Exhaust Emission Rates for Heavy-Duty On-road Vehicles in MOVES2014

United States Environmental Protection Agency

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

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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 MOVES2014. 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). 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).

From HC emissions, MOVES produces other estimates of organic gas emissions, including volatile organic compounds (VOCs) and total organic gases (TOG). From VOC emission rates and fuel properties, MOVES estimates 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[42] and Toxics[1] MOVES Reports. MOVES estimates PM emission rates according to 18 subspecies beyond elemental carbon, such as organic carbon, sulfate and nitrate, through the use of speciation profiles as documented in the Speciation Report[42].

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 both diesel and gasoline fuels, as well as compressed natural gas (CNG) vehicles, 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.

This report first introduces the principles used to model heavy-duty vehicles in MOVES. Then the emission rates for heavy-duty diesel, heavy-duty gasoline, and CNG transit buses are documented. Chapter 5 documents the crankcase emission rates used for each fuel type of heavy-duty vehicles. Chapter 6 documents the NO, NO_2, and HONO ratios that are used to estimate NO, NO_2, and HONO emissions from NO_x emissions.

Emission rates for criteria pollutants (HC, CO, NOx, and PM) are stored in the "EmissionRateByAge" table in the MOVES database. The emission rates in the EmissionRateByAge table are stored according to

1. MOVES regulatory class
2. Fuel Type (Diesel, Gasoline, and CNG)
3. Model year group
4. Vehicle age
5. Emission process (e.g. running exhaust, start exhaust, crankcase emissions)
6. 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[8].

In the next sections, the following parameters used to classify heavy-duty emissions in MOVES are discussed in more detail: heavy-duty regulatory classes, vehicle age, emission processes, and vehicle operating modes. Although not discussed in detail, the model year groupings are designed to represent major changes in EPA emission standards.

This report is an update to the previously released report (EPA-420-R-15-004, September, 2014). The revision includes edits in response to peer-review comments not included in the previous version (Appendix G.9). The revision also corrects typos in the main text and corrects two of the energy rate figures (Figure 2-33, Figure 3-17).

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 EPA PM emission standards for the 1994 through 2006 model years[2]. 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[3]").

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 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 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.

(1) Available Activity Information. As discussed in the Population and Activity Report[4], 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 type 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. MOVES2014 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).

(2) Assignment of Operating Modes within MOVES source types. As discussed in the Population and Activity Report[4], MOVES assigns operating modes according to source type. For light-duty source types (including passenger trucks and light-commercial trucks) running operating modes as assigned according to Vehicle Specific Power (VSP). For single-unit source types, operating modes are assigned according to Scaled Tractive Power (STP). As discussed in subsection 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 now 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 new 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.

The emission rates for all the heavy-duty sources types are discussed in this report. 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.

[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. MOVES2014 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.[4]

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) Light Commercial Trucks(32)	VSP
Light-heavy duty ≤ 14,000 lb. 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
[1] see CFR § 86.091(2).					
[2] MOVES assigns operating modes based on VSP or 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, NOx 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 'extended idle' process occurs during an extended period of idling operation such as when a vehicle is parked for the night and left idling. Extended idle is generally a different mechanism (usually a higher RPM engine idle to power truck accessories for operator comfort) than the regular 'curb' idle that a vehicle experiences while it is operating on the road.

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 methane, nitrous oxide (N_2O), and ammonia (NH_3) for gasoline and diesel heavy-duty vehicles are described in separate reports.[5,]

[6] The estimation of emission rates from these pollutants for CNG transit bus vehicles are covered in this report.

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.[7] 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.[7]

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 on-road 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.[8]

For heavy-duty vehicles, we relate emissions to power output, but in a different way. Heavy-duty vehicles are regulated using engine dynamometers, 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 located here, 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 on-road or chassis testing, by measuring the engine power and estimating the accessory loads and power-train efficiencies for the vehicle.

For on-road 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 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 on-road tests. Additionally, the road load equations may not reflect the actual vehicle test weight, and the tests may not have accurate grade information for the entire route tested. Thus, for on-road 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, and MOVES assigns operating modes to these source types using VSP. Thus, for LHD≤10K (RegClassID 40), f_{scale} is equal to the mean source mass of light-commercial trucks[4], 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 1-4.

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, using the following equation:

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

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 [$kW \cdot sec^2/m^2$],

C = the aerodynamic drag coefficient [$kW \cdot sec^3/m^3$],

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 is the acceleration due to gravity [9.8 m/s^2]

$\sin\theta$ is the (fractional) road grade

The derivation of the load road parameters is discussed in the Population and Activity Report[4]. 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.

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 (a, mph/sec)
0	Deceleration/Braking			$a_t \leq -2.0$ OR ($a_t < -1.0$ AND $a_{t-1} < -1.0$ AND $a_{t-2} < -1.0$)
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	$30 \leq STP_t$	$50 \leq v_t$	

Start emission rates are also distinguished according to operating modes in MOVES. 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 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, NOx and PM are differentiated by vehicle age. Currently, start and running emission rates for HC, CO, NOx 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 the text (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, NOx, PM, and ammonia (NH_3) emissions from extended idle and auxiliary power units (APU), and nitrous oxide (N_2O) from start and running emissions, and tire and brake wear from running emissions. This report documents the HC, CO, NOx, and PM emissions from extended idle and APU usage, however the documentation of heavy-duty nitrous oxide and ammonia[9] 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

MOVES running-exhaust emissions analysis 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 (NOx)

For NOx rates, we stratified heavy-duty vehicles into the model year groups listed in Table 1-6. These groups were defined based on changes in NOx emissions standards and the outcome of the Heavy Duty Diesel Consent Decree[11], which required additional control of NOx 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 NOx analysis based on emissions standards

Model year group	FTP 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	
2007-2009	1.2	1.25 times the family emission level
2010+	0.2	

2.1.1.1 *Data Sources*

In MOVES2010, we relied on two data sources for NO_X emissions from HHD, MHD, and urban buses:

ROVER. This dataset includes measurements collected during on-road 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 ongoing 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.

