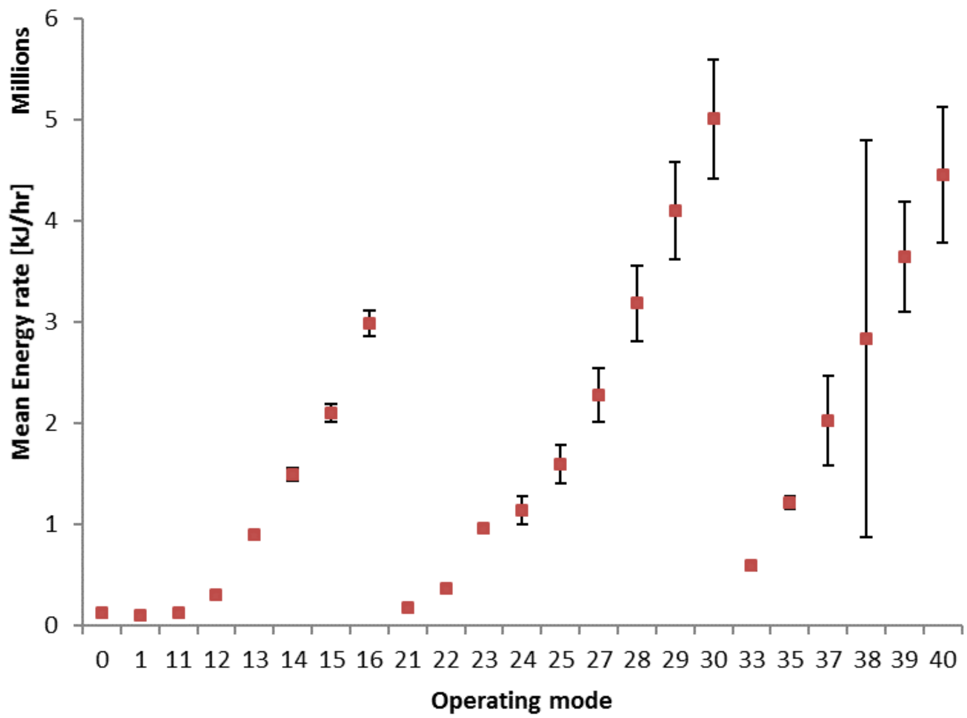

Figure 3-16. Gasoline Running Exhaust Energy Rates for LHD≤14K (1960-2013), LHD45 (1960-2015), MHD (1960-2015), and HHD (1960-2015)

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 2.1.1.4.1).

3.1.3.4 Energy Rates for LHD≤14K (2014-2060), LHD45, MHD, and HHD (2016-2060)

Updates to the energy rates were made to the heavy-duty gasoline energy rates for model years 2014-2020 based on the Phase 1 Medium and Heavy-Duty Greenhouse Gas Rule**Error! Bookmark not defined.** as discussed in Section 2.1.4.3 and shown in Table 3-20. Figure 3-17 displays the average energy consumption rates for the heavy-duty gasoline sources. The same relative changes observed for the average emission rates in Figure 3-17 are applied equally to all operating modes. The energy rates for all these source types are equivalent for model years 1960-

2013. The reduction in the average energy consumption rates is displayed in Figure 3-17, with separate reductions for the class 2b and 3 trucks (LHD≤14K), class 4-7 trucks (LHD45, MHD), and class 8 trucks (HHD). The energy rates for 2021 model year and beyond were updated in MOVES201X to reflect the CO_2 emission reductions expected from the Heavy-Duty GHG Phase 2 rule, as shown in Table 3-21, which have separate reductions for vocational and combination trucks. Figure 3-17 shows the average emission rates from 2012 through 2028 for each regulatory class in MOVES.

Table 3-20 Heavy-Duty Gasoline Reductions due to the Heavy-Duty GHG Phase 1 Rule

Vehicle Type	**Fuel**	**Model Years**	**CO_2 Reduction From 2013 Baseline**
LHD45, MHD, HHD	Gasoline	2016-2020	5%

Table 3-21 Heavy-Duty Gasoline Reductions due to the Heavy-Duty GHG Phase 2 Rule

VEHICLE TYPE	FUEL	MODEL YEARS	REDUCTION FROM 2017 BASELINE
LHD45	Gasoline	2021-2023	6.9%
		2024-2026	9.8%
		2027+	13.3%
Vocational MHD and HHD	Gasoline	2021-2023	6.9%
		2024-2026	9.8%
		2027+	13.3%
Short-haul Tractor-Trailers MHD and HHD	Gasoline	2018-2020	0.6%
		2021-2023	7.4%
		2024-2026	11.9%
		2027+	15.0%

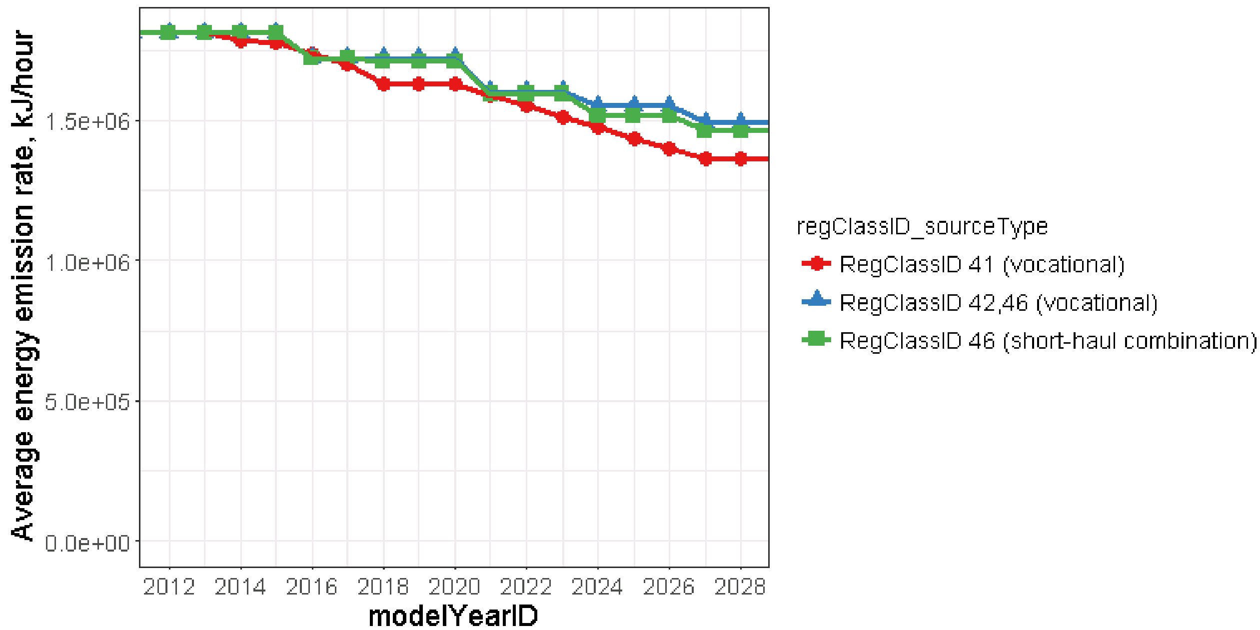

Figure 3-17. Average Energy Consumption Rates for LHD≤14K (regClassID 41), LHD45 (regClassID 42), MHD (regClassID 46) and HHD (regClassID 47) Gasoline Vehicles Across All Running Operating Modes[uv]

3.2 Start Emissions

The emissions standards for the Federal Test Procedure (FTP) are shown in Table 3-22 for the two applicable regulatory classes, LHD<14 and LHD>=14. These standards cover the model years 1990 through 2004. Note that the standards for CO and THC vary by regulatory class (LHD≤10K, LHD≤14K, LHD45), but not by model year, whereas those for NO_X vary by model year, but not by regulatory class. Note that for model years 2005-2007, a single standard was applied for NMHC+NO_X, but that by 2008, separate but lower standards were again in effect. Note also that by model year 2008, the standards for all three regulatory classes were uniform for the three gaseous pollutants.

Table 3-22. FTP Standards (g/hp-hr) for Heavy-Duty Gasoline Engines for Model Years 1990-2016

Model-Year Group	GVWR ≤ 14,000 lb			GVWR > 14,000 lb		
	CO	HC[1]	NO_X	CO	HC[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	1.0[2]		37.1	1.0[2]	
2008-2016	14.4	0.14	0.20	14.4	0.14	0.20

[1] Expressed as non-methane hydrocarbons (NMHC).
[2] Standard expressed as NMHC + NO_X.

The heavy-duty gasoline vehicle start emissions for MOVES regulatory class LHD≤10K and LHD≤14K vehicles are discussed in Section 3.2.1. Then, in Section 3.2.1.2, we discuss the development of the rates for MOVES regulatory class LHD45, MHD, and HHD gasoline vehicles.

3.2.1 HC, CO, and NO_X

Two sets of start emissions are derived for HC, CO, and NO_X for heavy-duty gasoline vehicles. First, we discuss the derivation of LHD≤10K and LHD≤14K in Section 3.2.1.1. Second, we discuss the emission rates for LHD45, MHD, and HHD in Section 3.2.1.2. In Section 3.2.1.3, we summarize and compare the two sets of start emission rates.

3.2.1.1 LHD≤10K and LHD≤14K

For LHD≤10K and LHD≤14K, 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-2004 rates based on the emission standards.

3.2.1.1.1 1960-2004 model year emission rates

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).[92] 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 MOVES2010b LHD2b3 regulatory class. In MOVES201X, LHD≤10K and LHD≤14K have identical start rates that are unchanged (except for the implementation of the Tier 3 rule) from LHD2b3 start emission rates from MOVES2010b.

Table 3-23 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 HC 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 VSP/STP or different scaling 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 3-23. Availability of Emissions Start Data by Model-Year Group and Age Group for Vehicles with GVWR < 14,000 Lbs.

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 E. 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 HC, 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 E-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 HC 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 HC and 1.2 for NO_X. These values approximate the maxima seen in these data and are broadly comparable to rates observed for light-duty vehicles.

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.

$$\overline{x}_a = \overline{x}_g e^{\frac{s_l^2}{2}}$$ **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 3-18 with the arithmetic mean (directly calculated and re-estimated) and geometric means shown separately.

We then addressed the question of the projection of age trends. As a general principle, we did not allow emissions to decline with age. We implemented this assumption by stabilizing emissions at the maximum level reached between the 6-7 and 10-14 age groups.

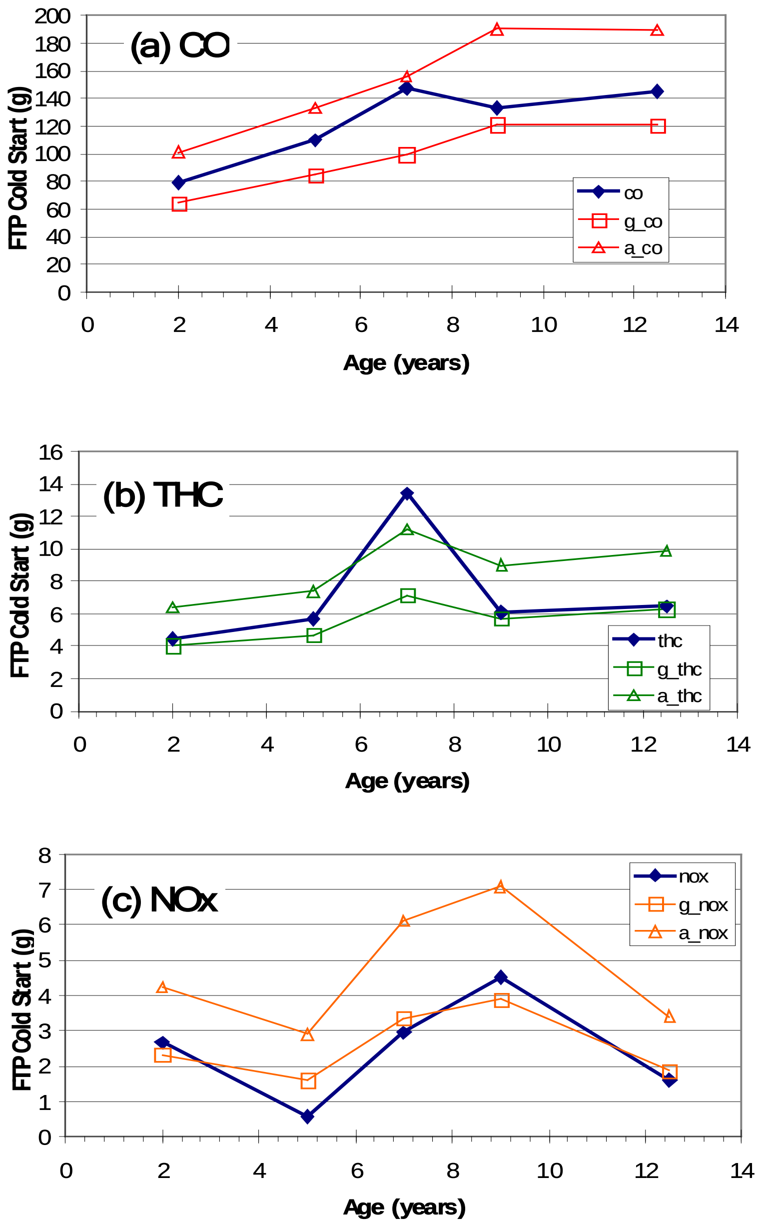

Figure 3-18. Cold-start FTP Emissions for Heavy-Duty Gasoline Trucks, Averaged by Age Group Only (g = Geometric Mean, a= Arithmetic Mean Recalculated from x_l and s_l)

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 3-24 and in Figure 3-19. Note that these results represent only "cold-start" rates (opModeID 108).

Table 3-24. 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*

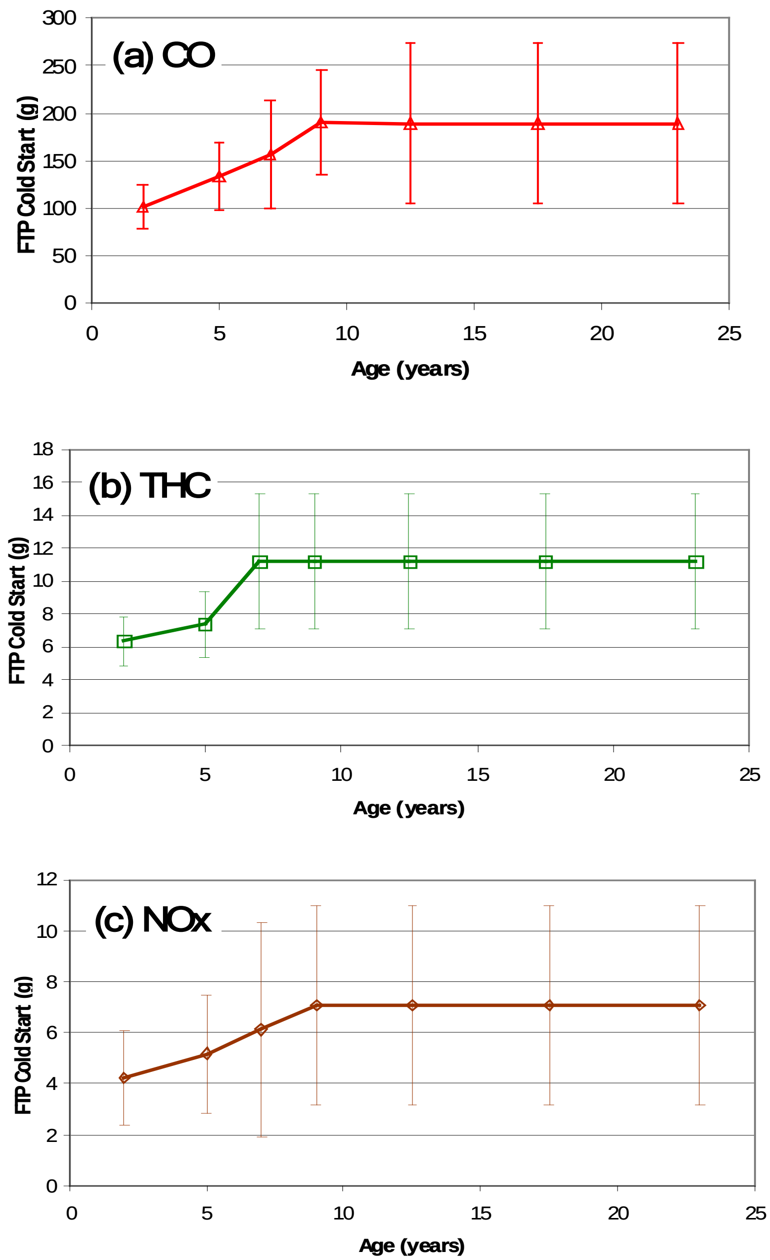

Figure 3-19. Cold-Start Emission Rates for Heavy-Duty Gasoline Trucks, with 95 Percent Confidence Intervals

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 2005-2017 model year start emission rates

For the 2005-2017 model year emission rates, we estimated reductions in the 1960-2004 emission rates, by comparing the standards between the two model year ranges. For CO, the approach was simple. We applied the values in Table 3-24 to all modelyear groups. The rationale for this approach is that the CO standards do not change over the full range of model years considered.

For HC and NO_X, we imputed values for the 2005-07 and 2008-2017 model-year groups by multiplying the values in Table 3-24 by ratios expressed in terms of the applicable standards. Starting in 2005, a combined HC+NO_X standard was introduced. It was necessary for modeling purposes to partition the standard into HC 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 HC value by multiplying the 1960-2004 value by the fraction f_{HC} as shown in Equation 3-7.

$$f_{\mathrm{HC}} = \frac{\left(\dfrac{0.14\ \mathrm{g/hp\text{-}hr}}{(0.14+0.20)\ \mathrm{g/hp\text{-}hr}}\right)(1.0\ \mathrm{g/hp\text{-}hr})}{1.1\ \mathrm{g/hp\text{-}hr}} = 0.37 \qquad \textbf{Equation 3-7}$$

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.

$$f_{\mathrm{NOx}} = \frac{\left(\dfrac{0.20\ \mathrm{g/hp-hr}}{(0.14+0.20)\ \mathrm{g/hp-hr}}\right)1.0\ \mathrm{g/hp\text{-}hr}}{4.0\ \mathrm{g/hp\text{-}hr}} = 0.147 \qquad \textbf{Equation 3-8}$$

For these heavy-duty rates, we neglected the THC/NMHC conversions, to which we gave attention for light-duty.

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 from the LHDH≤10K and LHD≤14K gasoline vehicles were estimated by applying the “start split-ratio” shown in Table 3-10 to a set of rates representing light-duty vehicles in Tier-2/Bin 8. Second, start emission rates adopted the same age effects as the light-duty start emission rates. The multiplicative age effects for start emission rates for vehicles in model years 2008-2017 are shown in Table 3-25.

Table 3-25. Multiplicative Age Effect Used for Start Emissions for LHD≤10K and LHD≤14K Vehicles for 2008-2017 Model Years Adopted from the Deterioration Effects for Light-Duty Trucks from the Light-Duty Emission Rate Report[9]

ageGroupID	HC	CO	NO_X
3	1	1	1
405	1.65	1.93	1.73
607	2.20	2.36	2.21
809	2.68	2.54	2.76
1014	3.30	3.00	3.20
1519	3.66	3.35	3.63
2099	4.42	4.06	4.11

3.2.1.1.5 Incorporating Tier-3 Standards: Model years 2018 and later

Emission rates for the start-exhaust process were developed employing the techniques described for running-exhaust emissions, as described above in Section 3.1.1.4 . Start rates for HC, CO and NO_X during the Tier-3 phase-in (2018-2022) are shown below in Figure 3-20 to Figure 3-22. Note that start rates are identical for both the LHD≤10K and LHD≤14K regulatory classes (regClassID = 40 and 41, respectively).