However, since the release of MOVES2010, two additional sources of data have become available. One source comprises data collected during compliance evaluations for the 2004 and 2007 Heavy-Duty Diesel Motor Vehicle Engines Rule. This dataset includes results for HHD, MHD and LHD vehicles. The second source includes the results of a study of heavy-duty trucks in drayage service in and around the port of Houston (Houston Drayage). Both programs are described in detail below.

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. The data available for use in MOVES2014 were collected during calendar years 2005 through 2010 and represent trucks manufactured in model years 2003 to 2009 (Table 2-2).

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, heavyheavy-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.

For MOVES2014, the HDIU and Houston Drayage data were analyzed to fulfill two objectives:

(1) to evaluate the rates in MOVES2010 and
(2) to provide a new data source for updating the emission rates

Updating MOVES emission rates currently in use was considered when two conditions were met: (1) when MOVES2010 rates for a specific regulatory-class and model-year-group combination were not based on actual data (i.e., due to gaps in the coverage of ROVER and Consent-Decree testing data[b]) and (2) when the comparisons between MOVES2010 and independent data show that more than a half of MOVES2010 emission rates are outside the boundary of the 95 percent confidence intervals of the independent data.

From each data set, we used only tests we determined to be valid. For the ROVER dataset, due to time constraints, we eliminated all tests that indicated any reported problems, including GPS

[b] Specific subsets of rates used in MOVES2010 were forecast by proportioning measured emission rates to emission standards as described in Section 2.1.1.4

malfunctions, PEMS malfunctions, etc., whether or not they affected the actual emissions results. For HDIU 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 measured by the 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, 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 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.

Table 2-2. Numbers of vehicles by model year group from the ROVER, WVU MEMS, HDIU, and Houston Drayage programs used for emission rate analysis

		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	-
Houston Drayage	**1991-1997**	8	-	-	-
	1998	1	-	-	-
	1999-2002	10	-	-	-
	2003-2006	8	-	-	-

2.1.1.2 *Calculate STP from 1-Hz data*

With on-road 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.

$$P_{eng} = \omega_{eng}\tau_{eng}$$ **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

Load \ Speed	Low	Mid	High
Low	Cooling Fan Air cond. Engine Access. Alternator Air Compress	Air cond. Engine Access. Alternator Air Compress	Air cond. Engine Access. Alternator
Mid	Cooling Fan Air cond. Engine Access. Alternator Air Compress	Cooling Fan Air cond. Engine Access. Alternator Air Compress	Air cond. Engine Access. Alternator
High	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. For LHD vehicles, we assumed negligible accessory losses.

Table 2-4. Estimates of accessory load in kW by power range

Engine power	HDT	MHD	Urban Bus
Low	8.1	6.6	21.9
Mid	8.8	7.0	22.4
High	10.5	7.8	24.0

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 through literature research

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% for all HD regulatory classes. Equation 2-2 shows the translation from engine power P_{eng} to axle power P_{axle}.

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

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

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

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 Means

Emissions in the data set were reported in grams per second. First, we averaged all the 1-Hz NOx 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. These data sets were assumed to be representative and each vehicle received the same weighting. Equation 2-3 summarizes how we calculated the mean emission rate for each stratification group (i.e. model year group, regulatory class, and operating mode bin).

$$\bar{r}_p = \frac{\sum_{j=1}^{n_{\text{veh}}} \left(\frac{\sum_{i=1}^{n_j} r_{p,j,i}}{n_j} \right)}{n_{\text{veh}}}$$ **Equation 2-3**

where

n_j = the number of 1-Hz data points 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 2.1.1.4.6, starting with Figure 2-3.

2.1.1.3.2 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}.

$$s^2_{with} = \frac{\sum_{j=1}^{n_j}(n-1)s_j^2}{n_{tot} - n_j}$$ **Equation 2-4**

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 2-5.

$$s^2_{\text{betw}} = \frac{\sum_{j=1}^{n_\text{j}}\left(\bar{r}_{p,j} - \bar{r}_p\right)^2}{n_\text{j} - 1}$$ **Equation 2-5**

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 2-6) and dividing the standard error by the mean emission rate to get the coefficient-of-variation of the mean c_p (Equation 2-7). We used the standard error to estimate the 95% confidence intervals of the mean emission rate, which are displayed in Figure 2-3 through Figure 2-19 for a subsample of the NOx heavy-duty emission rates. For each emission rate the coefficient of variation is stored in the emissionRateByAge table.

$$s_{\bar{r}_p} = \sqrt{\frac{s^2_{\text{betw}}}{n_{\text{j}}} + \frac{s^2_{\text{with}}}{n_{\text{tot}}}}$$ **Equation 2-6**

$$c_p = \frac{s_{\bar{r}_p}}{\bar{r}_p}$$ **Equation 2-7**

2.1.1.4 *Hole-filling Emission Rates*

The data included in the emissions analysis does not include 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 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 forecasted to be implemented to meet more stringent standards in 2007 and 2010.

2.1.1.4.1 Hole-filling Missing Operating Modes

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 2-8 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 2-8**

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 2-9.

$$Urban\ Bus\ rates_{1998} = \frac{HHD\ rates_{1998}}{HHD\ rates_{1999-2002}} \times Urban\ Bus\ rates_{1999-2002}$$ **Equation 2-9**

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.[c] As discussed in Section 2.1.1.8.3 we confirmed that the MHD rates were consistent with NOx 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% increase in 1991-1997 vs. 1998). Table 2-7 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[69] 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[69] established much tighter NOx emission standards (0.2 g/bhp-hr). While the NOx standard going into effect for MY 2007 is 0.2 g/bhp-hr, it was assigned to be phased in over a three year period ending in 2010. Rather than phasing in the after-treatment technology needed to meet the new standard, most manufacturers decided to meet a 1.2 g/bhp-hr standard for MY2007-2009, which did not require aftertreatment (down from 2.4 g/bhp-hr in 2006). For the 2007-2009 HHD, we used the data from the HDIU program as discussed in Section 2.1.1.8.1. For the NOx emission rates within the 2007-2009 model year group for MHD, Urban Bus, LHD45 and LHD≤14K, we estimated the NOx emission rates were 50% lower than the corresponding 2003-2006 emissions (proportional to the reduction in the NOx emission standards mentioned above).

[c] In MOVES2010, the LHD45 and LHD2b3 trucks were also based on MHD data, but were analyzed with the 2.06 mass scaling factor. In MOVES2014, the LHD45 and LHD≤14K emission rates were updated to be based on the MHD rates with the 17.1 mass scaling factor.

The emission rates for 2010 and later heavy-duty trucks developed in MOVES2010 continue to be used in MOVES2014. For these rates, we projected that HHD, MHD, Urban Bus, and LHD45 regulatory classes would meet the 2010 standards (0.2 mg/bhrp-hr) through the use of SCR. In the absence of data, we assumed that we would have a 90 percent NOx reduction efficiency from levels for MY2006 levels, which is consistent with the drop in NOx emission standards from 2.4 g/bhp-hr to 0.2 g/bhp-hr. In other words, we estimated the emission rates for regulatory classes HHD, MHD, Urban Bus, and LHD45 in model year 2010 and later by decreasing MY2003-2006 rates by 90 percent. The NOx emissions are projected to remain constant for 2010 and later vehicles for regulatory classes HHD, MHD, and Urban Buses. The light heavy-duty trucks are projected to have a decrease NOx 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 NOx Trap technology[d]. Cummins decided to use Lean NOx Trap (LNT) after-treatment 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 NOx during fuel-lean operation and conversion of stored NOx 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 NOx storage ability, resulting in elevated NOx emissions.

In order to determine the fraction of time that DPF's spend in PM regeneration mode, in 2007, EPA acquired a truck equipped with a LNT and a DPF and performed local on-road 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 on-road 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 NOx reduction of 81% for LNT equipped trucks between 2003-2006 and 2007-2009, as shown in Equation 2-10.

[d] In MOVES2014, we created a distinction of LHD≤14K and LHD≤10K to account for STP and VSP-based operating modes. LHD≤10K has the same emission rates in MOVES2010b as the old regulatory class LHD2b3 (which includes the Lean-NOx trap assumptions. In MOVES2014, the emission rates for LHD≤14K are set the same as LHD45, and do not include the Lean-NOx trap assumptions.

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

$$= (0.90) \times (0.10) + (0.10) \times (1) = 0.19$$

Equation 2-10

Because we assume that LNT-equipped trucks account for about 25 percent of the LHDDT market, 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 after-treatment and will exhibit the 2007-2009 model year emission rates described earlier in this section. Overall, these assumptions result in a 58% reduction in NOx emission rates in 2007-2009 from the MOVES2010 2003-2006 NOx emission rates as shown in Equation 2-11.

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

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

Equation 2-11

Starting in MY2010, we assume that the remaining 75 percent of LHD≤10K diesel trucks are equipped with SCR, and exhibit 90 percent NOx reductions from 2006 levels. These assumptions are outlined in Table 2-7.

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 results in a reduction emissions from diesel vehicles in regulatory classes LHD≤10K and LHD≤14K. Data on current NO_x emissions are limited, so we used a proportional approach to estimate the reductions related to Tier 3, reducing NO_x in proportion to the change in the emission standard. 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 2-6.

Table 2-6. Phase-in Assumptions for Tier-3 NOx Standards for light heavy-duty diesel vehicles.

Model Year	Phase-in fraction (%)	Reduction in Running Emission Rate (%)	Reduction in Start Emission Rate (%)
2017	0	0	0
2018	38	23	9
2019	54	33	12
2020	69	42	16
2021	85	52	19
2022	100	61.5	23

In generating the reduced rates for running operation, the starting point was a subset of rates for MY2017, extracted from the MOVES2010b EmissionRateByAge table, and taken to represent the pre-Tier-3 baseline.

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 2-6.