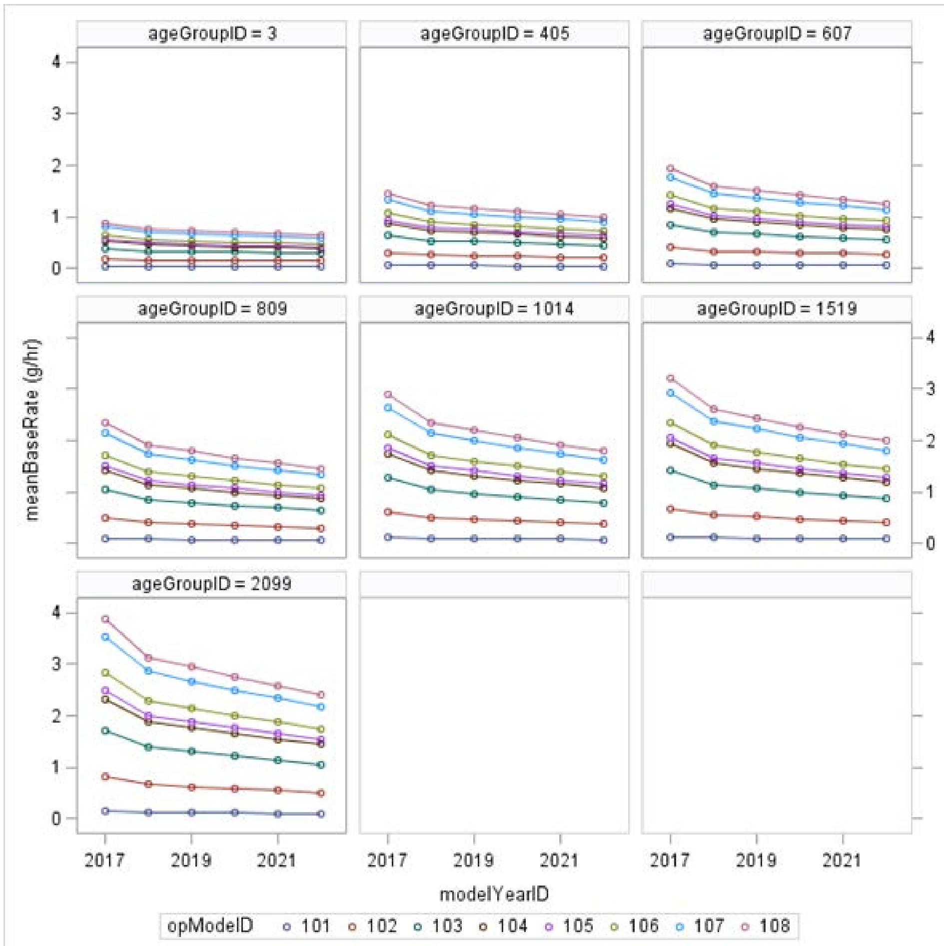

Figure 3-20. THC: Emission Rates for the Cold Start-Exhaust Process, for the LHD≤10K (regClassID 40) and the LHD≤14K (regClassID 41) Regulatory Classes, by Operating Mode and Age Group, During the Tier-3 Phase-In

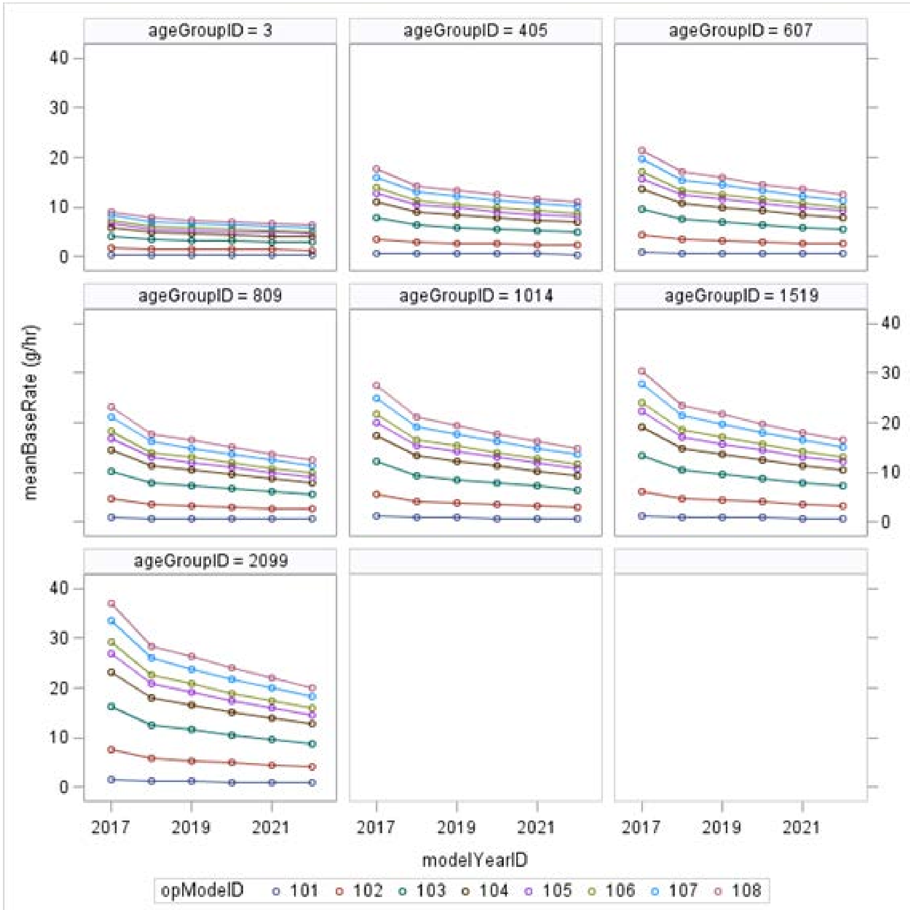

Figure 3-21. CO: Emission Rates for the Cold Start-Exhaust Process, for the LHD≤10K (Regclassid 40) and the LHD≤14K (Regclassid 41) Regulatory Classes, by Operating Mode and Age Group, During the Tier-3 Phase-In

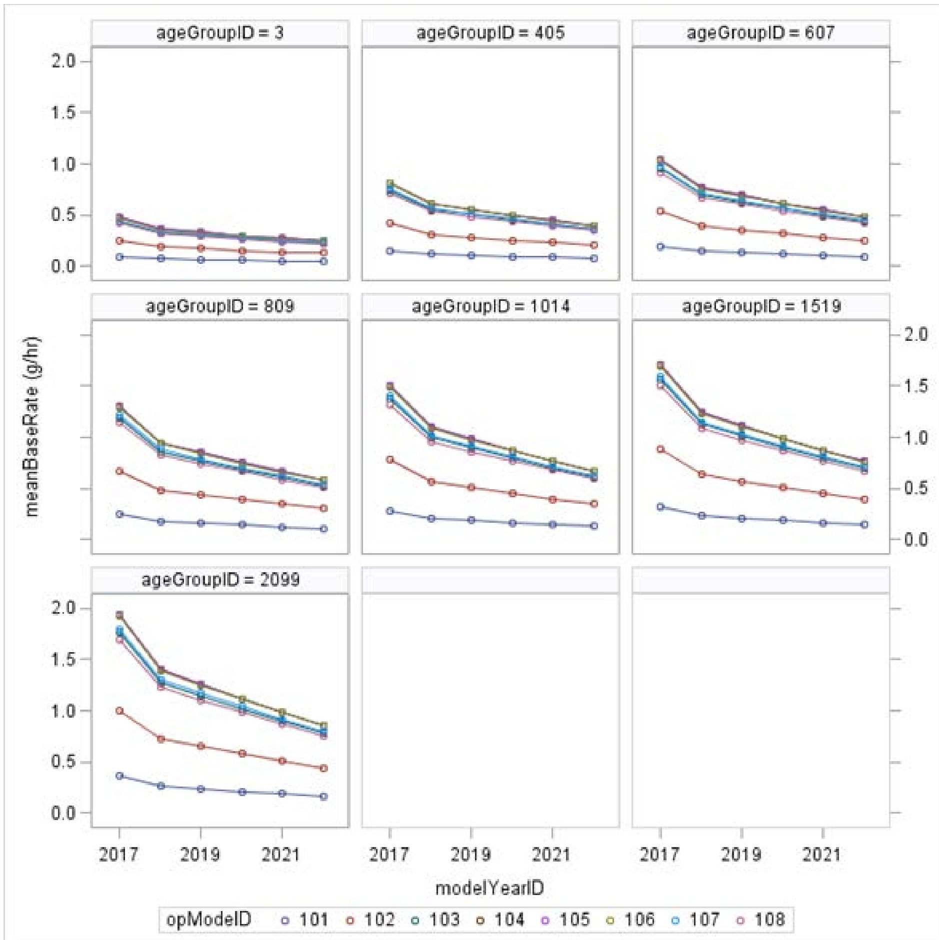

Figure 3-22. NO_X: Emission Rates for the Cold Start-Exhaust Process, for the LHD≤10K (Regclassid 40) and the LHD≤14K (Regclassid 41) Regulatory Classes, by Operating Mode and Age Group, During the Tier-3 Phase-In

3.2.1.2 LHD45, MHD, and HHD

The emission rates from LHD45, MHD, and HHD gasoline vehicles were estimated to be different than the cold start emission rates for LHD≤10K and LHD≤14K. 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 LHD≤10K and LHD≤14K start emission rates.

For CO and HC, 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.

$$f_{CO} = \frac{37.1\ \text{g/hp-hr}}{14.4\ \text{g/hp-hr}} = 2.58 \qquad \textbf{Equation 3-9}$$

The corresponding ratio for HC for 1990-2004 model year vehicles is 1.73, as shown in Equation 3-10.

$$f_{HC} = \frac{1.9\ \text{g/hp-hr}}{1.1\ \text{g/hp-hr}} = 1.73 \qquad \textbf{Equation 3-10}$$

The ratios derived in the previous two equations (2.58 and 1.73) were applied to estimate the start emission rates for the first three model year groups for the LHD45, MHD, and HHD gasoline vehicles (Table 3-28). Note that the ratios for CO and HC do not vary by model year group because the standards do not; See Table 3-22.

For MY 1960-2007, NO_X start emission rates for medium and heavy-duty vehicles are equal to the LHD≤10K and LHD≤14K start emission rates, because the same standards apply to both classes throughout. The approaches for all three regulatory classes in all model years are summarized in Table 3-28.

The outcomes of the methods described in the table are summarized graphically in Figure 3-23 for cold-start emissions. The decline in start emissions with the adoption of more stringent standards is shown over the period between model years 1990 and 2022, at the completion of the phase-in of Tier 3 standards for vehicles with GVWR ≤14,000 lbs.

3.2.1.2.2 2008 and later model year

The cold start emissions for 2008 model year and later LHD45, MHD, and HHD spark-ignited (gasoline) engines have been updated for MOVES201X based on new data. 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 gasoline engines are certified using the Heavy-Duty Gasoline Engine Federal Test Procedure (FTP) cycle (40 CFR Part 86, Appendix I.f.1). 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 MOVES201X update, includes the following engine families from 2016 and 2017 model years shown in Table 3-26.

Table 3-26: 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.

$$\begin{aligned} Grams\ per\ Start &= [Cold\ FTP\ Emission\ Results\ (g/(hp-hr)) \\ &- Hot\ FTP\ Emission\ Results(g/(hp-hr))] \\ &* FTP\ Cycle\ Work\ (hp-hr) \end{aligned} \qquad \textbf{Equation 3-11}$$

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. 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, but 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 HC, CO, and NO_X. The average and standard deviation of the HC, CO, and NO_X emission levels of the three engines are shown in Table 3-27. The engines included MY2016 and MY2017, 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 MOVES201X are the mean values shown in the table. The HC and NO_X cold start emissions for HD gasoline engines are increasing with this update, compared to what is currently in MOVES2014, while the CO emissions are decreasing.

Table 3-27: Cold Start Emissions for MY2008 and Later Heavy-Duty Gasoline Engines

Grams per Start	HC	CO	NO_X
Mean	5.57	31.5	1.88
Standard Deviation	0.6	6.36	1.04

3.2.1.3 Summary of HC, CO, and NO_X start emissions from heavy-duty gasoline vehicles

Table 3-28 summarizes the data and methods used to estimate HC, 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 3-23 displays the cold start emission rates across model years for the two different sets of start emission rates for heavy-duty gasoline vehicles. The LHD≤14K line in Figure 3-23 represents LHD≤10K and LHD≤14K. The LHD45 line in Figure 3-23 represents LHD45, MHD, and HHD starts.

Table 3-28. Methods Used to Calculate Start Emission Rates for Heavy-Duty Spark-Ignition Engines

Regulatory Class	Model-year Group	Method		
		CO	**THC**	**NO_x**
LHD≤ 10K and LHD < 14K	1960-2004	Values from Table 3-24	Values from Table 3-24	Values from Table 3-24
	2005-2007	Values from Table 3-24	Reduce in proportion to standards from 1960-2004	Reduce in proportion to standards from 1960-2004
	2008 - 2017	Values from Table 3-24	Section 3.2.1.1.5	Section 3.2.1.1.5
	2018 +	Section 3.2.1.1.5	Section 3.2.1.1.5	Section 3.2.1.1.5
LHD45, MHD, HHD	1960-2004	Increase in proportion to standards	Increase in proportion to standards from LHD≤ 10K and LHD < 14K	Same values as LHD≤ 10K and LHD < 14K
	2005-2007	Increase in proportion to standards	Increase in proportion to standards from LHD≤ 10K and LHD < 14K	Same values as LHD≤ 10K and LHD < 14K
	2008 +	Updated based on data	Updated based on data	Updated based on data

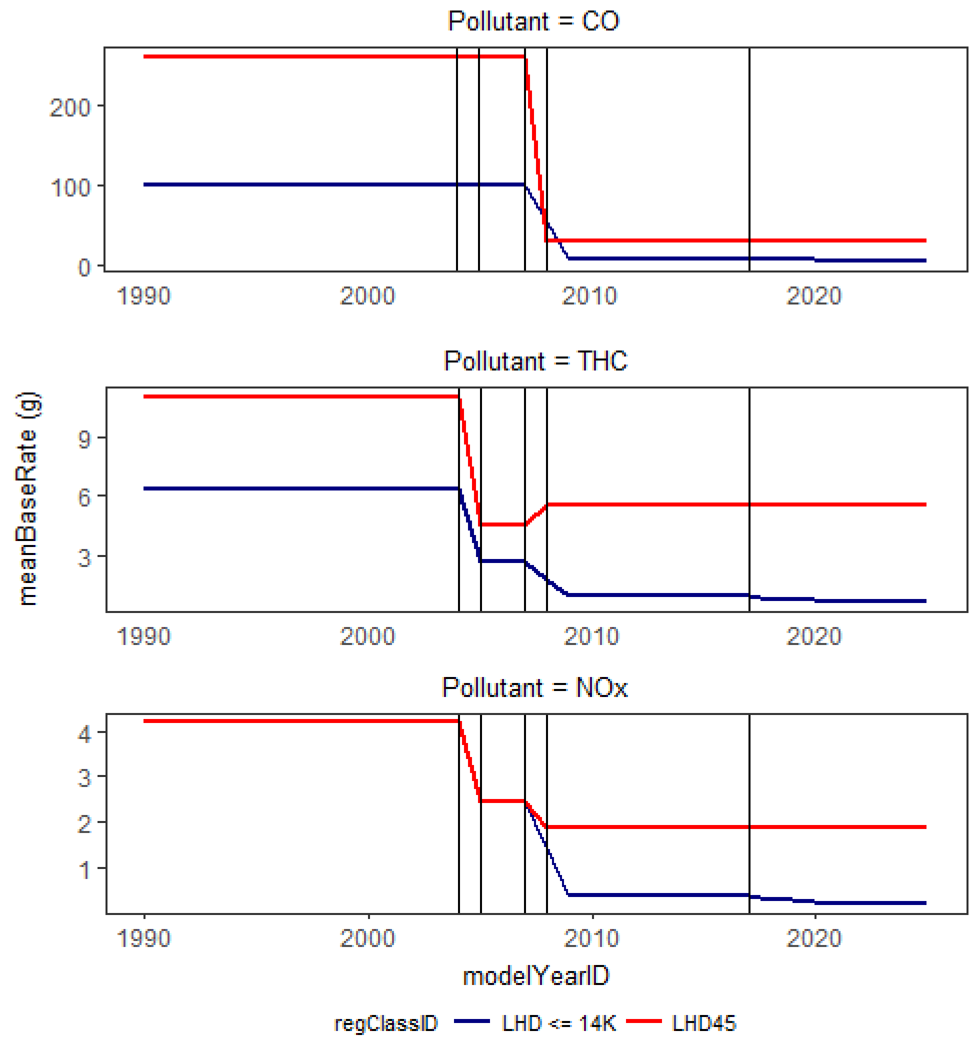

Figure 3-23. Cold-Start Rates (opModeID 108) vs. Model Year, by Pollutant, for Heavy-Duty Gasoline Vehicles in Two Regulatory Classes. LHD≤10K are Equivalent to LHD≤14K. MHD and HHD are Equivalent to LHD45. NOTE: The Reference Lines Indicate the Model Years 2004, 2005, 2007, 2008 and 2017, Respectively

3.2.2 Particulate Matter

Data on PM start emissions from heavy-duty gasoline vehicles were unavailable. As a result, we used the multiplication factor from the running exhaust emissions analysis of 1.40 (derived in Section 3.1.2.2) to scale up start emission rates for light-duty trucks (regClassID 30) for model years 1960-2003. For 2004+ model years, the emission rates are a factor of 1.4 times the model year 2003 light truck (regClassID 30) rates. The light-duty PM rates in 2004-2017 model year increase due to the updated data on emission rates and sales penetration of gasoline direct injection technology. Subsequently, the light-duty PM starts decrease beginning in model year 2018 with the implementation of the Tier-3 Vehicle Emissions and Fuel Standards Program. As discussed in Section 3.1.2, Tier 3 is not expected to impact the PM emissions of heavy-duty gasoline vehicles. Due to limited data regarding heavy-duty PM rates and uncertainty regarding the expected penetration of gasoline direct injection technology in heavy-duty gasoline vehicles, we have decided to project constant start emissions using the 2003 model year emission rates.

The start PM emission rates for heavy-duty gasoline vehicles exhibit the same relative effects of soak time, and deterioration as the light-duty PM start emission rates.

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 applied to 1996+ MY light-duty gasoline vehicle as documented in the light-duty emission rate report[9] and shown in Figure 2-42.

For MOVES201X, we collected new start emission rate data based on soak time from one heavy-duty gasoline truck to verify the rate adjustments. The data was gathered using PEMS using the procedure and methods discussed in Section 2. The vehicle tested was a 2012 MY box truck with a gasoline engine. The results from the testing are shown in Figure 3-24. 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, we retained the start emission fractions from MOVES2014.

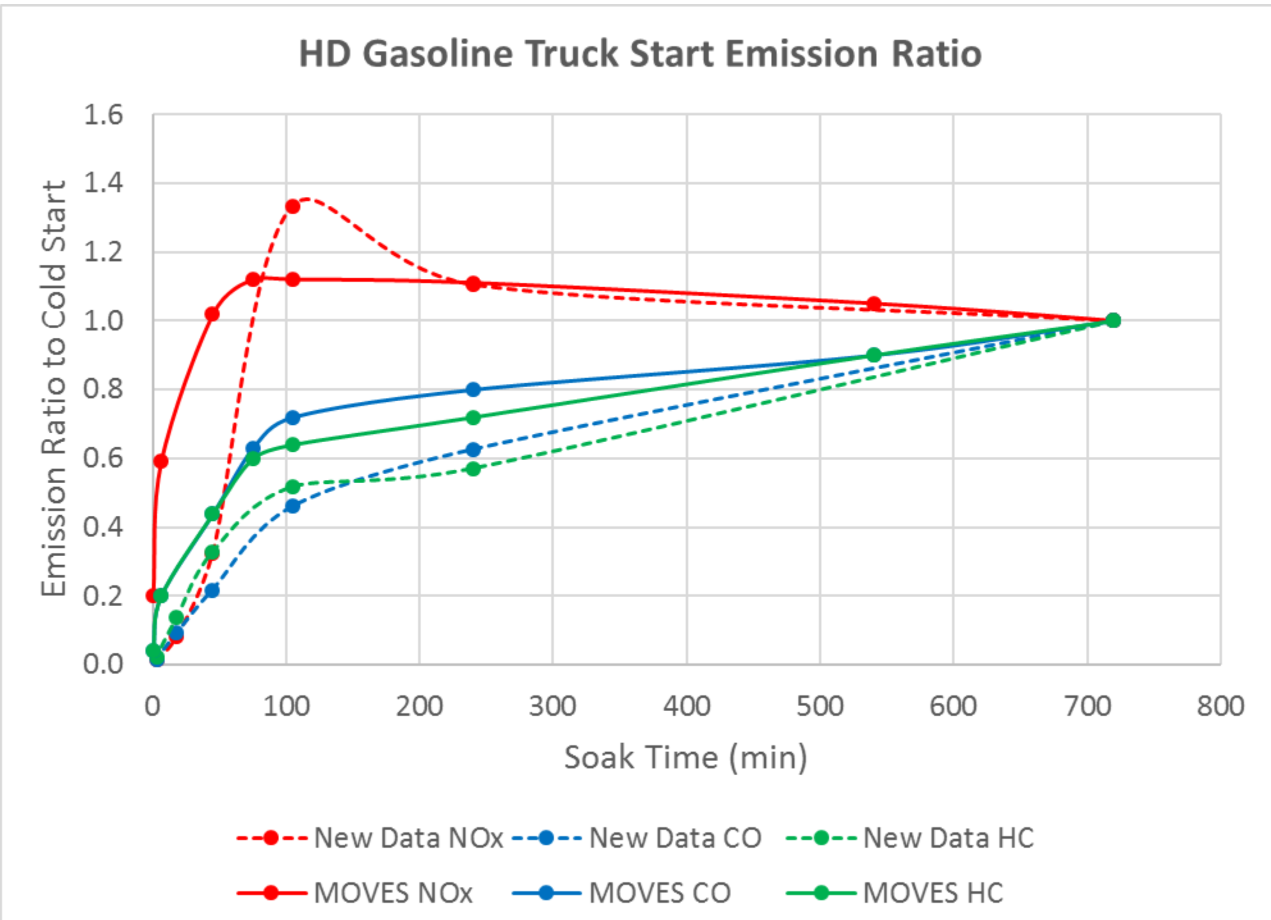

Figure 3-24 HD Gasoline Start Emission Ratio

3.2.4 Start Energy Rates

The MOVES energy rates are displayed in Figure 3-25 . The heavy-duty gasoline start energy rates were originally derived in MOVES2004, and updated in MOVES2010a as described in the corresponding reports.[46] 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 3-29 displays the relative contribution of running and start operation to total energy consumption from the heavy-duty gasoline regulatory classes from a national MOVES2014 run for calendar year 2011.[v] As for diesel vehicles, starts 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 3-29. Relative Contribution of Total Energy Consumption from Each Pollutant Process by Regulatory Class for Heavy-Duty Gasoline Vehicles in Calendar Year 2011

processID	processName	LHD≤10K	LHD≤14K	LHD45	MHD	HHD
1	Running Exhaust	96.3%	98.9%	99.0%	98.1%	98.1%
2	Start Exhaust	3.7%	1.1%	1.0%	1.9%	1.9%

The start energy rates are reduced for shorter soak times using the same factors for diesel vehicles, as presented in Table 2-38. The energy rates also increase with cold temperatures using the temperature effects documented in the 2004 Energy Report.[56]

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 2-20 and Table 2-22. As discussed in Section 2.2.4, the start energy rates are not projected to change due to the HD GHG Phase 2 standards.

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[v] MOVES201X did not update the gasoline energy rates from MOVES2014, and expect the contribution of starts to continue to be small in MOVES201X.

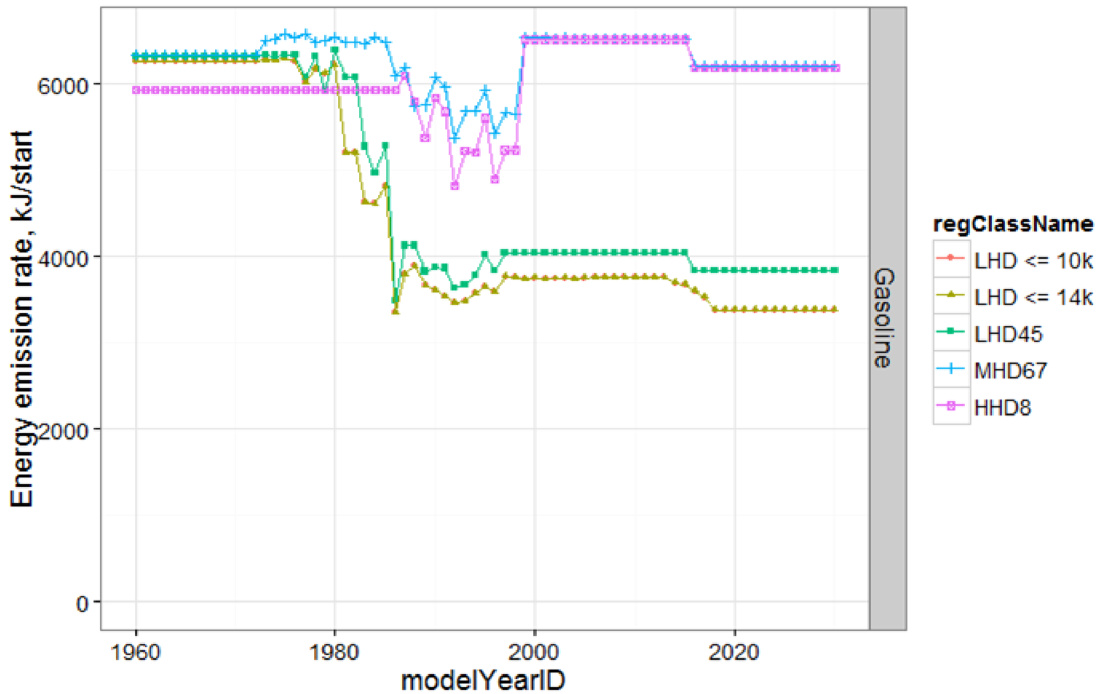

Figure 3-25. Heavy-Duty Gasoline Cold Start Energy Rates (Opmodeid 108) by Model Year and Regulatory Class

4 Heavy-Duty Compressed Natural Gas 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 rapid growth in CNG vehicles over the last 15 years has occurred among city transit bus fleets, as seen in Figure 4-1.[100]

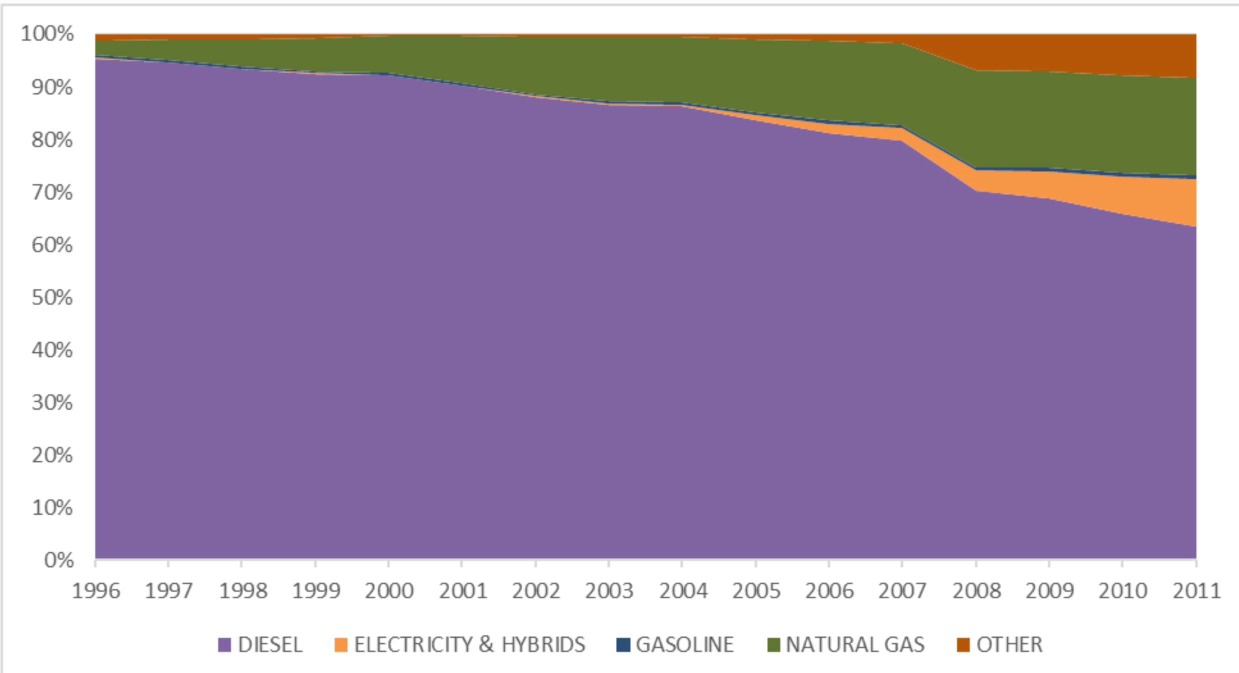

Figure 4-1. US Natural Gas Bus Population by Year and Fuel Type for 1996-2011 (APTA) [101]

MOVES2010b and earlier versions can model emissions from CNG bus fleets. However, in absence of better data, MOVES2010b used the nitrogen oxides (NOx), carbon monoxide (CO), particulate matter (PM), and hydrocarbon (HC) emissions rates originally developed for medium heavy-duty (MHD) gasoline vehicles (regClassID 46) as emissions rates for CNG urban buses (regClassID 48, sourceTypeID 42). MHD gasoline trucks are reasonable proxies for CNG buses in terms of vehicle weight and engine size. However, as this report shows, there are substantial differences between the MOVES2010b MHD gasoline emissions rates and real-world measurements of CNG transit buses.

The CNG bus (regClassID 48, sourceTypeID 42) emission rates in MOVES2014 were based on MHD gasoline vehicles (regClassID 46), chassis dynamometer measurement data, and certification data. Subsequent sections describe the method in detail. In brief, CNG buses emissions rates are calculated as such:

1 MY 1994-2001 and MY 2002-2006: Based on MHD gasoline rates for MY 1997 and 2004, respectively, adjusted by a ratio of cycle-average emissions from chassis dynamometer measurements of CNG buses and MHD gasoline rates applied to OpMode-based time distribution of the same chassis test cycle.

2 MY 2007 and beyond: Adjusted the CNG bus emissions rate for MY 2002-2006 by applying a ratio of certification data for target model year group and MY 2002-2006.

However, for MOVES201X, we expanded the modeling capabilities and made improvements to the emissions rates for newer model years, as described below, while maintaining the MOVES2014 method of developing the CNG emissions rates.

1. Allowed modeling of CNG for all heavy-duty source types (41 through 62). Consistent with MOVES2014, transit bus (sourceTypeID 42) is mapped to urban bus (regClassID 48). However, in MOVES201X, all other heavy-duty source types are mapped to the heavy heavy-duty regulatory class (regClassID 47). Further, the OpMode-based emission rates for the allowed CNG heavy-duty regulatory classes (regClassIDs 47 and 48) are identical. Thus, any differences in CNG emissions between source types is due to differences in population and activity.
2. Updated the model year grouping scheme for 2007 and beyond. The new model year groups, where certification data based adjustment ratio is applied, are 2007-2009 and 2010-2017. MOVES2014 only had the MY 2007-2012 group.
3. Utilized all CNG vehicles in the certification database to calculate the certification emissions rate based adjustment ratio for model years 2007 and beyond. In MOVES2014, we utilized only the CNG urban bus data in the certification database.

4.1 Comparison of Simulated Rates and Real-World Measurements

To evaluate whether the MOVES2010b rates for MHD gasoline vehicles were appropriate surrogates for CNG buses, we compared the cycle average rates in g/mile, for a given drive cycle, between MHD gasoline vehicles and published chassis dynamometer measurements of CNG buses. Cycle average distance-specific rates are calculated by dividing cycle total emissions by the cycle total distance. For the MHD gasoline vehicles, we estimated cycle total emissions for a given drive cycle, by combining the OpMode based emissions rates of MHD gasoline vehicles (as in EmissionRateByAge table) with the OpMode time distribution of the drive cycle. Thus, the MHD gasoline cycle average rates are simulated, while the CNG bus rates are actual chassis dynamometer measurement for the given cycle. The chassis dynamometer measured rates included only running emissions and were based on a variety of heavy-duty and transit bus driving cycles.

For our comparison, we considered two driving cycles:

- Central Business District (CBD)
- Washington Metropolitan Area Transit Authority (WMATA)

4.1.1 Heavy-Duty Transit Bus Driving Cycles

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 Figure 4-2).[102] 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).

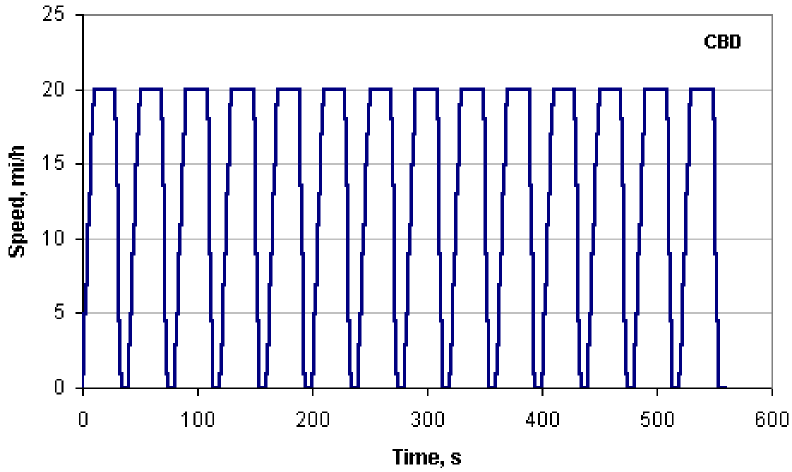

Figure 4-2. Driving Schedule Trace of the Central Business District (CBD) Cycle [103]

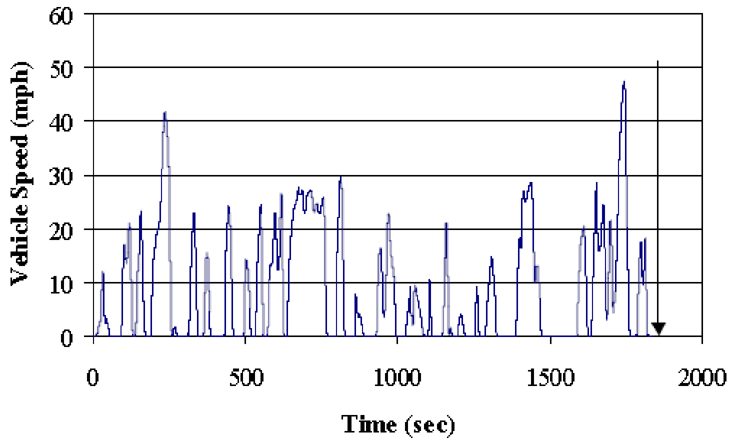

Figure 4-3 Driving Schedule Trace of the Washington Metropolitan Area Transit Authority (WMATA) Cycle[104]

4.1.2 Operating Mode Distribution for Heavy-Duty Transit Bus Driving Cycles

The MOVES2010b project level importer was used to input the second-by-second drive cycle. 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 1.3. 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. Using the measured vehicle masses across all the test programs reviewed, the CBD cycle had an average test mass of 14.957 metric tons and the WMATA cycle had an average mass of 16.308 metric tons, compared to the MOVES2010b default of 16.556 metric tons. We used the road load coefficients from MOVES2010b for transit buses, and any changes in the coefficients (*A*, *B*, and *C*) with the tested buses were assumed to be negligible.

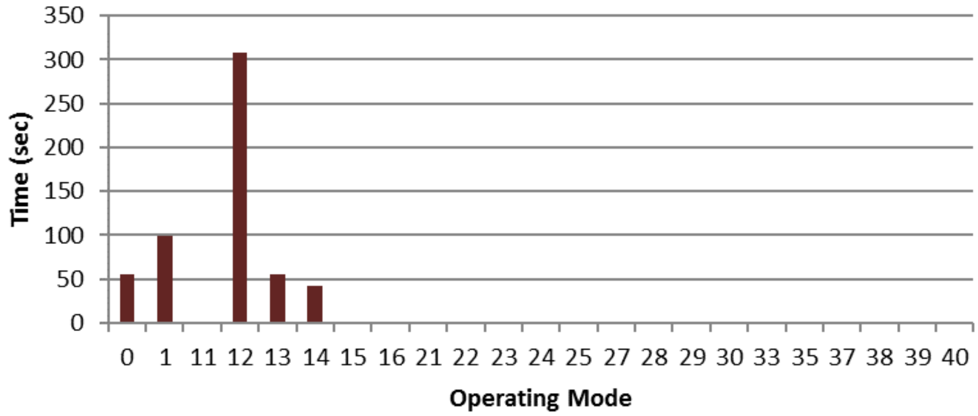

Figure 4-4. Operating Mode Distribution for the CBD Cycle

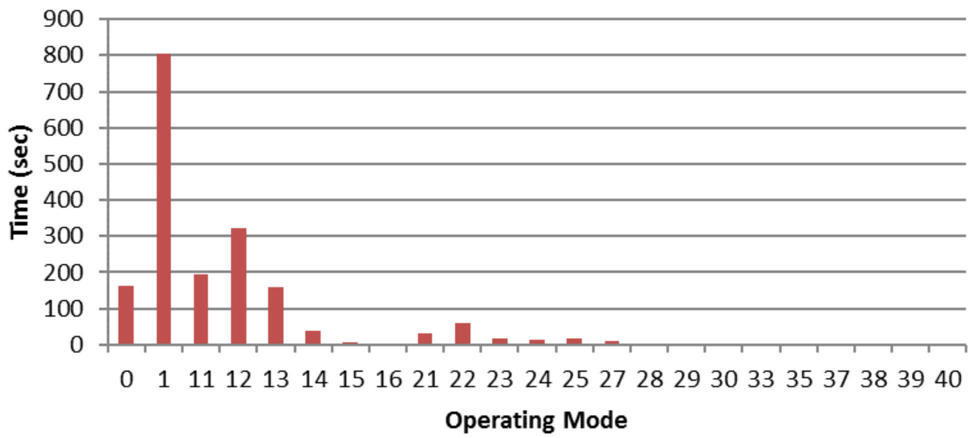

Figure 4-5. Operating Mode Distribution for the WMATA Cycle

4.1.3 Simulating Cycle Average Emission Rates

Having determined the total amount of time spent in each operating mode for a drive cycle, and using the MHD gasoline emission rates in the MOVES2010b database (DB), we were able to simulate the cycle total emissions for each pollutant for each cycle. Which, when divided by the cycle total distance gives us 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.

$$E_{p,simcycle} = \frac{\sum_{OM} R_{p,OM} * T_{OM,cycle}}{D_{cycle}} \qquad \textbf{Equation 4-1}$$

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.

4.1.4 Published Chassis Dynamometer Measurements

The real-world data was collected from programs that were conducted at several research locations around the country on heavy-duty chassis dynamometer equipment. In our analysis, we collected ~~35~~ 34 unique dynamometer measurements—which 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

Note that in MOVES, methane emissions are not estimated using emission rates, as are the other pollutants listed above. Rather, methane is estimated in relation to THC, using ratios stored in the MethaneTHCratio table. 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.

All criteria 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)[105] discussed later in this section. All other conversion factors to energy were taken from Melendez et al. (2005).

On a similar note, MOVES does not report particulate matter (PM) 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 rate used for comparison to the measurements.

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.[106]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)[108] and Ayala et al. (2003).[105] In the Ayala et al. (2002) study the 2000 model year CNG bus was tested and then retested after approximately two months of service,[108] which we treated as independent measurements. Ayala et al. (2003) again retested the same 2000 CNG bus 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[104]	National Renewable Energy Laboratory (NREL)	WMATA	2001 (4), 2004 (3)
Ayala 2003[105]	California Air Resources Board (CARB)	CBD	2000 (4), 2001 (2)
LeTavec 2002[107]	Atlantic Richfield Company (ARCO)	CBD	2001 (1)
Ayala 2002[108]	CARB	CBD	2000 (2)
Lanni 2003[109]	New York Department of Environmental Conservation	CBD	1999 (3)
McKain 2000[110]	West Virginia University (WVU)	CBD	1999 (3)
Clark 1997[111]	WVU	CBD	1996 (10)
McCormick 1999[112]	Colorado School of Mines	CBD	1994 (2)
TOTAL			**(34)**

As seen in Table 4-1, the CBD driving cycle was applied in each study except for one and had total 27 measurements covering MY 1994 to MY 2001. There are 7 vehicles tested per the WMATA cycle covering MY 2001 to MY 2004, of which 3 vehicles are MY 2001. Since, for MY 1994-2001, the CBD cycle had the largest sample size and appeared to be representative of the data from other cycles, we focused on the CBD cycle for our comparison of simulated MOVES2010b vs. chassis dynamometer measurement.

We approximated the vehicle's age by subtracting the year the study was conducted from the model year of the vehicle. From the test group listed in Table 4-1, 25 vehicles were less than three years old (ageGroupID "3") and remaining 9 vehicles were four to five years old (ageGroupID "405"). For only the CBD cycle group, 5 out of 27 vehicles were in ageGroupID "405", and their performance was generally similar to the 0-3 age vehicle results. Consequently, we combined the vehicles from age group 405 with the vehicles from group 3.[w]

4.1.5 Plots of Simulated Aggregates and Published Measurements

Below are graphs comparing distance-specific rates by model year for each pollutant, for the CBD cycle, from chassis dynamometer measurements and MOVES2010b MHD gasoline (same as CNG) simulation.

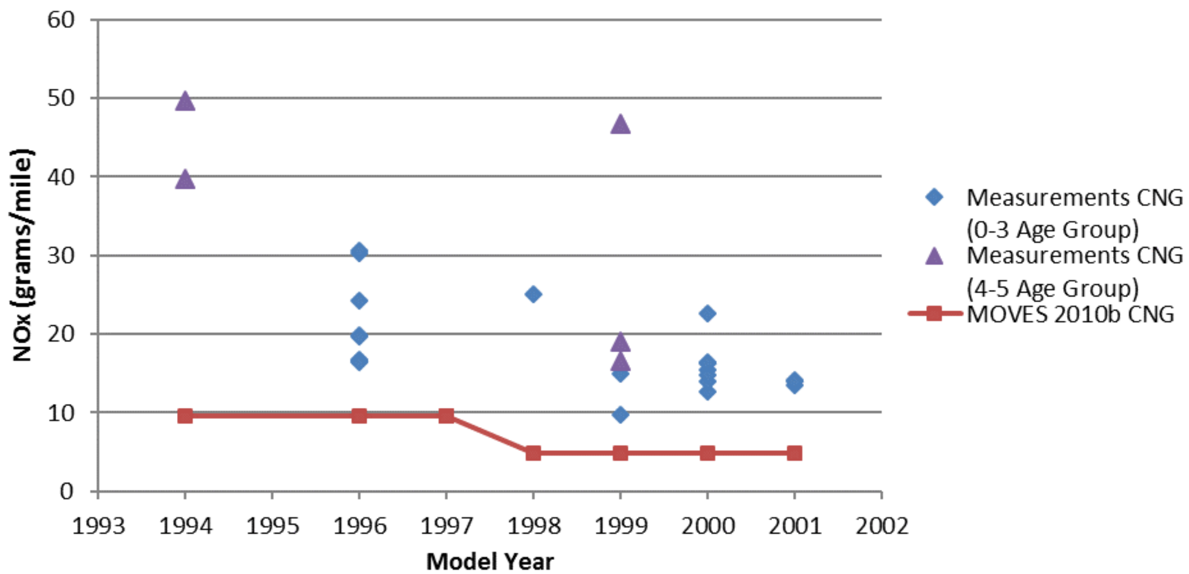

Figure 4-6. NOx Emission Comparisons of CNG Transit Bus Dynamometer Measurements and MOVES2010b Simulated Aggregates on the CBD Cycle

[w] Note that for MY 1994 in Figure 4.6 through Figure 4.10, MOVES2010b MHD gasoline (same as CNG) rates are based on age group 405. All other MOVES2010b rates are based on age group 3.