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 (page 100) and Equation 3-2 (page 99). 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 2-1. 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 yr ageGroup are replicated to the 4-5 year ageGroup, i.e., the onset of deterioration is delayed until the 6-7 year ageGroup. This effect is realized partially for model years 2018-2020 and fully in 2021.

Figure 2-1. NO_x: Emission rates for running-exhaust operation in selected operating modes vs. model year, for two light-heavy-duty regulatory classes (LOGARITHMIC SCALE).

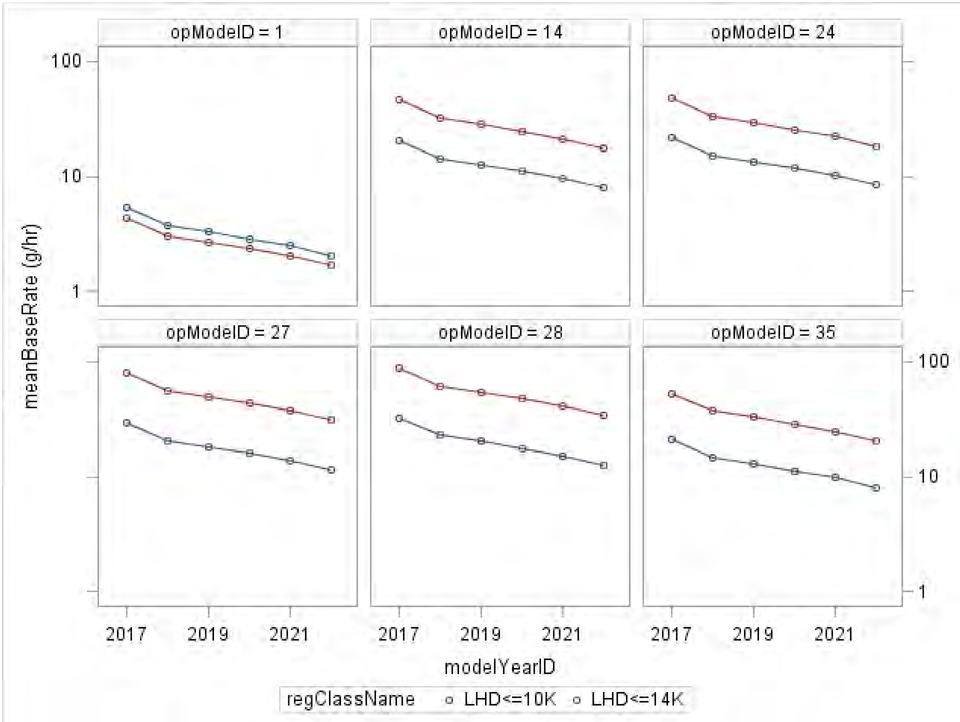
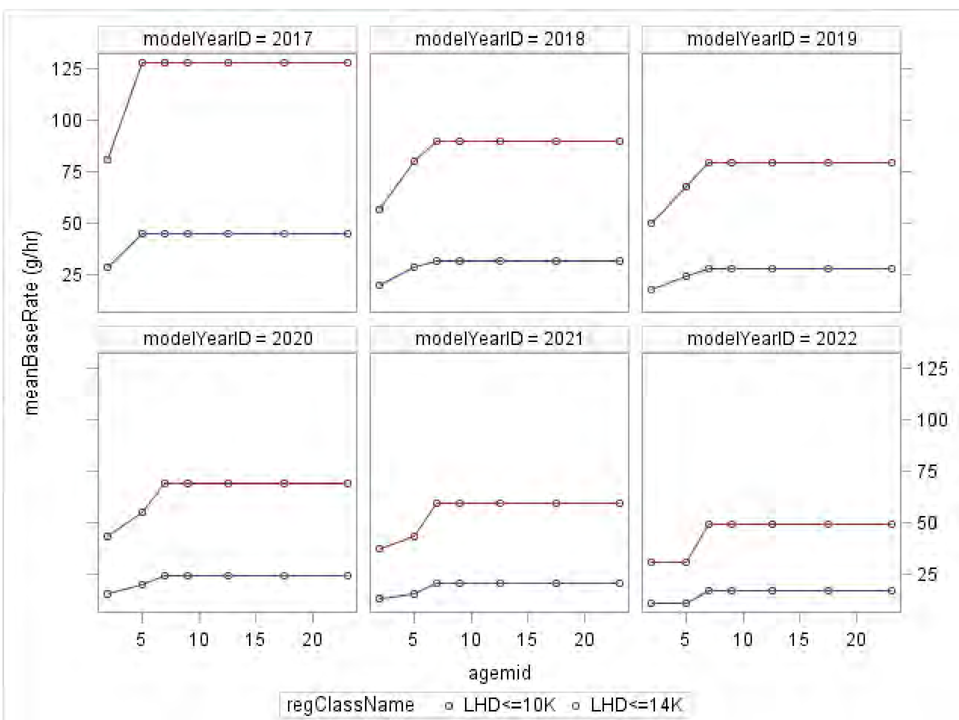


Figure 2-2. NO_x: Emission rates for running-exhaust operation in a single operating mode (27) vs. age, for two light-heavy-duty regulatory classes (LINEAR SCALE).