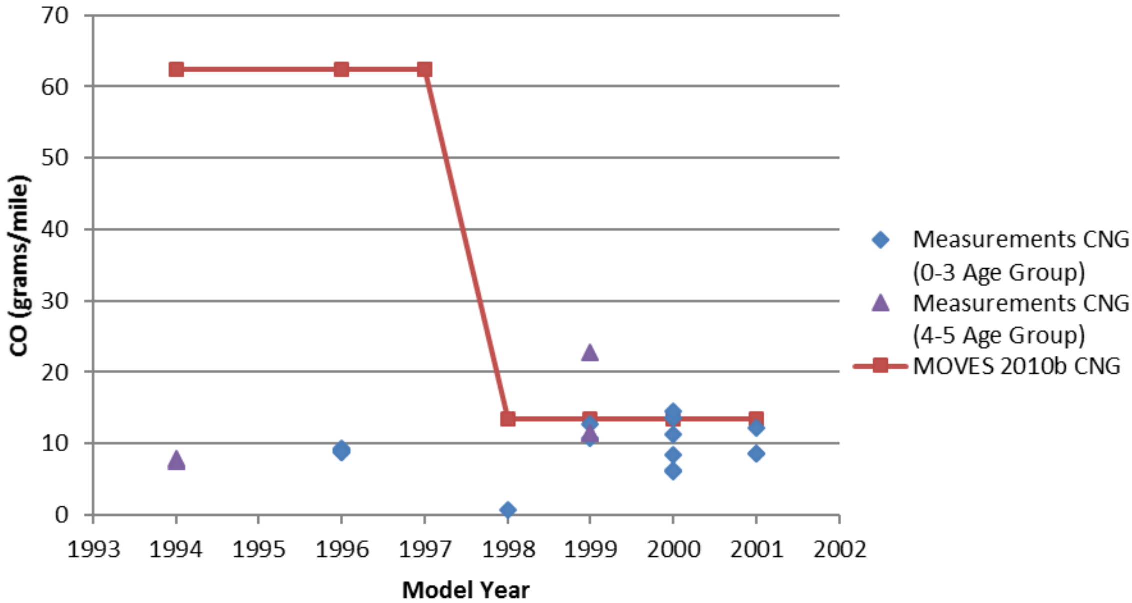

Figure 4-7. CO Emission Comparisons of CNG Transit Bus Dynamometer Measurements and MOVES2010b Simulated Aggregates on the CBD Cycle

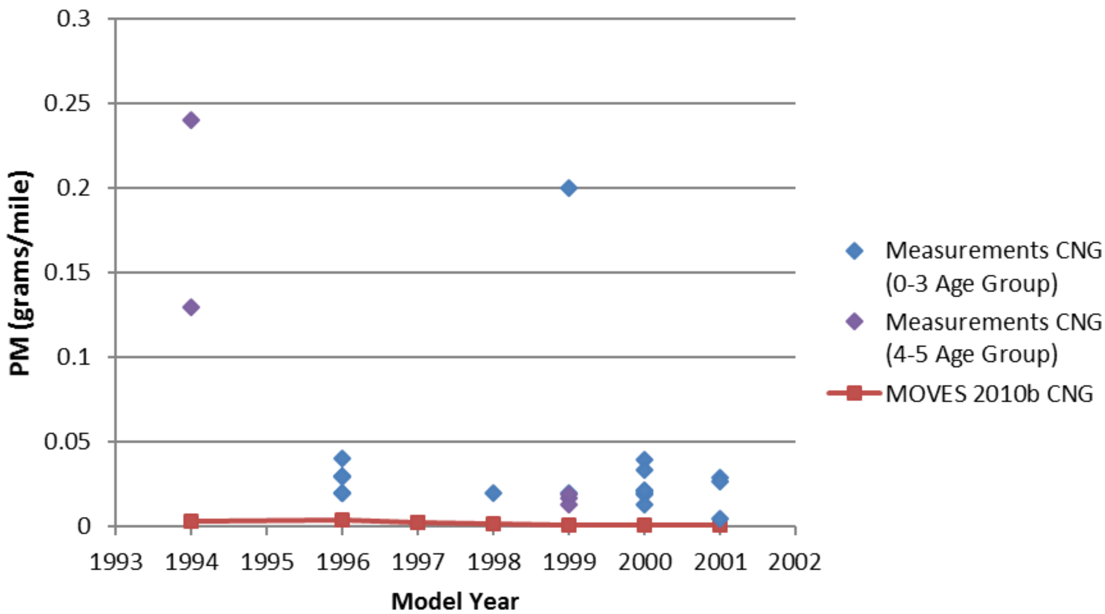

Figure 4-8. PM Emission Comparisons of CNG Transit Bus Dynamometer Measurements and MOVES2010b Simulated Aggregates on the CBD Cycle

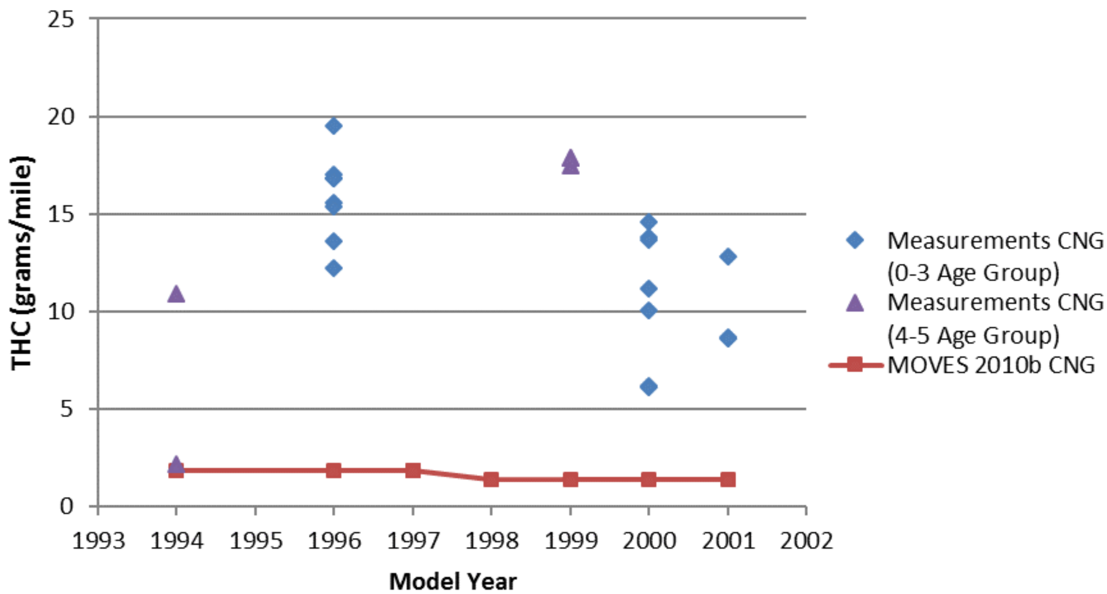

Figure 4-9. THC Emission Comparisons of CNG Transit Bus Dynamometer Measurements and MOVES2010b Simulated Aggregates on the CBD Cycle

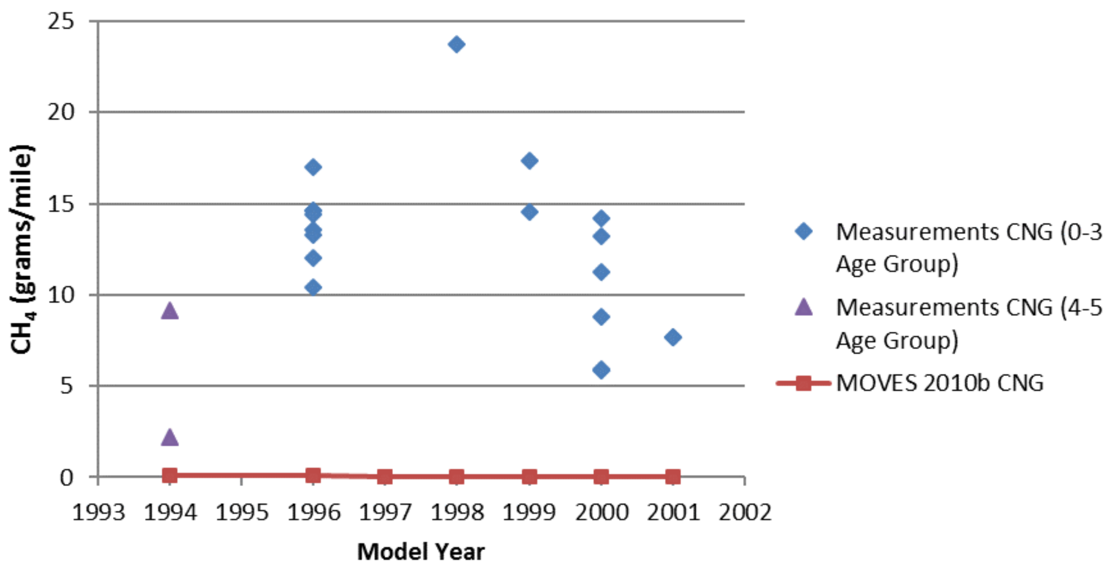

Figure 4-10. CH_4 Emission Comparisons of CNG Transit Bus Dynamometer Measurements and MOVES2010b Simulated Aggregates on the CBD Cycle

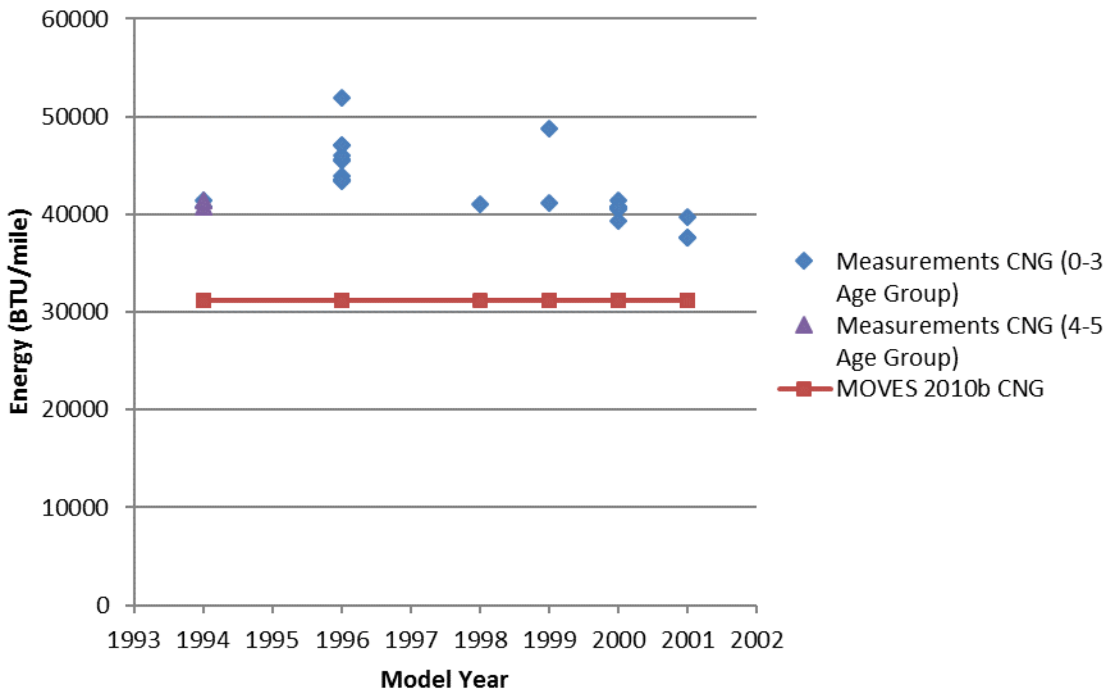

Figure 4-11. Total Energy Consumption Comparisons of CNG Transit Bus Dynamometer Measurements and MOVES2010b Simulated Aggregates on the CBD Cycle

Based on Figure 4-6 through Figure 4-11, compared to chassis dynamometer measurements, MOVES2010b MHD gasoline simulated rates are much lower for NO_X, PM, THC, CH_4 emissions and energy consumption. For CO, MOVES2010b rates are higher up to MY 1998 and comparable starting MY 1999. The under-prediction for THC is largely attributable to a significant underestimate of CNG related CH_4 in MOVES2010b. The relatively high real-world CH_4 emissions from CNG buses, compared to gasoline or diesel buses, are likely from the exhaust of un-combusted natural gas, but further study is warranted on this issue. Thus, we concluded that the MOVES2010b MHD gasoline rates based solely on MHD gasoline vehicle rates were not adequate. As discussed in the next section, we developed new rates based on MHD gasoline vehicle OpMode rates, cycle averages from the chassis dynamometer measurements, and certification data g/bhp-hr rates.

4.2 Development of Running Exhaust Emission Rates

Ideally, MOVES 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 modal data are not readily available in this case. However, the CNG bus emission rates in MOVES2014 by adjusting the MY emission rates as a group (as opposed to individual adjustments by operating mode). The methods to calculate the adjustment ratios are discussed in detail in subsequent sections.

In MOVES201X, we further improved the group based adjustment factor and allowed all HD vehicle types to be modeled with CNG fuel. We improved the adjustment factor by:

1. creating two model year groups, 2007-2009 and 2010-2017, to replace the 2007-2013 model year group in MOVES2014. This allows for better representation of differences in combustion and aftertreatment technology, such as stoichiometric-burn with three-way catalysts (TWC) that became more prevalent starting year 2010.
2. including all HD CNG engine emissions data, within a model year group, in arriving at the certification emission rate for that model year group. In MOVES2014, the certification emission rate was based on only engine families marked as urban bus (since we only allowed HD CNG buses to be modeled).

4.2.1 Determining Model Year Groups

Model year groups are defined based on availability of measurement data, emissions standards, and/or new vehicle technologies that affect real-world emissions. The intent is to create model year groups that capture differences in vehicles over time while still being manageable from a computational viewpoint.

4.2.1.1 MY 1994-2001

We evaluated the measured criteria pollutant rates (NO_X, CO, PM, and THC) to establish model year groups. Initially, for MOVES2014, we separated CNG buses with and without aftertreatment (AT), such as oxidation catalysts, to determine if this was a reasonable distinction, and to see if these vehicles' emission rates for criteria pollutants varied by model year and by age. For some model years, both vehicles with and without aftertreatment existed. Criteria emission improvements between the vehicles with aftertreatment versus those without were primarily inconclusive and did not exhibit any clear trends.[x] Therefore, we 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 the analysis to develop MY 1994-2001 rates. 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.

4.2.1.2 MY 2002-2006

Of the surveyed data, only one study had vehicles newer than MY 2001.[y,113] 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, compared to the 1994-2001 buses tested on the CBD cycle. As a result, we created a second 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.[114]

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[x] The CNG studies do show that aftertreatment has a large impact on several of the unregulated pollutants (e.g., formaldehyde) as discussed in the speciation[1] and air toxics[2] reports.

[y] A number of papers have discussed more recent vehicles. Examples include Clark et al. (2007).[113] Data from these newer studies would provide further validation and refinement to the rates discussed in this report, however it was not available in time.

4.2.1.3 MY 2007 and beyond

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.[115] Analysis of these data showed that from MY 2002 to MY 2012, there have been changes in average certification levels for all the pollutants considered in this report. In particular, NO_X and PM levels have dropped dramatically over the past decade. This effect is largely attributable to increasingly stringent emission standards, which have affected both diesel and CNG buses. Thus, in MOVES2014, we estimated emissions rates for model year group 2007-2012 and those same rates were continued for MY 2013 and beyond.

In MOVES201X, we split the MY 2007-2012 group into two groups, MY 2007-2009 and MY 2010-2017. The rates for MY 2018 and beyond are the same as MY 2010-2017. We decided to split the groups in this way because certification data showed a significant difference between the average emissions rates, for NO_X and CO, between these two model year groups. 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 NO_X emission rate 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 three-way catalyst. This technology transition is the likely reason for the increase in CO emissions rates from MY 2007-2009 to MY 2010-2017 and has been observed in more recent testing with three-way catalyst, stoichiometric CNG buses.[116,117]

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	NMHC[d]
2002-2006	22	1.208	1.355	0.0078	0.147
2007-2009	30 (24 for PM)	0.6123	1.940	0.0042	0.063
2010-2017	159 for NO_X and CO, 153 for HC, and 120 for PM	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 HC and/or PM.
[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.[118]

4.2.2 Emissions Rates by Model Year Group

4.2.2.1 MY 1994-2001 and MY 2002-2006

The OpMode based emissions rates for MHD gasoline vehicles were adjusted by the ratio of cycle-average emissions rates from chassis dynamometer measurements (see Section 4.1.4) 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 OpMode 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 OpMode 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, 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.

$$R_{CNG,OM,1994-2001} = R_{MDG,OM,1997} * \frac{E_{CNG,CBD,1994-2001}}{E_{MDG,simCBD,1997}}$$ **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:

$R_{CNG,OM,MYG}$ = OpMode based emissions rate for CNG vehicles for model year group (MYG) 1994-2001 or MY 2002-2006, in g/hr

$R_{MDG,OM,MY}$ = OpMode 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 $R_{MDG,OM,MY}$ OpMode rates. See Table 4-3.

4.2.2.2 MY 2007-2009, MY 2010-2017, and MY 2018+

Due to lack of published data on MY 2007 and later in-use vehicles, we used certification emissions rates, shown in Table 4-2, to scale the OpMode 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.[119] These real-world effects were present in the chassis dynamometer measurements that were used in estimating 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 model year 2007 and later. This scaling factor is the right-most term in Equation 4-4 shown below.

$$r_{CNG,OM,newMYG} = r_{MDG,OM,2004} * \frac{E_{CNG,WMATA,2004}}{E_{MDG,simWMATA,2004}} * \frac{C_{CNG,newMYG}}{C_{CNG,2002-2006}}$$ **Equation 4-4**

Where:
$C_{CNG,newMYG}$ = Average certification emission rate of all heavy-duty CNG engine families of model year MY 2007-2009 or MY 2010-2017, 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

4.2.2.3 Application of Heavy-Duty Greenhouse Gas Phase 1 and Phase 2 Rules

The adjustment ratio for energy consumption for MY 2002-2006 (Equation 4-3) is applied to all model years starting 2007. For MY 2007+, we did not scale the energy consumption rates like we did for criteria pollutants (Equation 4-4) because even though we have certification data on CO_2 emission rates for recent 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. Further, for energy consumption, we split the MY 2010-2017 group into MY 2010-2013 and MY 2014-2017 groups. The MY 2010-2013 energy consumption rates are same as MY 2002-2006. 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 (see Table 2-20). Similarly, for MY 2018 and later, the energy consumption rates of CNG vehicles are further reduced (from the MY 2017 base rate) as per the Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium and Heavy-Duty Engines and Vehicles — Phase 2 rule (see Table 2-21). 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 2-21). The anticipated improvements in fuel efficiency from the Phase 2 rules are stored in the EmissionRateAdjustment table.

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**	**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
2010-2017[d]	all	2004	0.152	0.357	0.391	0.671	2.33	1.15[e]
2018+[d]	Same as MY 2010-2017, except the ratio for Total Energy[e]							

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 OpMode 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 ECNG and EMDG values in this table and the values in Table 4.2

[e] Total Energy adjustment ratio of 1.15 is only applicable to MY 2010-2013. 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.

4.2.2.3.1 Comparison between MOVES201X and Real-World Rates for MY 2010+ CNG Vehicles

We compared the MY 2011 OpMode based emissions rates from MOVES2014, MOVES201X, and the average of five CNG vehicles in the HDIU data set. The HDIU vehicles had the same MY 2011 engine, certified to the 0.20 g/bhp-hr NO_X standard. The comparisons are shown in Figure 4-12 through Figure 4-15. For NO_X, the MOVES201X rates are considerably lower than MOVES2014 and more representative of real-world measured rates. For CO, MOVES201X rates are somewhat higher than MOVES2014, but still much lower than real-world. For THC, MOVES201X rates are more comparable to real-world at low speed, but less comparable at medium and high speeds. PM emission rates in real-world and MOVES are very low and trends are inconclusive.

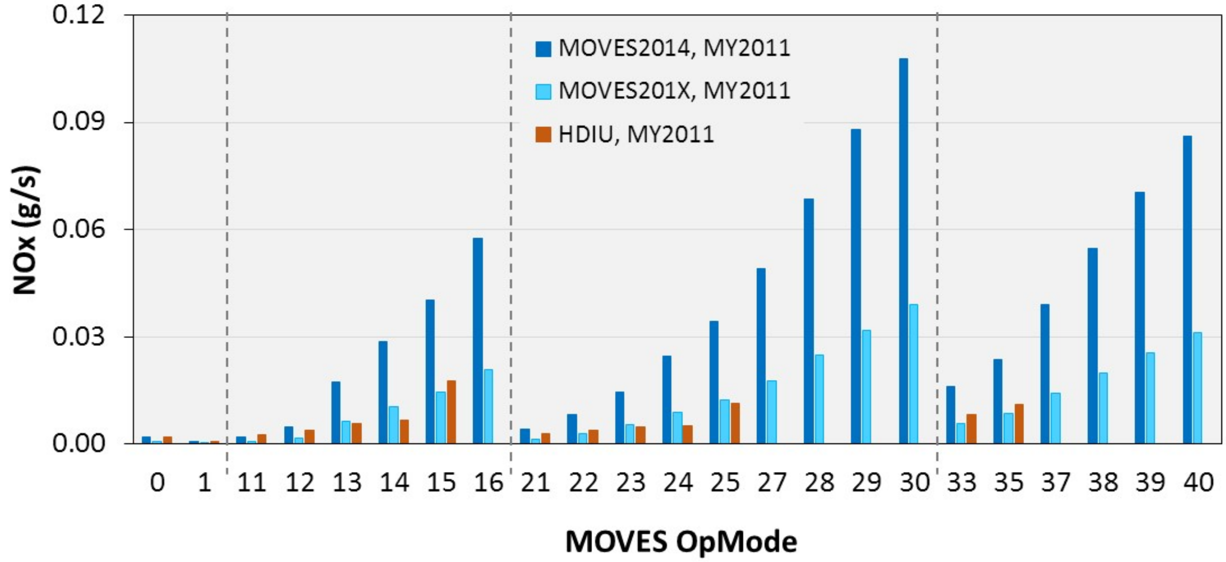

Figure 4-12 Comparison of MY 2011 NO_X Emissions Rates from MOVES2014, MOVES201X, and HDIU Data

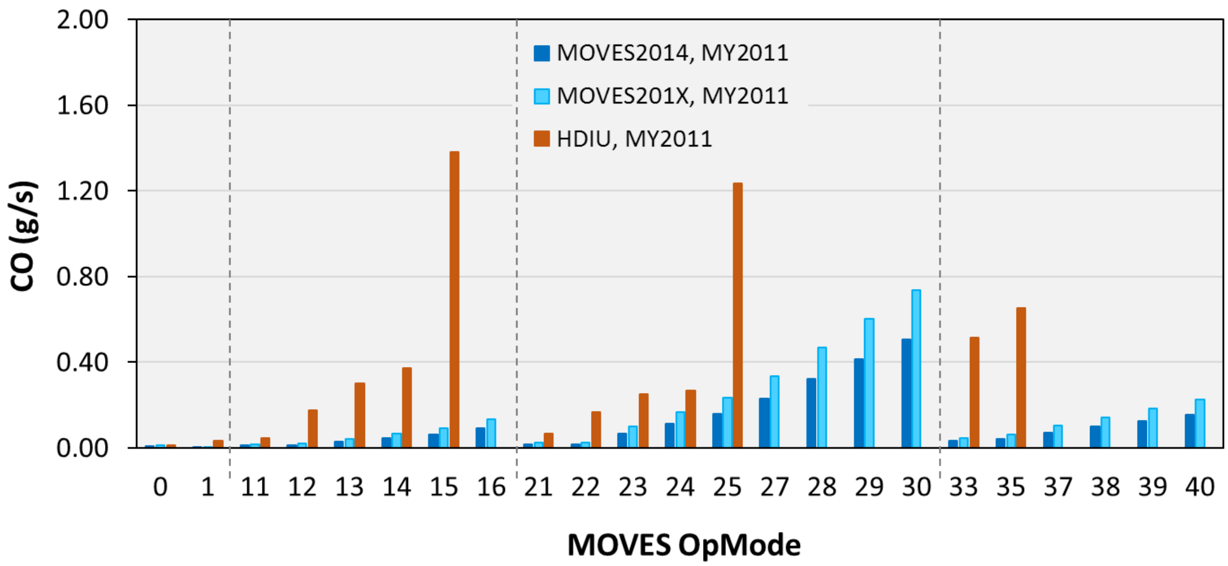

Figure 4-13 Comparison of MY 2011 CO Emissions Rates from MOVES2014, MOVES201X, and HDIU Data

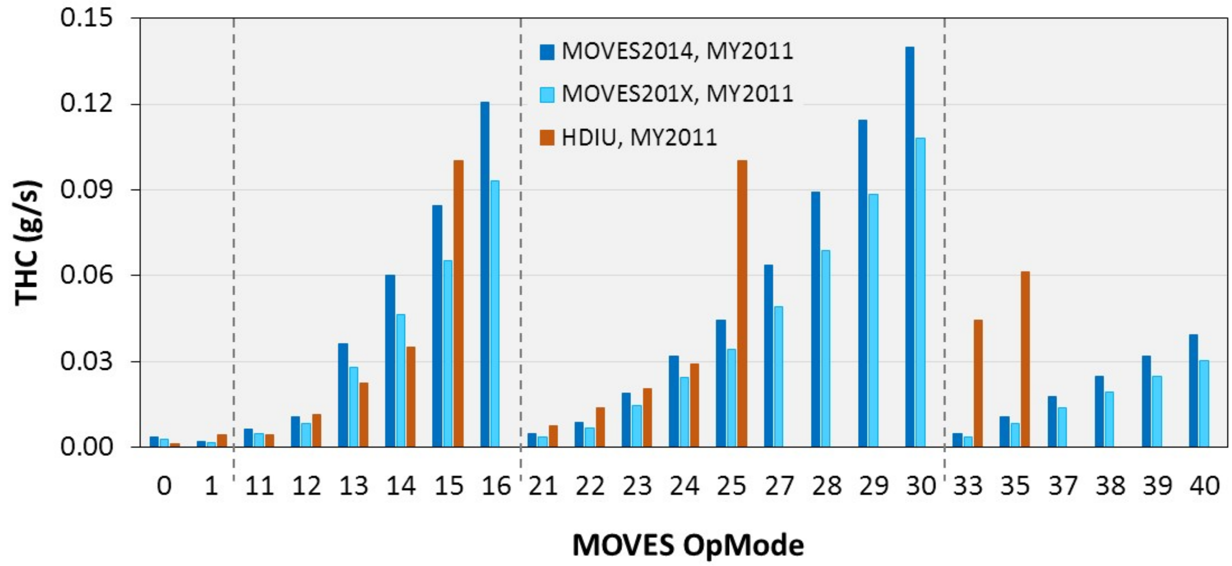

Figure 4-14 Comparison of MY 2011 THC Emissions Rates from MOVES2014, MOVES201X, and HDIU Data

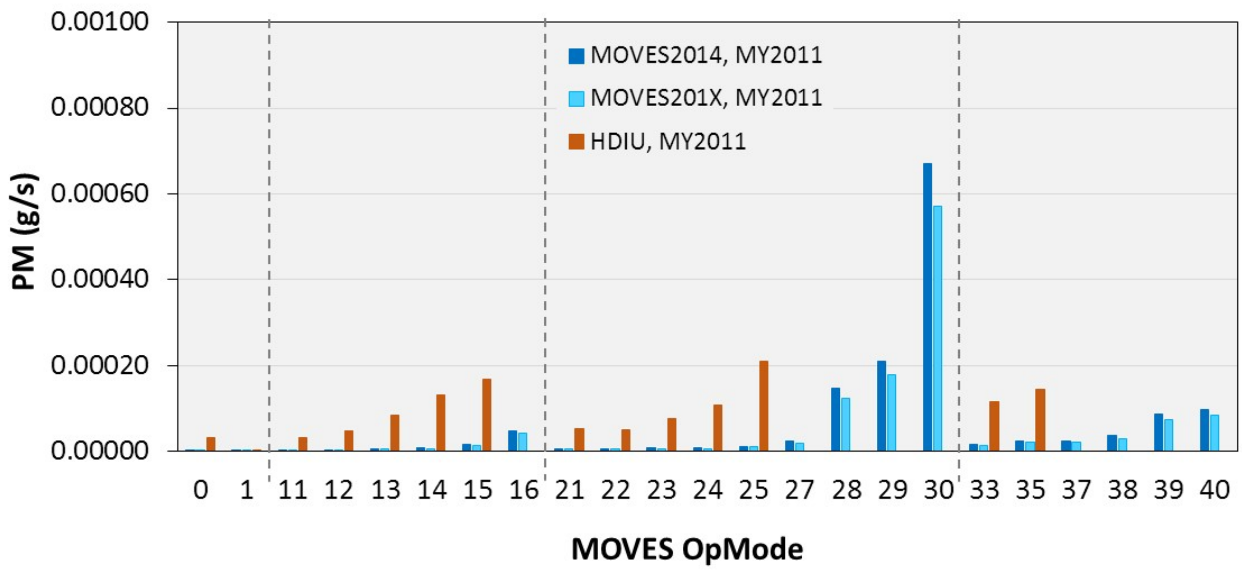

Figure 4-15 Comparison of MY 2011 PM Emissions Rates from MOVES2014, MOVES201X, and HDIU Data

4.2.2.3.2 Other Model Years, Age Groups, and Deterioration

We assumed that the MY 1993 and earlier CNG buses have the same emission rates as MY group 1994-2001. The emission rates for MY 2018 and later CNG vehicles are identical to MY group 2010-2017, with the exception of energy consumption rates as described in the previous paragraph.

Due to limited data on older vehicles in the literature, the ratios 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 3-17 in Section 3.1.1.5 for HC, CO and NOx, and Section 3.1.2.3 for PM).

4.3 Start Exhaust Emission Rates

In the absence of any measured start exhaust emissions from CNG vehicles, their start rates are copied from the MOVES pre-2010 heavy-duty diesel start rates for all pollutants including energy rates. We believe this is an environmentally conservative approach, rather than assuming zero CNG start emissions. 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 rates.

4.4 Ammonia and Nitrous Oxide emissions

No data were available on ammonia emissions rates from CNG vehicles at the time the rates were developed. We used the ammonia emissions for heavy-duty gasoline vehicles, which are documented in a separate report.[7]

The nitrous oxide emission rates for CNG in MOVES remain unchanged from MOVES2009 and later versions and are documented in the MOVES201X Greenhouse Gas Emissions Report.[6]

5 Heavy-Duty Crankcase Emissions

Crankcase 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.[120]

5.1 Background on Heavy-Duty Diesel Crankcase Emissions

Federal regulations permit 2006 and earlier heavy-duty diesel-fueled engines equipped with "turbochargers, pumps, blowers, or superchargers" to vent crankcase emissions to the atmosphere.[121] 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'.[120] 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 [122] [123] [124]. Beginning with 2007 model year heavy-duty diesel vehicles, federal regulations no longer permit crankcase emissions to be vented to the atmosphere, unless they are included in the certification exhaust measurements.[125] Most manufacturers have adopted open crankcase filtration systems.[120] 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.[120] In the ACES Phase 1 program, four MY2007 diesel engines from major diesel engine manufactures (Caterpillar, Cummins, Detroit Diesel, and Volvo) all employed filtered crankcase ventilation systems.[126]

A summary of published estimates of diesel crankcase emissions as percentages of the total emissions (exhaust + crankcase) are provided in Table 5-1. For the conventional diesel technologies, hydrocarbon and particulate matter emissions have the largest contributions from crankcase emissions. There is a substantial decrease in PM emissions beginning with the 2007 model year diesel engines. The 2007 diesel technology reduces the tailpipe emissions more than the crankcase emissions, resulting in an increase in the relative crankcase contribution for HC, CO, and PM emissions. NO_X emissions for the 2007 and later are reported as a negative number. In reality, the crankcase emission contribution cannot be negative, and the negative number is attributed to sampling variability.

Table 5-1 Literature Review on the Contribution of Crankcase Emissions to Diesel Exhaust

Study	Model Year	Type	# Engines/ Vehicles	HC	CO	NO_X	PM
Hare and Baines, 1977[129]	1966, 1973	Conv. Diesel	2	0.2%-3.9%	0.01-0.4%	0.01%-0.1%	0.9%-2.8%
Zielinska et al. 2008[122], Ireson et al. 2011[123]	2000, 2003	Conv. Diesel	2				13.5% - 41.4%
Clark et al. 2006[128], Clark et al. 2006[127]	2006	Conv. Diesel	1	3.6%	1.3%	0.1%	5.9%
Khalek et al. 2009	2007	DPF-equipped	4	95.6%	27.2%	-0.2%	38.2%

5.2 Modeling Crankcase Emissions in MOVES

MOVES calculates THC, CO, NO_X, and $PM_{2.5}$ using a gaseous and a particulate crankcase emission calculator. Within the calculator, crankcase emissions are calculated as a fraction of tailpipe exhaust emissions, including start, running, and extended-idle. 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 and later diesel engines are based on certification levels.

In response to the changes in certification testing of 2007 engines, we changed the data and the methodology with which crankcase emissions are modeled in MOVES. For 2007 and later diesel engines, the crankcase emissions are included in the base exhaust emission rates. The MOVES crankcase calculator divides the base exhaust emission rates into components representing the contributions from exhaust and crankcase emissions. The exhaust emission ratio is equal to 1.0 for all pre-2007 diesel engines, and less than 1.0 for all 2007 and later diesel engines, to account for the inclusion of crankcase emissions in the base rates. More details on the crankcase calculator is provided in the MOVES Speciation Report.[1]

The gaseous crankcase calculator chains the crankcase emission rates to the base exhaust emissions, but it does not reduce the exhaust emission contribution, which is desired for the 2007+ diesel technologies. The 2007+ diesel subsection discusses how MOVES handles THC, CO, and NO_X to avoid double-counting crankcase emissions.

5.3 Conventional Heavy-Duty Diesel

Table 5-2 includes the crankcase/tail-pipe emission ratios used for conventional diesel exhaust. For HC, CO, and NO_X, we selected the values measured on the MY2006 diesel engine reported by Clark et al. 2006.[128] These values compare well with the previous HC, CO, NO_X values reported much earlier by Hare and Baines (1977),[129] which represent much older diesel technology. The similarity of the crankcase emission ratios across several decades of diesel engines, suggests that for conventional diesel engines, crankcase emissions can be well represented as a fraction of the exhaust emissions.

For $PM_{2.5}$ emissions, we use a crankcase/tail-pipe 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[122] and Ireson et al. 2011[123] reported crankcase contributions to total $PM_{2.5}$ emissions as high as 40 percent. Jääskeläinen (2012)[120] 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.[130]

Table 5-2 MOVES Conventional Diesel Crankcase/Tail-Pipe Ratios for HC, CO, NO_X, and $PM_{2.5}$

Pollutant	Crankcase/Tailpipe Ratio	Crankcase/(Crankcase + Tailpipe) Ratio
HC	0.037	0.036
CO	0.013	0.013
NO_X	0.001	0.001
$PM_{2.5}$	0.200	0.167

As outlined in the MOVES2014 TOG and PM Speciation Report, MOVES does not apply the crankcase/tailpipe emission ratio in Table 5-4 to the total exhaust $PM_{2.5}$ emissions. MOVES applies the 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.

The pre-2007 diesel ratios are derived such that the total crankcase $PM_{2.5}$/exhaust $PM_{2.5}$ ratio is 20 percent, and the crankcase emissions EC/PM fraction reflects measurements from in-use crankcase emissions. Zielinska et al. 2008[122] reported that the EC/PM fraction of crankcase emissions from two conventional diesel buses is 1.57 percent. Tailpipe exhaust from conventional 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 from the lubricating oil.[122,123] The crankcase emission factors shown in Table 5-3 are derived such that the crankcase $PM_{2.5}$ emissions are 20 percent of the $PM_{2.5}$ exhaust measurements, and have an EC/PM split of 1.57 percent.

The PM_{10} 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 5-3. MOVES Exhaust and Crankcase Ratios for Pre-2007 Diesel by Pollutant, Process, and Model Year Group for $PM_{2.5}$ Species

Pollutant	Process	Start	Running	Extended Idle
EC	Exhaust	1	1	1
nonECnonSO4PM		1	1	1
SO4		1	1	1
H2O		1	1	1
EC	Crank-case	0.009	0.004	0.012
nonECnonSO4PM		0.295	0.954	0.268
SO4		0.295	0.954	0.268
H2O		0.295	0.954	0.268

5.4 2007+ Heavy-Duty Diesel

The 2007+ heavy-duty diesel THC, CO, and NO_X crankcase emissions are included in the exhaust emissions. However, with the current gaseous crankcase emission calculator code, the crankcase contribution of THC, CO, and NO_X to the base exhaust emission rates cannot be properly accounted. The crankcase to tailpipe emission ratios for THC, CO, and NO_X are set to zero as shown in Table 5-4 and MOVES produces no crankcase emissions for each of the pollutants.

Table 5-4 also lists the crankcase to tailpipe emission ratios based on ACES Phase 1 tests. Based on the ACES Phase 1 program, the MOVES estimate of no crankcase emissions is reasonable for NO_X, but not for THC and CO emissions. MOVES does not report separate crankcase emissions for THC and CO because they are included in the exhaust emission rates for 2007 and later model years from heavy-duty diesel vehicles. Users can use the ratios listed in Table 5-4 to post-process the exhaust emission rates if separate estimates of crankcase emissions of THC and CO emissions are desired.

Table 5-4 MOVES 2007 and Later Diesel Crankcase/Tailpipe Ratio for HC, CO, and NO_X

Pollutant	MOVES crankcase/tailpipe ratio	ACES Phase 1 crankcase/tail-pipe ratio	ACES Phase 1 crankcase/(crankcase + tail-pipe) ratio
HC	0	21.95	95.6%
CO	0	0.37	27.2%
NO_X	0	0.00	0.0%

For $PM_{2.5}$ emissions, we used data from the ACES Phase 1 test program to inform the crankcase and exhaust ratios for the updated $PM_{2.5}$ crankcase emissions calculator. The crankcase emissions measured in the ACES Phase 1 test program contributed 38 percent of the total $PM_{2.5}$ emissions on the hot-FTP driving cycle. Other tests suggest that the crankcase emissions can contribute to over 50 percent of the particulate matter emissions from 2007 and later diesel technologies.[130]

For $PM_{2.5}$ emissions, MOVES applies crankcase ratios to each of the intermediate $PM_{2.5}$ species (EC, nonECnonSO4PM, SO4, and H2O). For 2007+ heavy-duty diesel engines, the same crankcase ratio is applied to each of the intermediate species (0.62 for exhaust and 0.38 for crankcase). The

MOVES $PM_{2.5}$ speciation profile developed from the ACES Phase 1 study combined the crankcase and tailpipe emissions. As such, MOVES uses the same speciation profile for both crankcase and tailpipe emissions. The resulting exhaust and crankcase emission ratios for 2007 and later heavy-duty diesel are provided in Table 5-5. As explained in Section 5.2, the exhaust crankcase emission factor is less than one for 2007+ diesel vehicles to account for the contribution of crankcase emissions in the base exhaust emission rates.

Table 5-5 MOVES Exhaust and Crankcase Emission Factors for 2007 + Heavy-Duty Diesel by Pollutant, Process, and Model Year Group for $PM_{2.5}$ Species

Pollutant	Process	All processes
EC	Exhaust	0.62
nonECnonSO4PM		0.62
SO4		0.62
H2O		0.62
EC	Crank-case	0.38
nonECnonSO4PM		0.38
SO4		0.38
H2O		0.38

5.5 Heavy-Duty Gasoline and CNG 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, which are documented in the MOVES light-duty emission rates report.[9] We assume 4 percent of PCV systems fail, resulting in the small crankcase to exhaust emission ratios shown in Table 5-6 for 1969 and later gasoline engines. Due to limited information, we used the gasoline heavy-duty crankcase emission factors for heavy-duty CNG engines because they have low crankcase PM emissions.

Table 5-6 Crankcase to Tailpipe Exhaust Emission Ratio for Heavy-Duty Gasoline and CNG Vehicles for HC, 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

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 5-7. No information is available to estimate separate speciation between exhaust and crankcase, so the factors are the same between the PM subspecies.

Table 5-7 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

		1960-1968 Gasoline Vehicles	**1969-2050 Gasoline/ CNG**
Pollutant	**Process**	**All processes**	**All processes**
EC	Exhaust	1	1
nonECnonSO4PM		1	1
SO4		1	1
H2O		1	1
EC	Crankcase	0.2	0.008
nonECnonSO4PM		0.2	0.008
SO4		0.2	0.008
H2O		0.2	0.008

6 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.[131,132] 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 $NO_y = NO_X + NO_z$.[131] NO_z compounds are formed in the atmosphere as oxidation products of NO_X.[132]

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, than they can bias the NO_2 measurements high.[133]

MOVES produces estimates of 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. For the heavy-duty vehicle source types, the NO_X fractions only vary according to fuel type, model year, and emission process. The NO_X fractions in MOVES were developed from a literature review reported by Sierra Research to the EPA, from emission test programs conducted in the laboratory with constant volume sampling dilution tunnels.[7]

MOVES also produces estimates of 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.[134] In MOVES, we assume HONO contributes to the NO_X values, because either (1) the chemiluminescent analyzers are biased slightly high by HONO in the exhaust stream, or (2) 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. HONO emissions are also estimated using the non2ratio MOVES table. For each source type, fuel type, and emission process, the NO, NO_2, and HONO values in the non2ratio sum to unity.

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).This is because we are correcting the exhaust NO_X emission in MOVES for potential interference with HONO measurements. 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 a MOVES users developing air quality inputs of

NO, NO_2, and HONO, should 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).

Future work is needed to (1) update the NO_X and HONO fractions in MOVES based on more recent measurements, (2) reconcile the definition of NO_X in MOVES, while also correctly accounting for the emissions of NO_z species that may impact NO_X measurements and (3) reconcile measurement differences that may occur between NO_y species measured at the tailpipe, with NO_y species measured on road side measurements.[135]

6.1 Heavy-Duty Diesel

Table 6-1 shows the NO_X and HONO fractions for heavy-duty diesel vehicles. The conventional diesel (1960-2006 model year) NO_X fractions were estimated as the average reported fraction from three studies of heavy-duty vehicles not equipped with diesel particulate filters.[7] The 2010+ NO_2 fractions are based on the average of three diesel programs of diesel vehicles measured with diesel particulate filters. The 2007-2009 values are an average of the 1960-2006 and 2010-2050 values, which assumes that the NO_X fractions changed incrementally, as trucks equipped with catalyzed diesel particulate filters were phased-into the fleet. The NO_X fractions are the same across all diesel source types (including light-duty) and across all emission processes (running, start, extended idle), except for auxiliary power units, which use the conventional NO_X fractions (1960-2006) for all model years because it is assumed that the APUs are not fitted with diesel particulate filters. The NO_2 fractions originally developed from the Sierra report[7] were reduced by 0.008 to account for the HONO emissions.