2.1.1.4.6 Summary

Table 2-7 summarizes the methods used to estimate emission rates for each regulatory–class/model-year-group combination. The emission rates in MOVES2010 were based on the analysis of ROVER and Consent Decree testing data. For MOVES2014, we made a decision to update the emission rates for model year group 2007-2009 for HHD, based on the comparison of the emission rates in MOVES2010 to HDIU and Houston Drayage data, discussed in Section 2.1.1.8. MOVES2014 also included the impact of the Tier 3 regulations on the LHD≤14K and LHD≤10K regulatory classes. For all other combinations of regulatory classes and model year groups, the rates from MOVES2010 were retained in MOVES2014.

Table 2-7. Summary of methods for heavy-duty diesel NOx 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[1,3]	Same rates as HHD	Data analysis[1]	Same rates as HHD	Proportioned to 1998 FTP standards per Table 2-1
1998	Data analysis[1,3]	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[1,3]	Data analysis[1]	Data analysis[1]	Same rates as MHD	MHD engine data with 2.06 mass factor
2003-2006	Data analysis[1,3]	Data analysis[1,3]	Data analysis[1]	Same rates as MHD	Data analysis with 2.06 mass factor[2]
2007-2009	Data analysis[2]	MHD 2003-2006 rates proportioned to FTP standards per Table 2-1[3]	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)[3]
2010 - 2016	HHD 2003-2006 rates proportioned to FTP standards per Table 2-1	MHD 2003-2006 rates proportioned to FTP standards per Table 2-1	Urban Bus 2003-2006 rates proportioned to FTP standards per Table 2-1	Same rates as MHD	MOVES2010 LHD≤10K 2003-2006 rates proportioned to FTP standards per Table 2-1
2017-2050	Same as HHD 2010-2016	Same as MHD 2010-2016	Same as Urban Bus 2010-2016	MHD rates proportioned to Tier 3 standards	MOVES2010 LHD≤10K 2003-2006 rates proportioned to Tier 3 standards

1Analysis based on ROVER and Consent Decree testing data; 2 Analysis based on HDIU data; 3 Confirmed by HDIU and Houston Drayage data

2.1.1.5 *Tampering and Mal-maintenance*

Table 2-8 shows the estimated aggregate NOx 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 2-8 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 2-7) may be the different due to the T&M NOx effects (Table 2-8) 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 NOx increases than LHD≤14K trucks, due to the assumed penetration of lean NOx trap (LNT) aftertreatment which was assumed to penetrate 25% of LHD≤10K trucks starting in 2007, 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 we 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 in the tampering and mal-maintenance emission increases in Table 2-8 with the assumptions and calculations detailed in Appendix B.

Table 2-8. Fleet-average NOx emissions increases in MOVES from zero-mile levels over the useful life due to tampering and mal-maintenance (T&M)

Model years	NOx increase (TM_{NOx}) for LHD≤10K trucks [%]	NOx increase (TM_{NOx}) for LHD≤14K trucks [%]	NOx 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%) T&M NOx emission increases for model year groups before 2010. However, we did not implement these increases in MOVES because we assumed that NOx increases due to T&M only occurred in engines equipped with NOx aftertreatment technologies. (largely 2009 model year and earlier). This is due to a few reasons:

- The WVU MEMS data did not show an increase in NOx 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 NOx deterioration value for SCR-equipped heavy-duty diesel vehicles in 2010-2012 is a 77% increase. Though 77% 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% lower than the 2009 model year effective standard (1.2 g/bhp-hr). This still yields a substantial reduction of about 71% from 2009 zero-mile levels to 2010 fully deteriorated levels.

As more data becomes available for future model years, we plan to update these tampering and mal-maintenance and overall aging effects.

2.1.1.6 *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 NOx 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 2-12 and Equation 2-14. 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 MY1991-98, as shown in Equation 2-13 and Equation 2-15.

.

Operating modes (OM) 21-30

$$\bar{r}_{reflash,91-98,27} = \bar{r}_{91-98,16}\left(\frac{\bar{r}_{1999,27}}{\bar{r}_{1999,16}}\right)$$ **Equation 2-12**

$$\bar{r}_{reflash,91-98,\mathrm{OM}x} = \bar{r}_{reflash,91-98,27}\left(\frac{\bar{r}_{91-98,\mathrm{OM}x}}{\bar{r}_{91-98,27}}\right)$$ **Equation 2-13**

Operating modes (OM) 31-40

$$\bar{r}_{reflash,91-98,37} = \bar{r}_{91-98,16}\left(\frac{\bar{r}_{1999,37}}{\bar{r}_{1999,16}}\right) \quad \textbf{Equation 2-14}$$

$$\bar{r}_{reflash,MY1991-1998,OMx} = \bar{r}_{reflash,91-98,37}\left(\frac{\bar{r}_{91-98,\mathrm{OM}x}}{\bar{r}_{91-98,37}}\right) \quad \textbf{Equation 2-15}$$

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.

2.1.1.7 *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 2-3 and Figure 2-4 show that NOx emission rates increase with STP for HHD trucks. Figure 2-5 adds the MHD and 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.

Figure 2-3. Trends in NOx Emissions by operating mode from HHD trucks for model year 2002. Error bars represent the 95% confidence interval of the mean.