Table 6-1. NO_X and HONO Fractions for Heavy-Duty Diesel Vehicles

Model Year	NO	NO_2	HONO
1960-2006[a]	0.935	0.057	0.008
2007-2009	0.764	0.228	0.008
2010-2060	0.594	0.398	0.008

Note:
[a] All Model Year of Auxiliary Power Units (APUs) use the 1960-2006 NO_X and HONO fractions

6.2 Heavy-Duty Gasoline

The NO_X fractions for heavy-duty gasoline are based on the MOVES values used for light-duty gasoline measurements. Separate values are used for running and start emission processes. As stated in the Sierra Report,[7] the values are shifted to later model year groups to be consistent with emission standards and emission control technologies. These values are shown in Table 6-2 for both light-duty and heavy-duty gasoline vehicles. The NO_2 fractions originally developed from the Sierra report[7] were reduced by 0.008 to account for the HONO emissions.

Table 6-2. NO_X and HONO Fractions for Light-Duty (Sourcetypeid 21, 31, 32) and Heavy-Duty Gasoline Vehicles (Sourcetypeid 41, 42, 43, 51, 52, 53, 54, 61, 62)

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

6.3 Compressed Natural Gas

We used the average of three NO_2/ NO_X fraction reported on three CNG transit buses with DDC Series 50 G engines by Lanni et al. (2003)[109] with the 0.008 HONO fraction assumed for other source types, to estimate the NO_X fractions of NO, NO_2, and the HONO fraction. These assumptions yield the NO_X and HONO fractions in Table 6-3, which are used for all model year CNG heavy-duty vehicles.

Table 6-3 NO_X and HONO Fractions CNG Heavy-Duty Vehicles

Model Year	NO	NO_2	HONO
1960-2060	0.865	0.127	0.008

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

Tampering and mal-maintenance (T&M) effects represent the fleet-wide average increase in emissions over the useful life of the engines. In laboratory testing, properly maintained engines often yield very small rates of emissions deterioration through time. However, we assume that in real-world use, tampering and mal-maintenance yield higher rates of emissions deterioration over time. As a result, we feel it is important to model the amount of deterioration we expect from this tampering and mal-maintenance. We estimated these fleet-wide emissions effects by multiplying the frequencies of engine component failures by the emissions impacts related to those failures for each pollutant. Details of this analysis appear later in this section.

Appendix B-1. Modeling Tampering and Mal-maintenance

As T&M affects emissions through age, we developed a simple function of emission deterioration with age. We applied the zero-age rates through the emissions warranty period (5 years/100,000 miles), then increased the rates linearly up to the useful life. Then we assumed that all the rates level off beyond the useful life age. Figure B-1 shows this relationship. The actual emission levels were determined through data analysis detailed below.

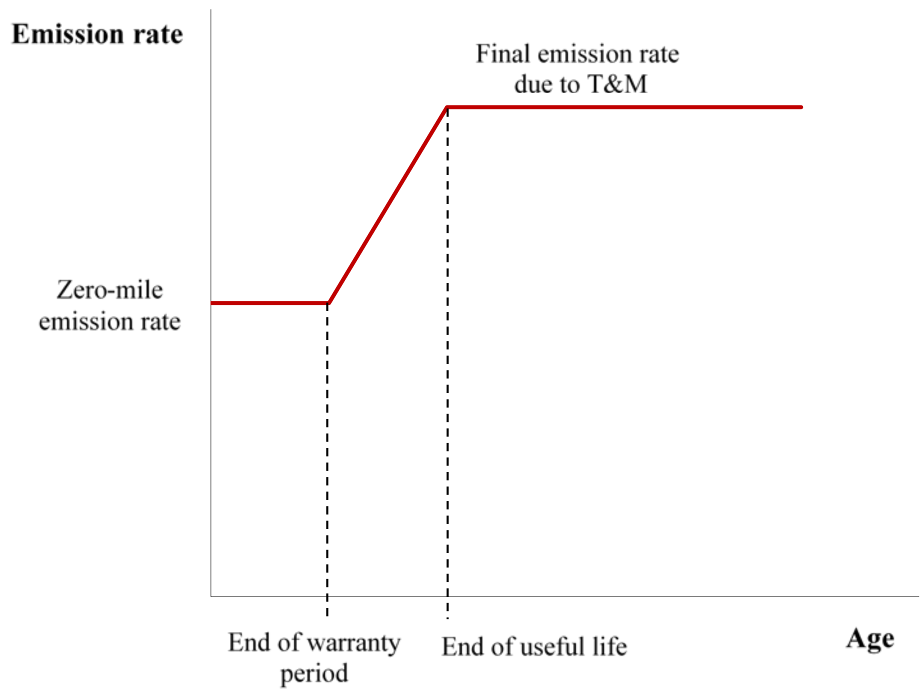

Figure B-1. Qualitative Depiction of the Implementation of Age Effects

The 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[136] (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.

Table B-4. Warranty and Useful Life Requirements by Regulatory Class

Regulatory class	Warranty age[a] (Requirement: 100,000 miles or 5 years)	Useful life mileage/age requirement	Useful life age[a]
HHD	1	435,000/10	4
MHD	2	185,000/10	5
LHD45	4	110,000/10	4
LHD2b3	4	110,000/10	4
BUS	2	435,000/10	10

a. The 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.

While both age and mileage metrics are given for these periods, whichever comes first determines the applicability of the warranty. As a result, since MOVES deals with age and not mileage, we needed to convert all the mileage values to age equivalents, as the mileage limit is usually reached before the age limit. The data show that on average, heavy heavy-duty trucks accumulate mileage much more quickly than other regulatory classes. 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 quickly. Therefore, their useful life period is governed by the age requirement, not the mileage requirement.

Since MOVES deals with age groups and not individual ages, the increase in emissions by age must be calculated by age group. We assumed that there is 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). 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-2 shows the multiplicative T&M adjustment factor by age. We determined this factor using the mileage-age data from Table B-1 and the emissions-age relationship that we described in Figure B-1. We multiplied this factor by the emissions increase of each pollutant over the useful life of the engine, which we determined from the analysis in sections B.7 through B.9.

Table B-5. T&M Multiplicative Adjustment Factor by Age ($f_{TM,age\ group}$)

Age Group	LHD	MHD	HHD	Bus
0-3	0	0.083	0.25	0.03125
4-5	1	0.833	1	0.3125
6-7	1	1	1	0.5625
8-9	1	1	1	0.8125
10-14	1	1	1	1
15-19	1	1	1	1
20+	1	1	1	1

In this table, a value of 0 indicates no deterioration, or zero-mile emissions level (ZML), and a value of 1 indicates a fully deteriorated engine, or maximum emissions level, at or beyond useful life (UL). The calculation of emission rate by age group is described in Equation B-1. TM_{pol} represents the estimated emissions rate increase through the useful life for a given pollutant.

$$\bar{r}_{pol,agegrp} = \bar{r}_{pol,ZML}(1+ f_{TM,agegroup}TM_{pol}) \qquad \textbf{Equation B-1}$$

Appendix B-2. Data Sources

EPA used the following information to develop the tamper and mal-maintenance occurrence rates used to develop emission rates used in MOVES:

- California's ARB EMFAC2007 Modeling Change Technical Memo[137] (2006). The basic EMFAC occurrence rates for tampering and mal-maintenance were developed from Radian and EFEE reports and internal 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
- EPA internal engineering judgment

Appendix B-3. T &M Categories

EPA generally adopted the categories developed by CARB, with a few exceptions. The high fuel pressure category was removed. We added a category for misfueling to represent the use of nonroad diesel in cases when ULSD onroad diesel is required. We combined the injector categories into a single group. We reorganized the EGR categories 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 category.

EPA grouped the LHDD, MHDD, HHDD, and Diesel bus groups together, except for model years 2010 and beyond. We assumed that the LHDD group will primarily use Lean NO_X Traps (LNT) for the NO_X control in 2010 and beyond. On the other hand, we also assumed that Selective Catalyst Reduction (SCR) systems will be the primary NO_X aftertreatment system for HHDD. Therefore, the occurrence rates and emission impacts will vary in 2010 and beyond depending on the regulatory class of the vehicles.

Appendix 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.

Appendix B-5. T &M Occurrence Rates and Differences from EMFAC2007

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 hardware would evolve through 2010, rather than be replaced with completely new systems that would justify a higher rate of failure. We assumed that many of the 2010 changes would occur with the aftertreatment systems which are accounted for separately.

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[138] 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.

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.

Appendix B-6. Tampering & Mal-maintenance Occurrence Rate Summary

Tamper & Malmaintenance
Frequency of Occurrence: Average rate over life of vehicle

	Frequency Rates					
	1994-97	1998-2002	2003-2006	2007-2009	2010+ HHDT	2010+ LHDT
Timing Advanced	5%	2%	2%	2%	2%	2%
Timing Retarded	3%	2%	2%	2%	2%	2%
Injector Problem (all)	28%	28%	13%	13%	13%	13%
Puff Limiter Mis-set	4%	0%	0%	0%	0%	0%
Puff Limiter Disabled	4%	0%	0%	0%	0%	0%
Max Fuel High	3%	0%	0%	0%	0%	0%
Clogged Air Filter - EPA	8%	8%	8%	8%	8%	8%
Wrong/Worn Turbo	5%	5%	5%	5%	5%	5%
Intercooler Clogged	5%	5%	5%	5%	5%	5%
Other Air Problem - EPA	6%	6%	6%	6%	6%	6%
Engine Mechanical Failure	2%	2%	2%	2%	2%	2%
Excessive Oil Consumption	5%	3%	3%	3%	3%	3%
Electronics Failed - EPA	3%	3%	3%	3%	3%	3%
Electronics Tampered	10%	15%	5%	5%	5%	5%
EGR Stuck Open	0%	0%	0.2%	0.2%	0.2%	0.2%
EGR Disabled/Low Flow - EPA	0%	0%	10%	10%	10%	10%
Nox Aftertreatment Sensor	0%	0%	0%	0%	10%	10%
Replacement Nox Aftertreatment Sensor	0%	0%	0%	0%	1%	1%
Nox Aftertreatment Malfunction - EPA	0%	0%	0%	0%	13%	16%
PM Filter Leak	0%	0%	0%	5%	5%	5%
PM Filter Disabled	0%	0%	0%	2%	2%	2%
Oxidation Catalyst Malfunction/Remove - EPA	0%	0%	0%	5%	5%	5%
Mis-fuel - EPA	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%

Appendix B-7. NO_X Emission Effects

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 internal testing experience. EPA estimated that the lean NO_X traps (LNT) in LHDD are 80 percent efficient and the selective catalyst reduction (SCR) systems in HHDD 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.[139] Visteon reports a 60-80 percent NO_X reduction with open loop control.[140]

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 HHDD vehicles with SCR systems would experience 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 LHDD vehicles with LNT systems would experience 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.

Tamper & Malmaintenance
NOX Emission Effect

	1994-97	1998-2002	2003-2006	2007-2009	2010+ HHDT	2010 LHDT
Federal Emission Standard	5.0	5.0	4.0	2.0	0.2	0.2
Timing Advanced	60%	60%	60%	60%	6%	12%
Timing Retarded	-20%	-20%	-20%	-20%	-20%	-20%
Injector Problem (all)	-5%	-1%	-1%	-1%	-1%	-1%
Puff Limiter Mis-set	0%	0%	0%	0%	0%	0%
Puff Limiter Disabled	0%	0%	0%	0%	0%	0%
Max Fuel High	10%	0%	0%	0%	0%	0%
Clogged Air Filter	0%	0%	0%	0%	0%	0%
Wrong/Worn Turbo	0%	0%	0%	0%	0%	0%
Intercooler Clogged	25%	25%	25%	25%	3%	5%
Other Air Problem	0%	0%	0%	0%	0%	0%
Engine Mechanical Failure	-10%	-10%	-10%	-10%	-10%	-10%
Excessive Oil Consumption	0%	0%	0%	0%	0%	0%
Electronics Failed	0%	0%	0%	0%	0%	0%
Electronics Tampered	80%	80%	80%	80%	8%	16%
EGR Stuck Open	0%	0%	-20%	-20%	-20%	-20%
EGR Disabled / Low Flow	0%	0%	30%	50%	5%	10%
Nox Aftertreatment Sensor	0%	0%	0%	0%	200%	200%
Replacement Nox Aftertreatment Sensor	0%	0%	0%	0%	200%	200%
Nox Aftertreatment Malfunction	0%	0%	0%	0%	500%	300%
PM Filter Leak	0%	0%	0%	0%	0%	0%
PM Filter Disabled	0%	0%	0%	0%	0%	0%
Oxidation Catalyst Malfunction/Remove	0%	0%	0%	0%	0%	0%
Mis-fuel						

Combining the NO_X emission effects with the frequency results in the initial Tampering & Malmaintenance (T&M) effects shown in the Table B-4 below. As noted in Section 2.1.1.5, MOVES does not use the estimated NO_X increase from T&M for 2009 and earlier model years, and assumes no NO_X increase. This is incorporated into the 3rd column of Table B-4 labeled with (Remove 2009 and earlier).

Table B-7. Fleet-Average Tampering & Mal-Maintenance (TM) NO_X Emission Increases (Percent) from Zero-Mile Levels Calculated Over the Useful Life.

Model years	$TM_{NOx,nonOBD}$ (Initial)	$TM_{NOx,nonOBD}$ (Remove 2009 and earlier)	f_{OBD}	$TM_{NOx,OBD}$
1994-1997	10	0	0	-
1998-2002	14	0	0	-
2003-2006	9	0	0	-
2007-2009	11	0	0	-
2010-2012 SCR	87	87	0.33	77
2010-2012 LNT	72	72	1	48
2013+ SCR	87	87	1	58

$TM_{NOx,nonOBD}$ are calculated using the NO_X emission effects and frequencies shown above. $TM_{NOx,OBD}$ incorporate the OBD assumptions discussed in Section B.10, including the assumed penetration of OBD (f_{OBD})

The LHD≤10K trucks have different T&M NO_X increases than LHD≤14K trucks, due to the assumed penetration of lean NO_X trap (LNT) aftertreatment which was assumed to penetrate 25 percent of LHD≤10K trucks starting in 2007, consistent with the assumptions previously made in Section 2.1.1.4.4.

The T&M rates for LHD≤10K in 2007-2009 are calculated by adjusting Equation 3-10 to account for T&M of LNT aftertreatment, as shown in Equation B-2:

$$\frac{2007-2009\ LNT\ NOx\ emissions\ (T\&M)}{2003-2006\ LHD \le 10K\ NOx\ emissions}$$

$$= (normal\ op.frequency) \times \left(\frac{LNT\ normal\ emissions}{baseline\ emissions}\right) \times (T\&M\ effect) + (DPF\ reg.frequency) \times \left(\frac{baseline\ emissions}{baseline\ emission}\right) \quad \textbf{Equation B-2}$$

$$= (0.90) \times (0.10) \times (1.72) + (0.10) \times (1) \times (1) = 0.2548$$

The ratio of 2007-2009 LHD≤ 10K (with T&M) over the baseline 2003-2006 NO_X rates is calculated by adjusting Equation 3-11 to account for the T&M effects of LNT, as shown in Equation B-3.

$$\frac{2007-2009\ LHD \le 10K\ NOx\ emissions\ (T\&M)}{2003-2006\ LHD \le 10K\ NOx\ emissions}$$

$$= (LNT\ market\ share)\left(\frac{2007-2009\ LNT\ NOx\ emissions\ (T\&M)}{2003-2006\ LHD \le 10K\ NOx\ emissions}\right) + (non-LNT\ market\ share)\left(\frac{2007-2009\ emission\ standards}{2003-2006\ NOx\ emissions\ standards}\right) \quad \textbf{Equation B-3}$$

$$=0.25\times0.2548 + 0.75\times0.5 = 0.4225$$

Then, the overall T&M effect for 2007-2009 LHD≤ 10K is calculated in Equation B-4 by dividing Equation B-2 by Equation 3-11.

$$\frac{2007-2009\ LHD \le 10K\ NOx\ emissions\ (T\&M)}{2007-2009\ LHD \le 10K\ NOx\ emissions\ (zero\ mile)}$$

Equation B-4

$$= \left(\frac{2007-2009\ LHD \le 10K\ NOx\ (T\&M)}{2003-2006\ LHD \le 10K\ NOx\ emissions}\right) \Big/ \left(\frac{2007-2009\ LHD \le 10K\ NOx\ (zero\ mile)}{2003-2006\ LHD \le 10K\ NOx\ emissions}\right)$$

$$= 0.4387/0.4225 = 1.04 = 4\%\ increase\ due\ to\ T\&M$$

For 2010+, LHD≤14K, 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). Thus, for calculating the T&M NO_X effects for 2010-2012, we weighted the LNT-specific and 2013+SCR-specific T&M effects (from Table B-4) according to the market shares, as shown in Equation B-5:

$$2010+\ LHD{\le}10K\ NOx\ emissions\ T\&M$$
$$= LNT\ market\ share \times 2010{-}2012\ \text{LNT T\&M} + non{-}LNT\ market\ share \times 2013{+}\text{SCR}$$
$$= 0.25 \times 0.48 + 0.75 \times 0.58 = 56\%$$

Equation B-5

For LHD≤14K and Other HD we use the SCR T&M effects from Table B-4. For LHD≤14K we assume full OBD penetration starting in 2010. For the other HD, we assume only 33 percent OBD penetration in 2010-2012, and full penetration for 2013+ model years. The NO_X T&M effects by the MOVES regulatory classes and model year groups are shown in Table B-5.

Table B-8. NO_X T&M Effects (Percent) by MOVES Regulatory Classes and Model Year Groups

Model Year Groups	LH≤10K	LHD≤14K	Other HD
2007-2009	4%	0%	0%
2010-2012	56%	58%	77%
2013+	56%	58%	58%

Appendix B-8. PM Emission Effects

EPA developed the PM emission effects from 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 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. This results in a fleet average PM Tampering & Mal-maintenance effect of 100 percent in 2007-2009 and 89 percent in 2010-2012.

Tamper & Malmaintenance
PM Emission Effect

	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%

Appendix B-9. HC 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 HC zero level emissions will increase by 50 percent. This still represents a 70 percent reduction in HC emissions between zero-mile 2006 emissions and fully deteriorated 2007 vehicles.

We reduced CARB's HC emission effect for timing advanced because earlier timing should reduce HC, not increase them. The effect of injector problems was reduced to 1000 percent based on EPA's engineering staff experience. We increased the HC 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 HC. Lastly, we used the HC 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.

Tamper & Malmaintenance
HC Emission Effect

	1994-97	1998-2002	2003-2006	2007-2009	2010+ HHDT	2010 LHDT
Federal Emission Standard	1.3	1.3	1.3	0.2	0.14	0.14
Timing Advanced	0%	0%	0%	0%	0%	0%
Timing Retarded	50%	50%	50%	50%	10%	10%
Injector Problem (all)	1000%	1000%	1000%	1000%	200%	200%
Puff Limiter Mis-set	0%	0%	0%	0%	0%	0%
Puff Limiter Disabled	0%	0%	0%	0%	0%	0%
Max Fuel High	10%	0%	0%	0%	0%	0%
Clogged Air Filter	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	0%	0%	0%	0%	0%	0%
Engine Mechanical Failure	500%	500%	500%	500%	100%	100%
Excessive Oil Consumption	300%	300%	300%	300%	60%	60%
Electronics Failed	50%	50%	50%	50%	10%	10%
Electronics Tampered	0%	0%	0%	0%	0%	0%
EGR Stuck Open	0%	0%	100%	100%	20%	20%
EGR Disabled / Low Flow	0%	0%	0%	0%	0%	0%
Nox Aftertreatment Sensor	0%	0%	0%	0%	0%	0%
Replacement Nox Aftertreatment Sensor	0%	0%	0%	0%	0%	0%
Nox Aftertreatment Malfunction	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	0%	0%	0%	50%	50%	50%
Mis-fuel						

A separate tampering analysis was not performed for CO; rather, the HC effects were assumed to apply for CO.

Combining all of the emissions effects and failure frequencies discussed in this section, we summarized the aggregate emissions impacts over the useful life of the fleet in the main body of the document in Table 2-9 (NO_X), Table 2-16 (PM), and Table 2-19 (HC and CO).

Appendix 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 tampering and mal-maintenance by 33 percent. Data were not available for heavy-duty trucks equipped with OBD, and this number is probably a conservative estimate. Still, due to the implementation of other standards, PM and NO_X reductions from 2010 and later model year vehicles will be substantial compared to prior model years regardless of the additional incremental benefit from OBD. We assumed, since the rule phased-in OBD implementation, that 33 percent of all engines would have OBD in 2010, 2011, and 2012 model years, and 100 percent would have OBD by 2013 model year and later. Equation B-6 describes the calculation of TM_{pol}, the increase in emission rate through useful life, where f_{OBD} represents the fraction of the fleet equipped with OBD (0 percent for model years 2009 and earlier, 33 percent for model years 2010-2012, and 100 percent for model years 2013 and later). The result from this equation can be plugged into Equation B-1 to determine the emission rate for any age group.

$$TM_{pol} = TM_{pol,nonOBD}\left(1 - f_{OBD}\right) + 0.67 \cdot TM_{pol,nonOBD} f_{OBD}$$ **Equation B-6**

These OBD impacts apply to any truck in GVWR Class 4 and above. Lighter trucks are assumed to follow light-duty OBD impacts and will be fully phased in starting in model year 2010. As data for current and future model years become available, we may consider refining these estimates and methodology.

Appendix C. Evaluation of NOx Emission Rates in MOVES2010

This section presents the comparisons of NO_X rates in MOVES2010 to the emissions data from the Heavy-Duty In-Use (HDIU) and Houston Drayage programs. The HDIU data includes HHD, MHD, and LHD trucks. The Houston Drayage only includes HHD trucks (Table 2-2).

The purpose of the evaluation was to examine the need for updating the NO_X rates in MOVES2010 based on the analysis of the newly acquired independent data. As discussed in Section 2.1.1.1, HDIU and Houston Drayage data became available after the MOVES2010 release and have served two purposes – to evaluate the rates in MOVES2010 and to provide data for updating existing emission rates. The emission rates for a regulatory class and model year group combination were considered for an update if:

1. MOVES2010 rates were not based on actual data, and
2. The comparison to 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.

Appendix C-1. Heavy Heavy-Duty Trucks

Figure C-1 through Figure C-3 show that MOVES2010 rates for pre-2003 model years are generally in good agreement with the Houston Drayage data and within the range of uncertainty of means calculated from these data. The error bars represent the 95 percent confidence intervals of the mean. The MOVES2010 rates for 1998 HHD trucks are lower in the high-speed operating modes (33 and above) compared to the Houston Drayage data (Figure C-2), but only a single truck is represented in the comparison. As expected, the drayage fleet typically did not reach the high-speed/high-power operating modes (operating modes 28-30 and 38-40) during normal operation.

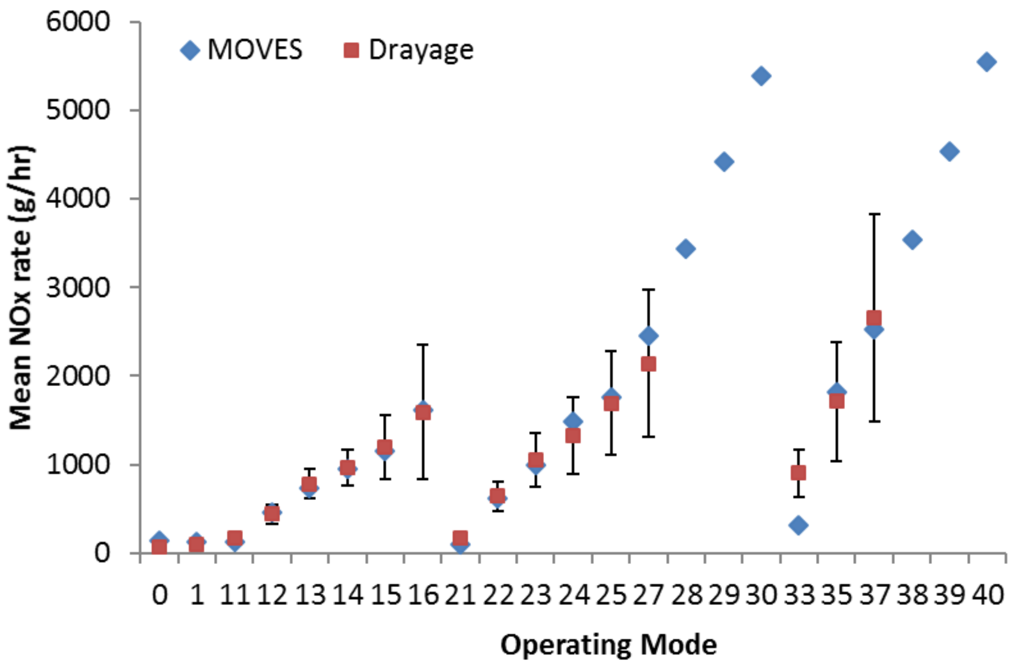

Figure C-1. Comparison of Means: MOVES2010 emission rates vs. Houston Drayage Data (n=8) for model years 1991-1997 HHD trucks. Error bars represent the 95 percent confidence interval of the mean

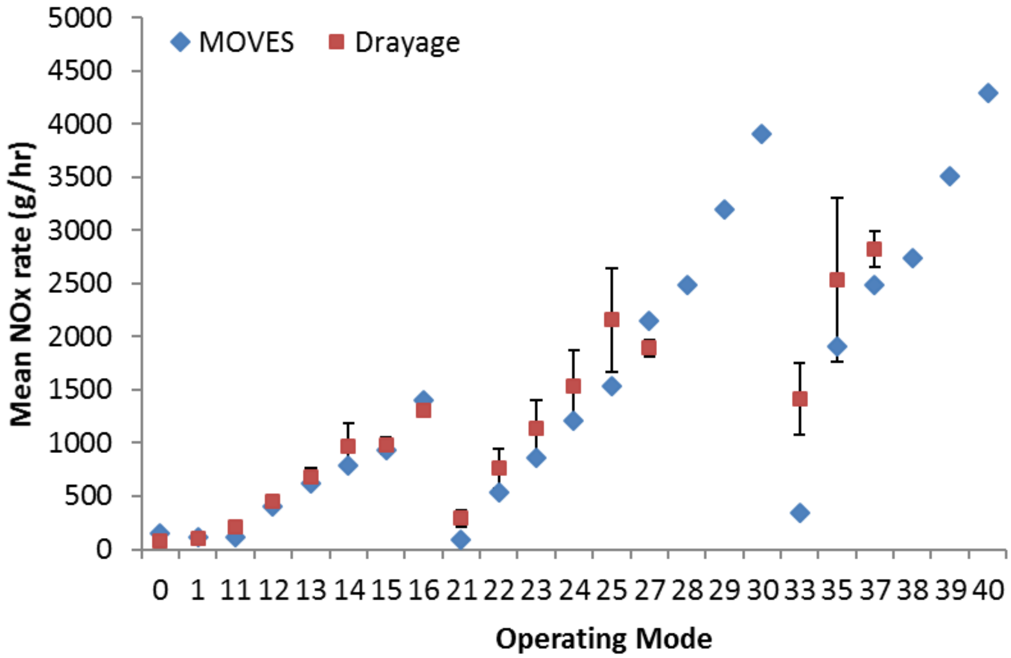

Figure C-2. Comparison of Means: MOVES2010 emission rates vs. Houston Drayage Data (n=1) for model year 1998 HHD trucks. Error bars represent the 95 percent confidence interval of the mean

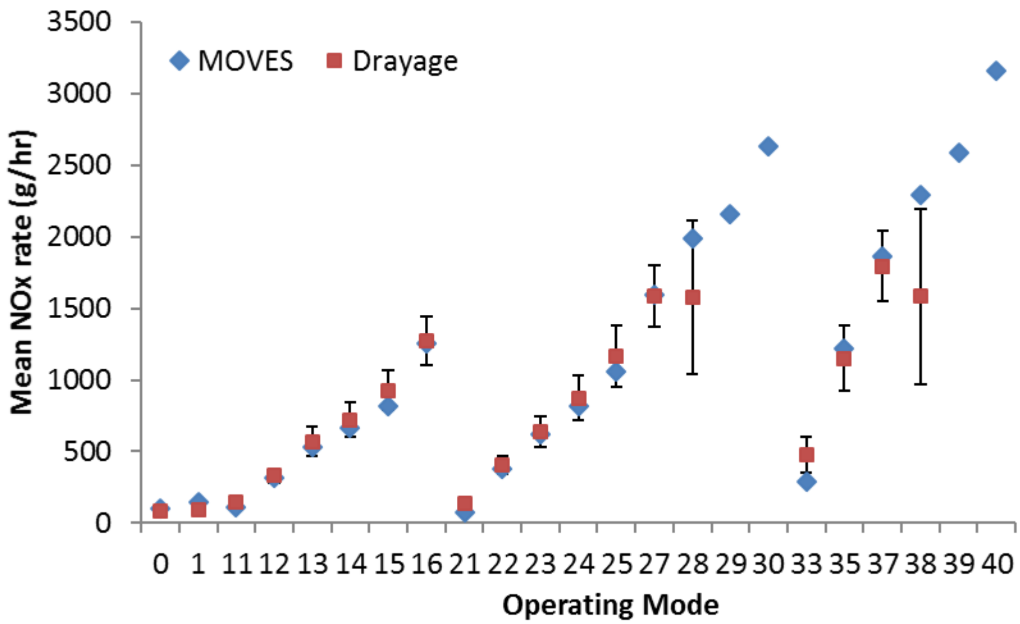

Figure C-3. Comparison of Means: MOVES2010 emission rates vs. Houston Drayage Data (n=10) for model year 1999-2002 HHD trucks. Error bars represent the 95 percent confidence interval of the mean

In Figure C-4 and Figure C-5, MOVES2010 rates for model years 2003-2006 are compared to results from the Houston Drayage and HDIU datasets, respectively. Although MOVES' rates for middle and high speed operating modes are lower, they are within the 95 percent confidence intervals of the mean of Houston Drayage data in Figure C-4. When compared to HDIU data in Figure C-5, MOVES2010 is generally within the variability of the data except for the low speed operating modes. Although both comparisons showed that MOVES2010 rates were slightly lower, since the rates in MOVES2010 for model years 2003-2006 were based on a larger sample of actual test data from ROVER and Consent Decree Testing (n=91), no change was made to the rates in MOVES2014.

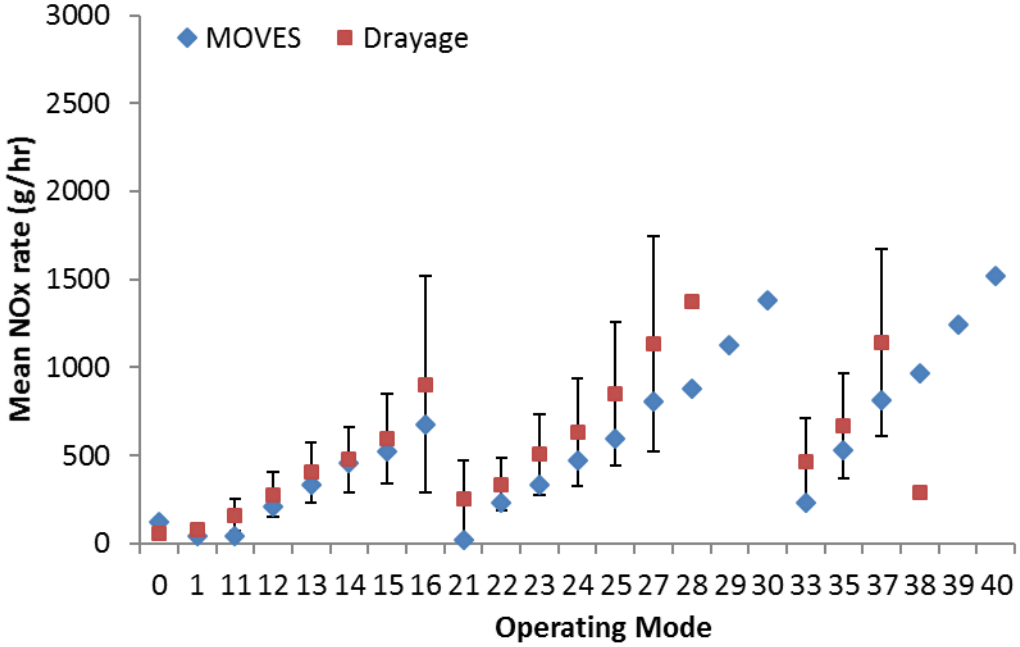

Figure C-4. Comparison of Means: MOVES2010 emission rates vs. Houston Drayage Data (n=8) for model year 2003-2006 HHD trucks. Error bars represent the 95 percent confidence interval of the mean

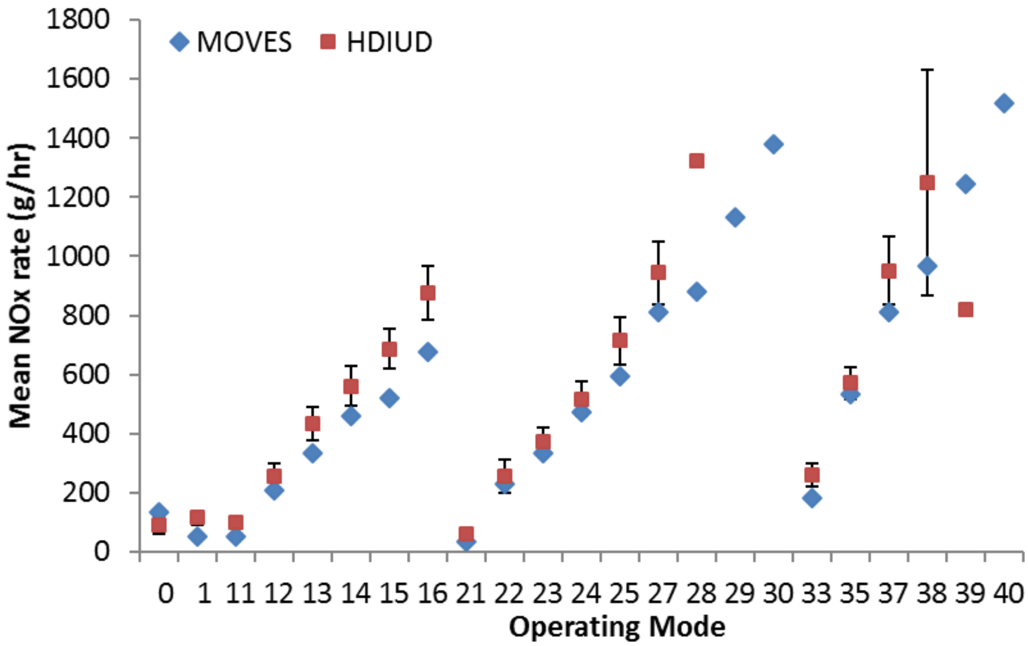

Figure C-5. Comparison of Means: MOVES2010 rates vs. HDIU (n=40) for model years 2003-2006 HHD trucks. Error bars represent the 95 percent confidence interval of the mean

In MOVES2010, the rates for model years 2007-2009 were forecast from those for model year group 2003-2006 based on the ratio of emissions standards for these two model-year groups, as described in Section 2.1.1.4.3. This approach was adopted in view of the fact that neither of the two datasets used at the time (ROVER and Consent Decree) included data for trucks in this model-year group. However, for MOVES2014, the availability of the HDIU dataset makes it possible to compare the projected rates to a set of relevant measurements. Figure C-6 shows that the MOVES2010 rates are lower than the corresponding means from the HDIU data and are generally outside the uncertainty of these means across operating modes. Because the rates for this model year group met the two conditions described above in Section 2.1.1.8, this subset of rates was updated in MOVES2014 on the basis of HDIU data.

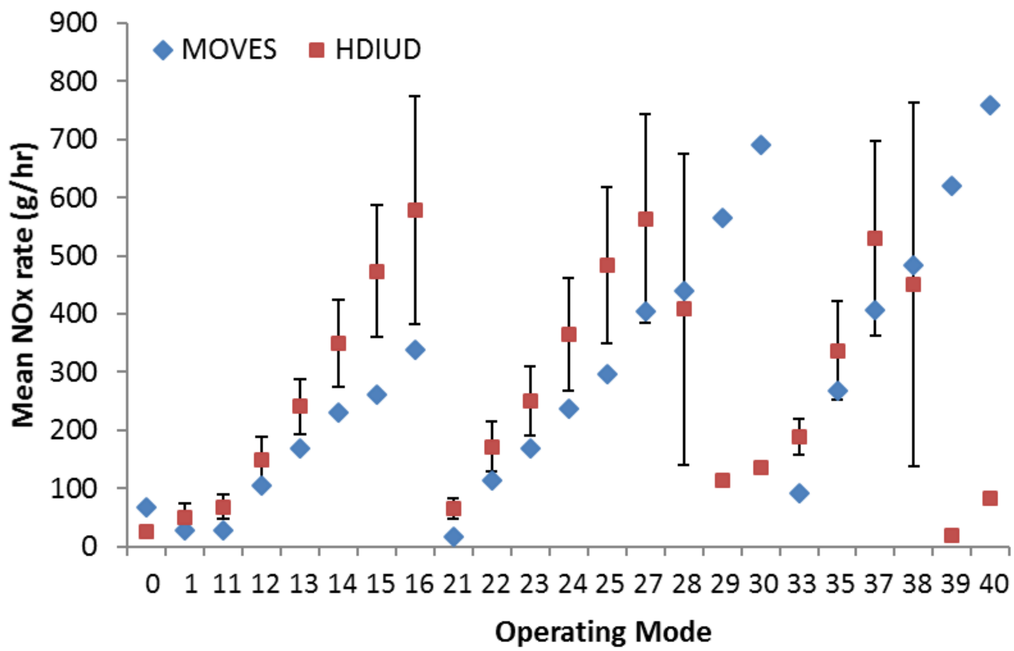

Figure C-6. Comparison of Means: MOVES rates vs. HDIU (n=68) for model years 2007-2009 HHD trucks. Error bars represent the 95 percent confidence interval of the mean

Appendix C-2. Medium Heavy-Duty Trucks

Figure C-7 and Figure C-8 show that MOVES2010 rates for MHD trucks compare well with the HDIU data for both model year groups 2003-2006 and 2007-2009. The data is generally scarce in high-power operation modes, and thus, no 95 percent confidence interval was calculated. The comparisons validated the MOVES2010 rates for MHD trucks, and no change was made in MOVES2014.

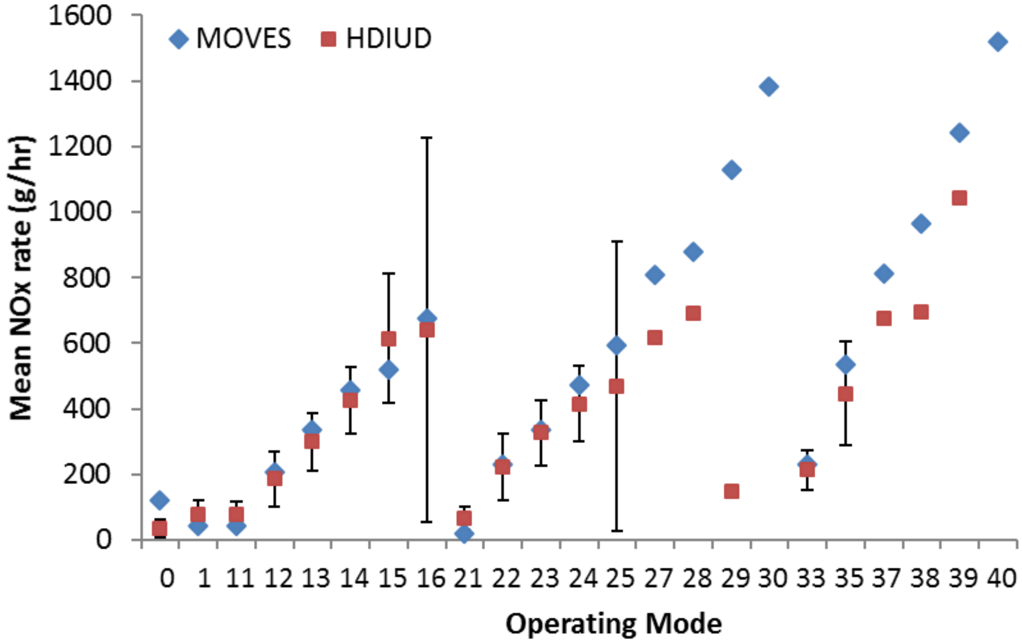

Figure C-7. Comparison of Means: MOVES2010 rates vs. HDIU (n=25) for model years 2003-2006 MHD trucks. Error bars represent the 95 percent confidence interval of the mean

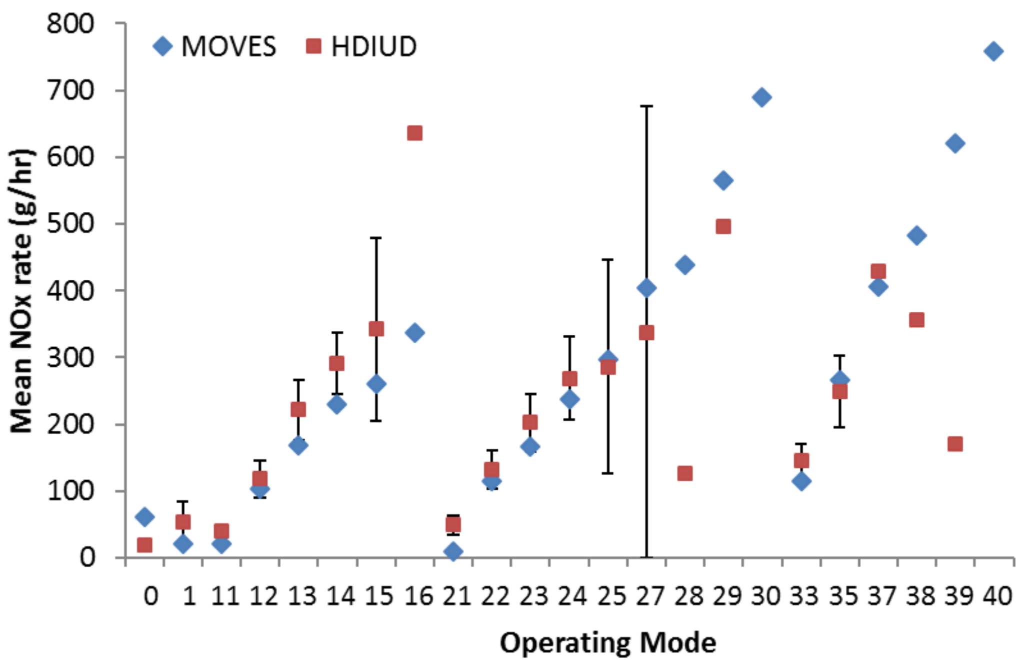

Figure C-8. Comparison of Means: MOVES2010 rates vs. HDIU (n=71) for model years 2007-2009 MHD trucks. Error bars represent the 95 percent confidence interval of the mean

Appendix C-3. Light Heavy-Duty Trucks

The comparisons of the MOVES2010 LHD45 rates to the corresponding LHD45 HDIU trucks for model years 2003-2006 (Figure C-9) and 2007-2009 (Figure C-10) show that MOVES2010 rates compare well with the HDIU data. Therefore, MOVES2010 rates for these model year groups were retained in MOVES2014.