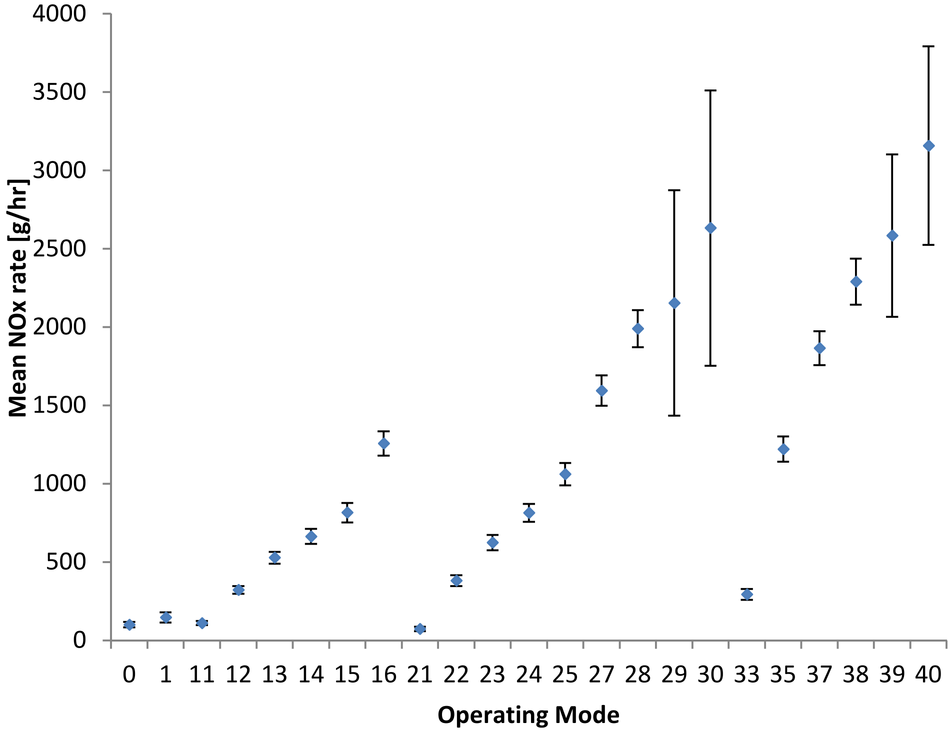
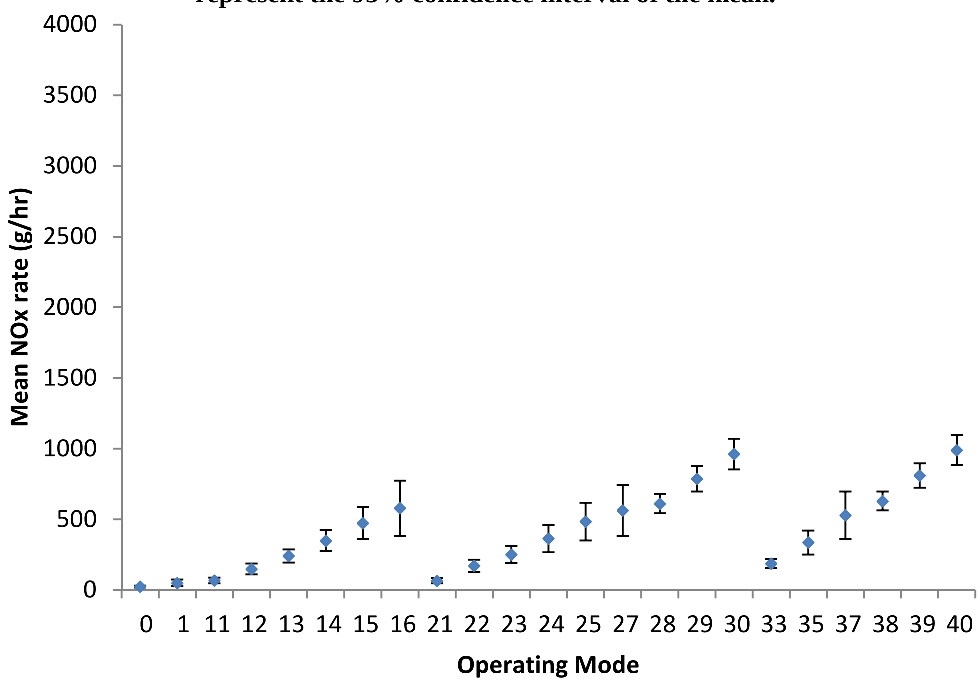
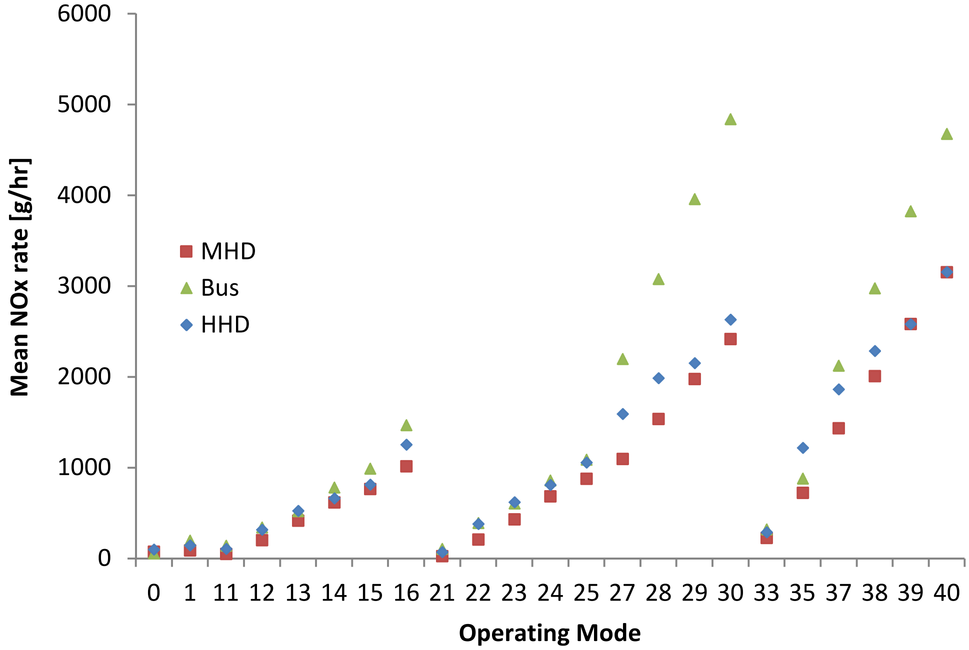