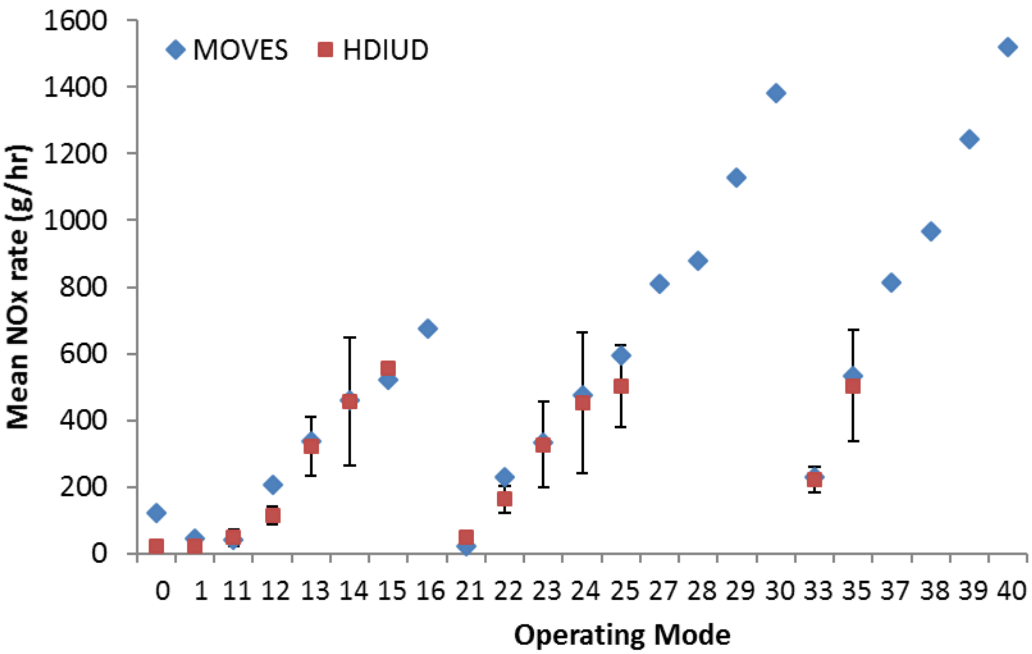

Figure C-9. Comparison of Means: MOVES2010 rates vs. HDIU (n=15) for model years 2003-2006 LHD45 trucks. Error bars represent the 95 percent confidence interval of the mean

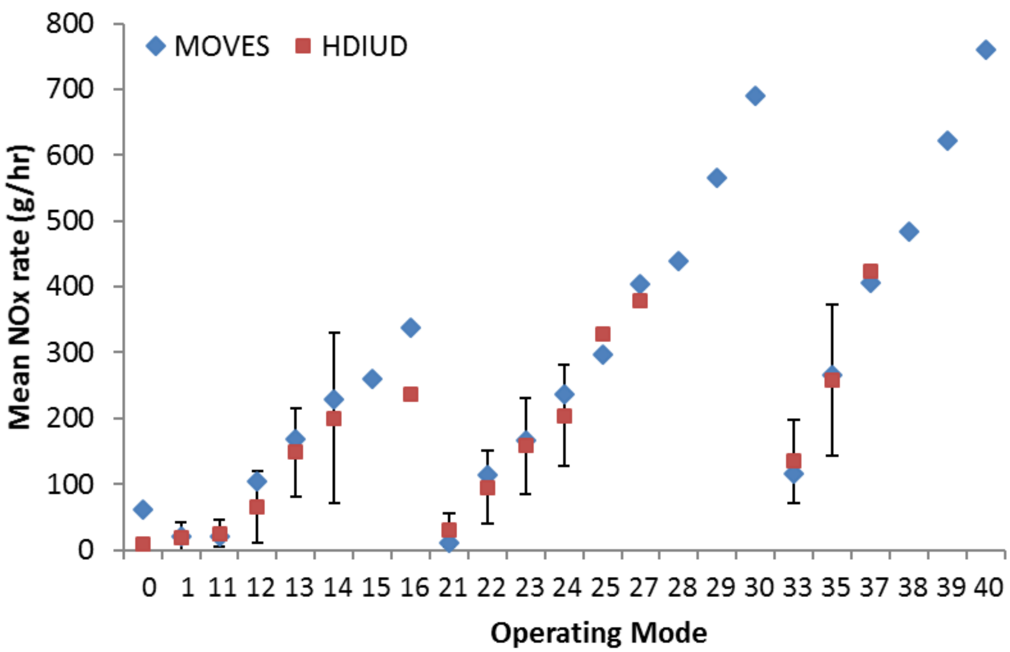

Figure C-10. Comparison of Means: MOVES2010 rates vs. HDIU (n=24) for model years 2007-2009 LHD45 trucks. Error bars represent the 95 percent confidence interval of the mean

Appendix D. Extended Idle Data Summary

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**

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**

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**

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**

2007 Extended Idle Emissions calculation:

- Assumed 8-hour idle period where the emissions controls, such as EGR, oxidation catalyst, and NO_X aftertreatment, are still active for the first hour.
- HC emissions standards:
  - Pre-2007: 0.50 g/bhp-hr
  - 2007: 0.14 g/bhp-hr
- NO_X emissions standards:
  - Pre-2010: 5.0 g/bhp-hr
  - 2010: 0.2 g/bhp-hr

Idle HC Rate Reduction = 1 - [(1/8 * 0.14 g/bhp-hr + 7/8 * 0.5 g/bhp-hr) / 0.5 g/bhp-hr] = 9 percent
Idle NO_X Rate Reduction = 1 - [(1/8 * 0.2 g/bhp-hr + 7/8 * 5.0 g/bhp-hr) / 5.0 g/bhp-hr] = 12 percent

Appendix E. Developing PM emission rates for missing operating modes

In cases where an estimated rate 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 D-9. Regression Coefficients for PM Emission Factor Model

Model-year group	Speed Class (mph)	Type	Medium Heavy-Duty	Heavy Heavy-Duty
1960-87	1-25	Intercept (β_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 (β_1)	0.02821	0.0968
		Transformation Coefficient ($0.5\sigma^2$)	0.5864	0.84035

$$\ln(\mathrm{PM}) = \beta_0 + \beta_1 \mathrm{STP} + 0.5\sigma^2$$

Where :

β_0 = an intercept term for a speed class within a model year group, as shown in the table above,

β_1 = a slope term for STP, and

σ^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 2-4).

Appendix F. Heavy-Duty Gasoline Start Emissions Analysis Figures

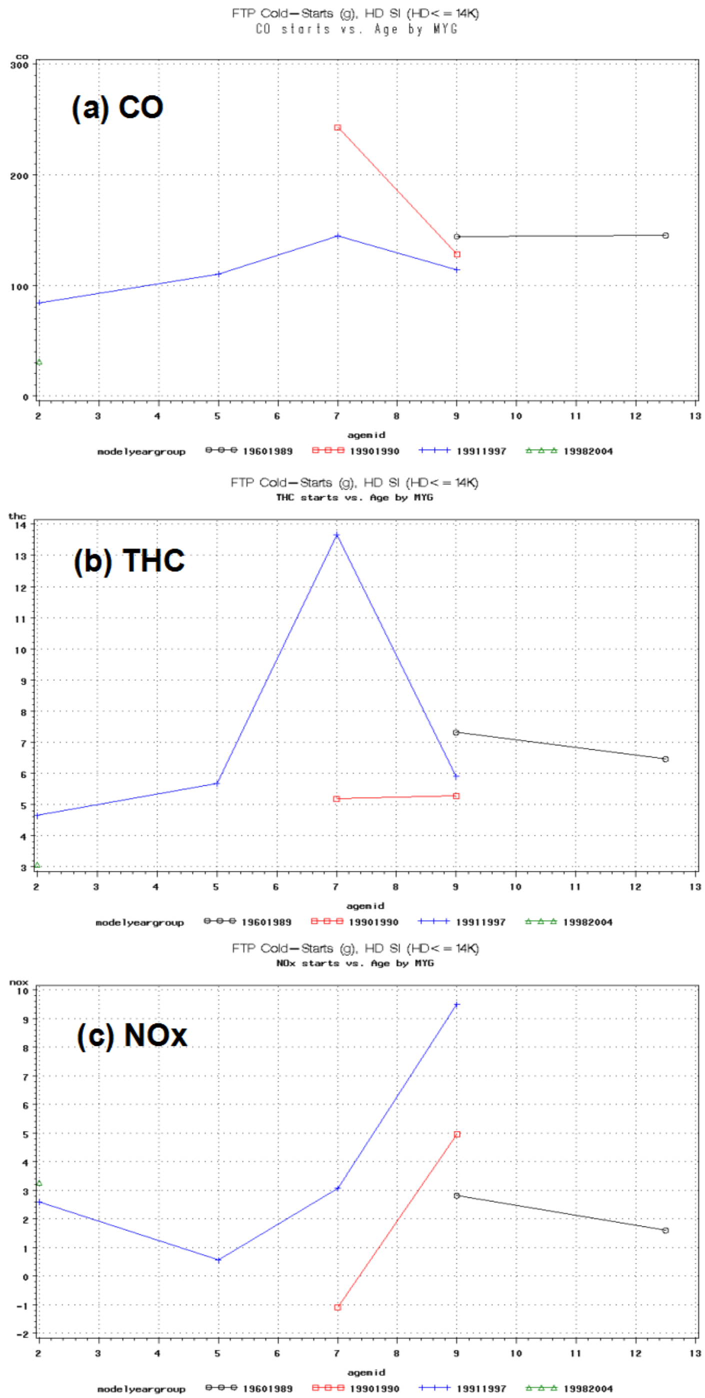

Figure E-2. Cold-Start FTP Emissions for Heavy-Duty Gasoline Vehicles, Averaged by Model-year and Age Groups

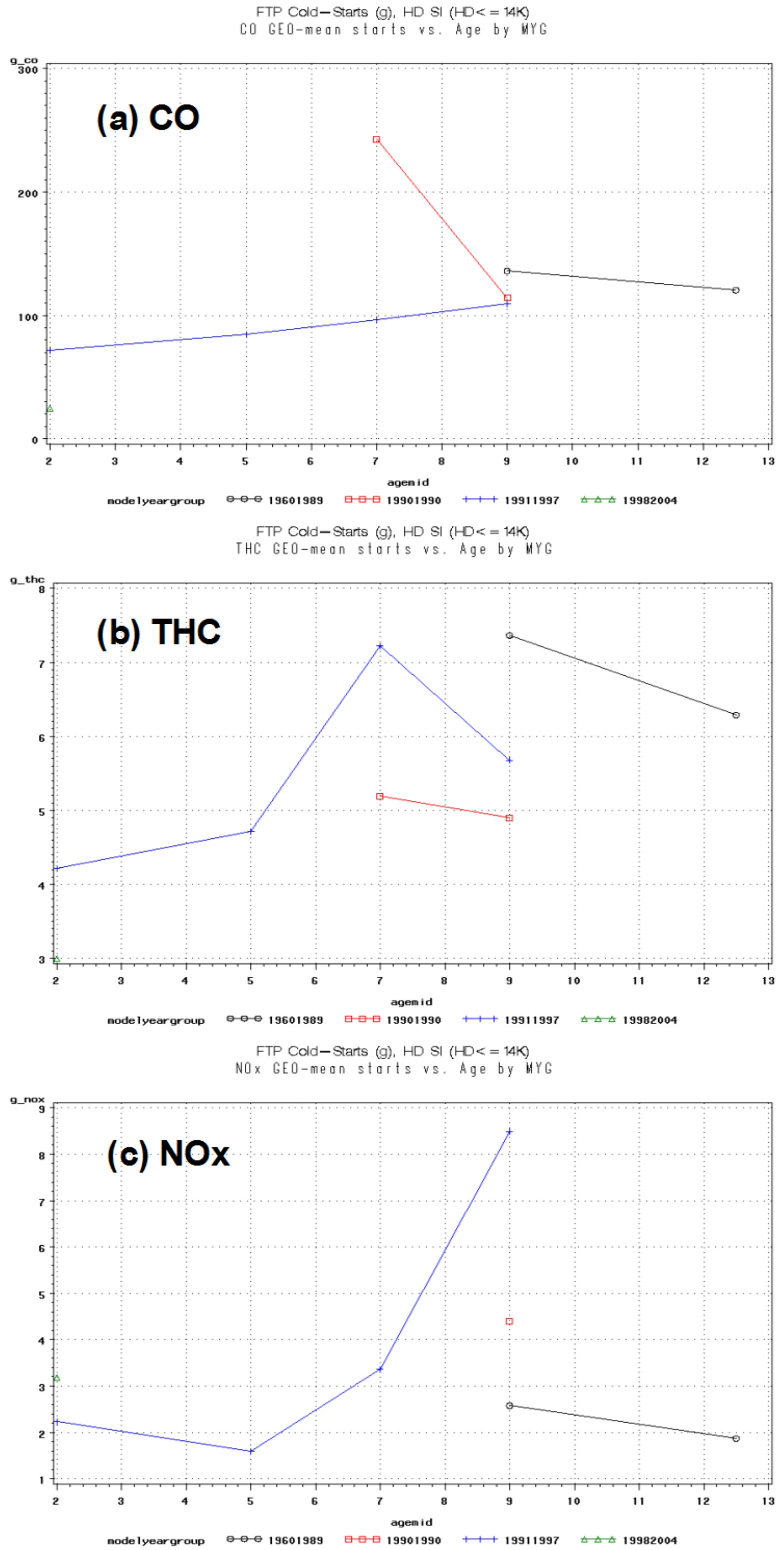

Figure E-3. Cold-Start FTP Emissions for Heavy-Duty Gasoline Vehicles, GEOMETRIC MEANS by Model-year and Age Groups

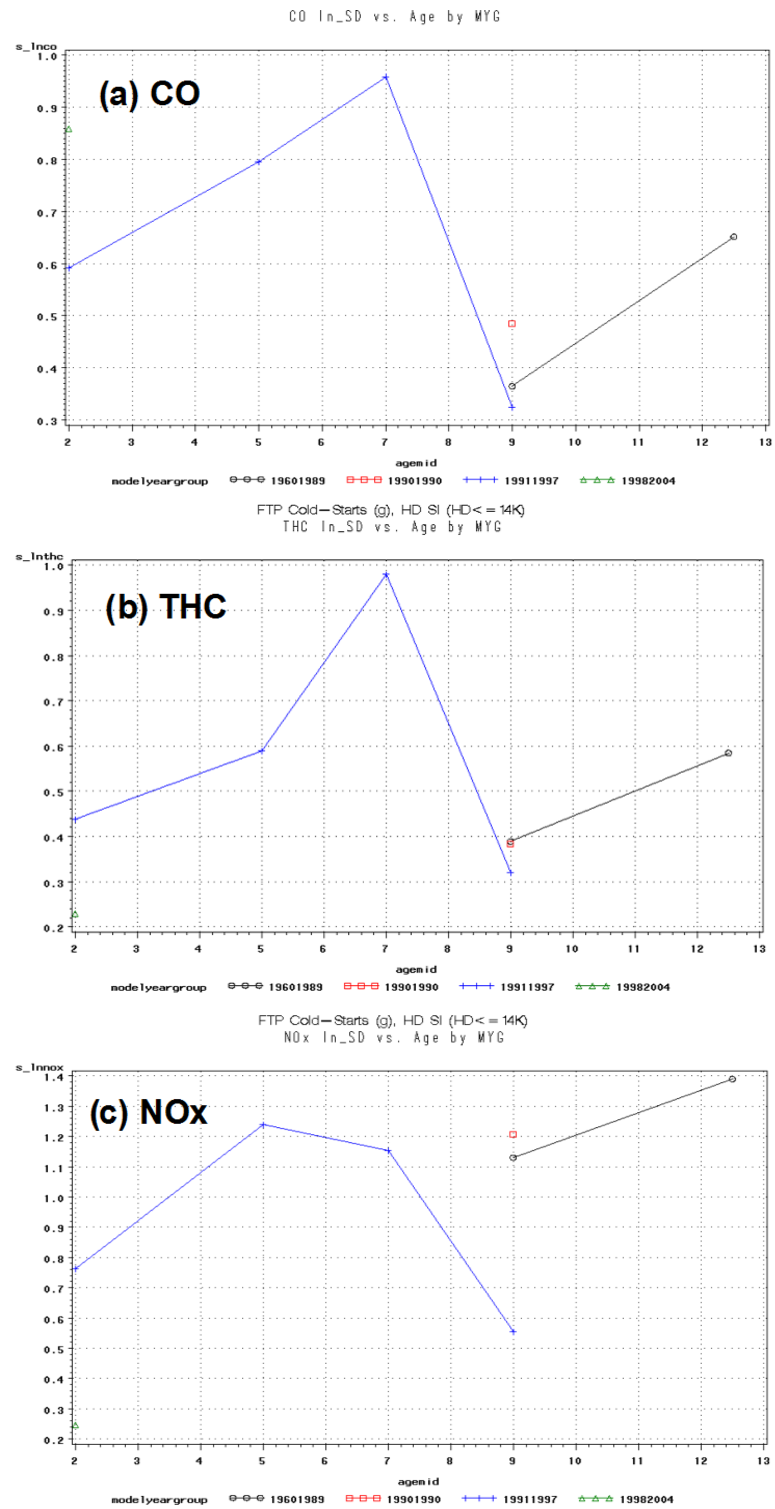

Figure E-4. Cold-start FTP Emissions for Heavy-Duty Gasoline Trucks: LOGARITHMIC STANDARD DEVIATION by Model-year and Age Groups

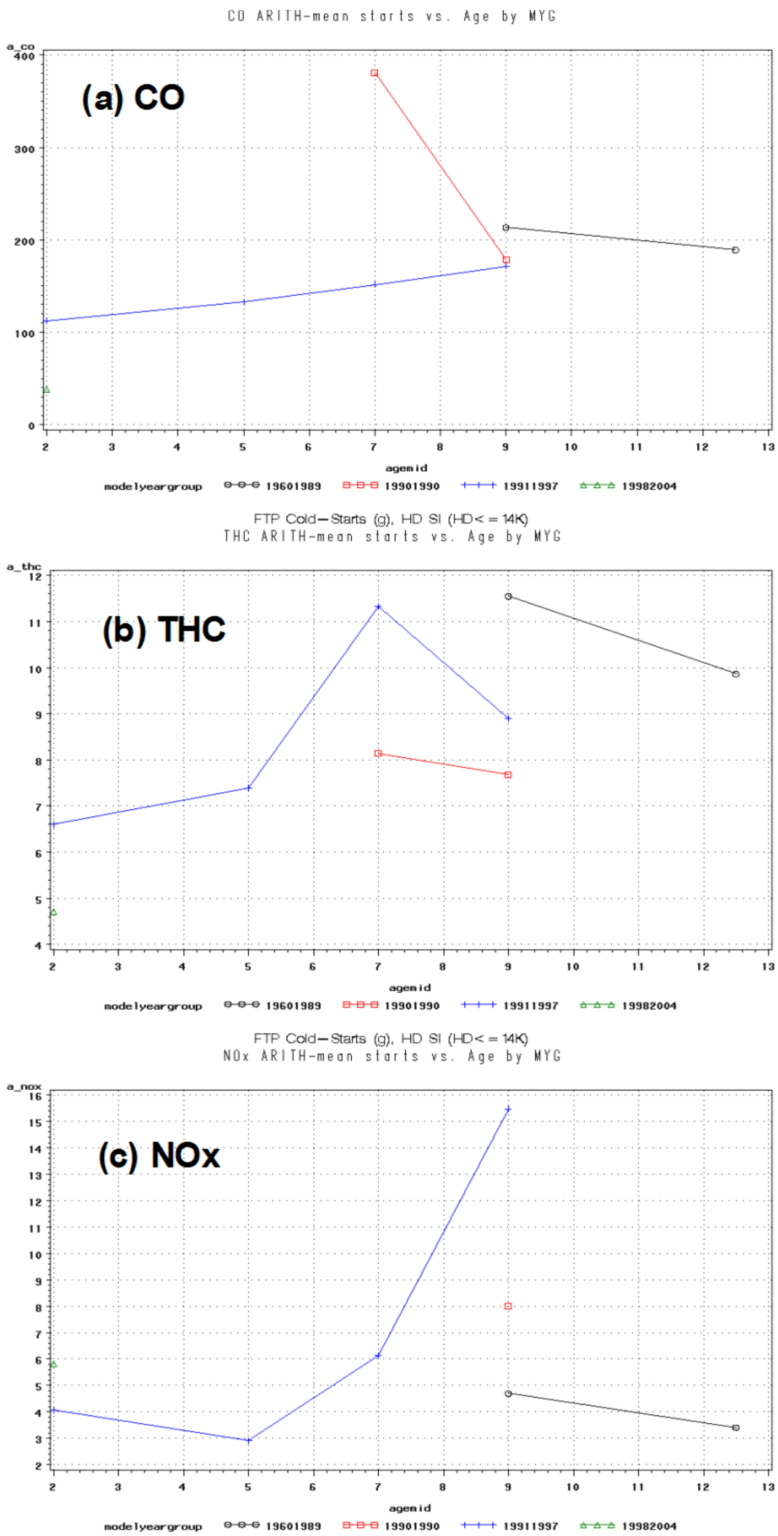

Figure E-5. Cold-Start Emissions for Heavy-Duty Gasoline Trucks: RECALCULATED ARITHMETIC MEANS by Model-year and Age Groups

Table E-10. 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	

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