Figure 2-4. Trends in NOx Emissions by operating mode from HHD trucks for model year 2007. Error bars represent the 95% confidence interval of the mean.



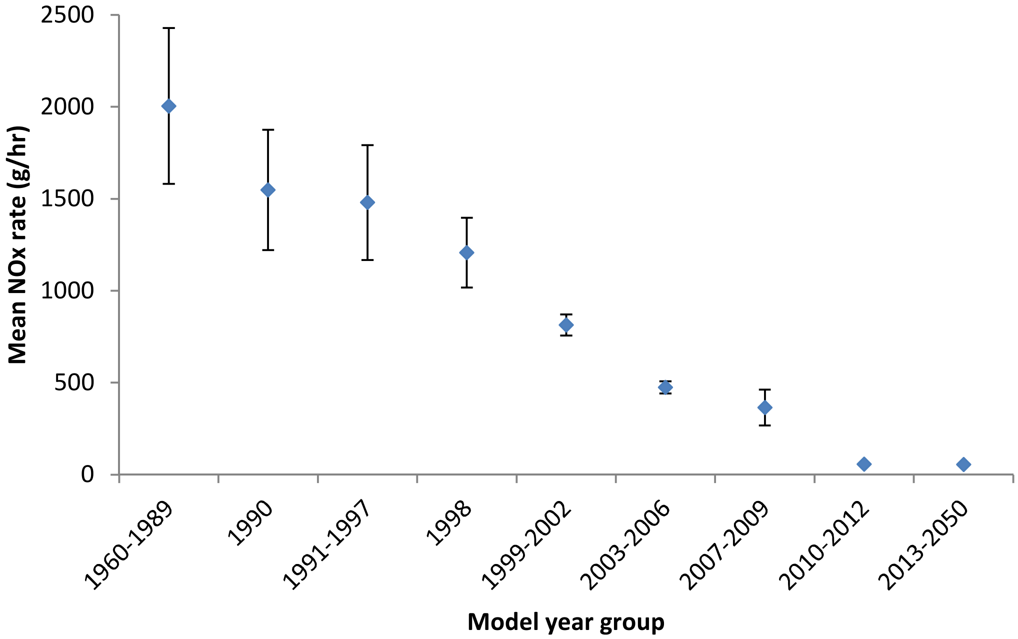
The highest operating modes in each speed range will rarely be attained due to the power limitations of heavy-duty vehicles, but are included in the figures (and in MOVES) for completeness. Nearly all of the activity occurs in modes 0, 1, 11-16, 21-28, and 33-38, with activity for buses and MHD vehicles 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 2-5. Trends in NOx 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 NOx zero-mile NOx emission rates.



The effects of model year, representing a rough surrogate for technology or standards, can be seen in Figure 2-6, which shows decreasing NOx rates by model year group for a sample operating mode (opModeID24) 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 NOx standards. Increasingly stringent emissions standards have caused NOx emissions to decrease significantly.

Figure 2-6. Trends in NOx by model year for HHD trucks in operating mode 24. Error bars represent the 95% confidence interval of the mean.



Age effects were implemented for after-treatment-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 2-7. Relative Standard Errors (based on coefficients-of-variation for means) from previous model year groups were used to estimate uncertainties for MY 2010.

Figure 2-7. Modeled NOx trends by age for model year 2010 for operating mode 24 for MHD, HHD, and Urban Bus regulatory classes for model year 2002. Error bars represent the 95% confidence interval of the mean.

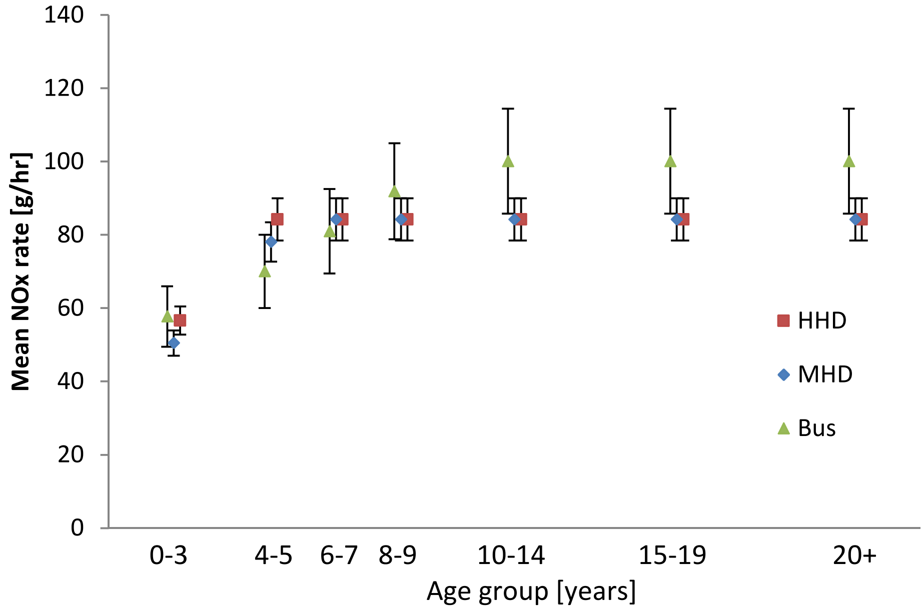


Figure 2-8 and Figure 2-9 shows the mean emission rates for LHD≤ 10K trucks for model years 2003-2006 and 2007-2009, respectively. The estimated uncertainties are greater than for the other heavy-duty regulatory classes, since there were fewer vehicles in our test data. As described previously, model years 2007-2009 vehicles includes vehicles with LNTs (with NO_x increases during PM regeneration) and vehicles without any aftertreatment.

Figure 2-8. Mean NOx rates by operating mode for model years 2003-2006 LHD≤10K (RegClassID 40) trucks age 0-3. Error bars represent the 95% confidence interval of the mean.

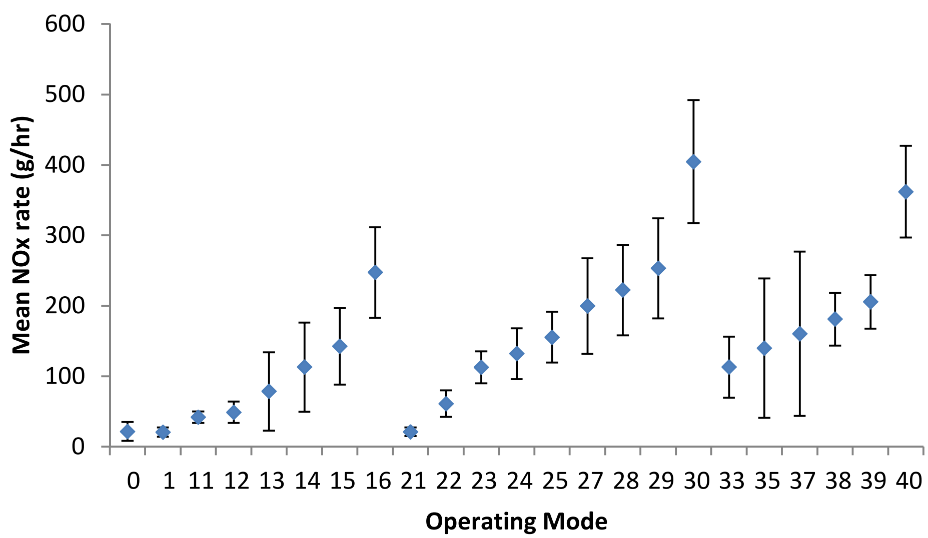
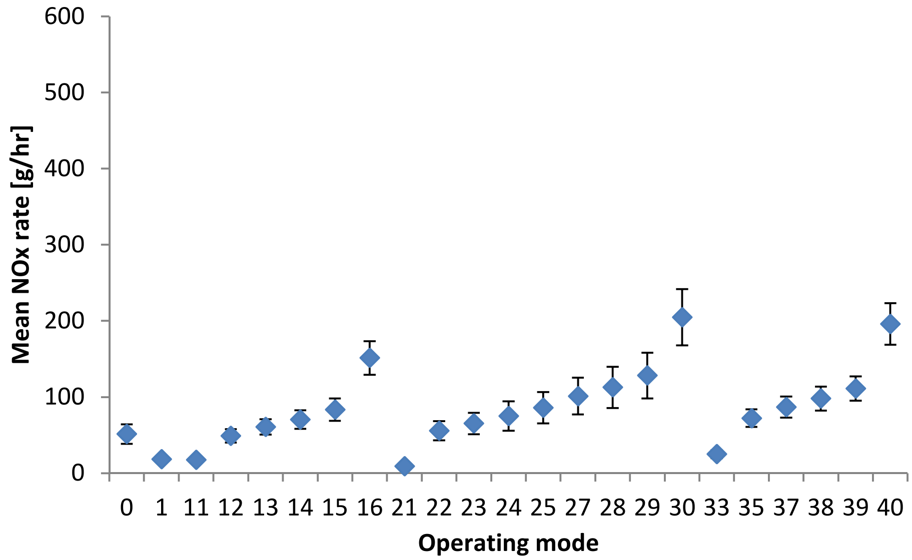


Figure 2-9. Mean NOx rates by operating mode for model years 2007-2009 LHD≤10K trucks age 0-3. Error bars represent the 95% confidence interval of the mean.



2.1.1.8 *Evaluation of NOx Emission Rates in MOVES2010*

This section presents the comparisons of NOx 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 NOx 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.

2.1.1.8.1 Heavy-Heavy Duty Trucks

Figure 2-10 through Figure 2-12 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% 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 2-11), 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 2-10. Comparison of Means: MOVES2010 emission rates vs. Houston Drayage Data (n=8) for model years 1991-1997 HHD trucks. Error bars represent the 95% confidence interval of the mean.

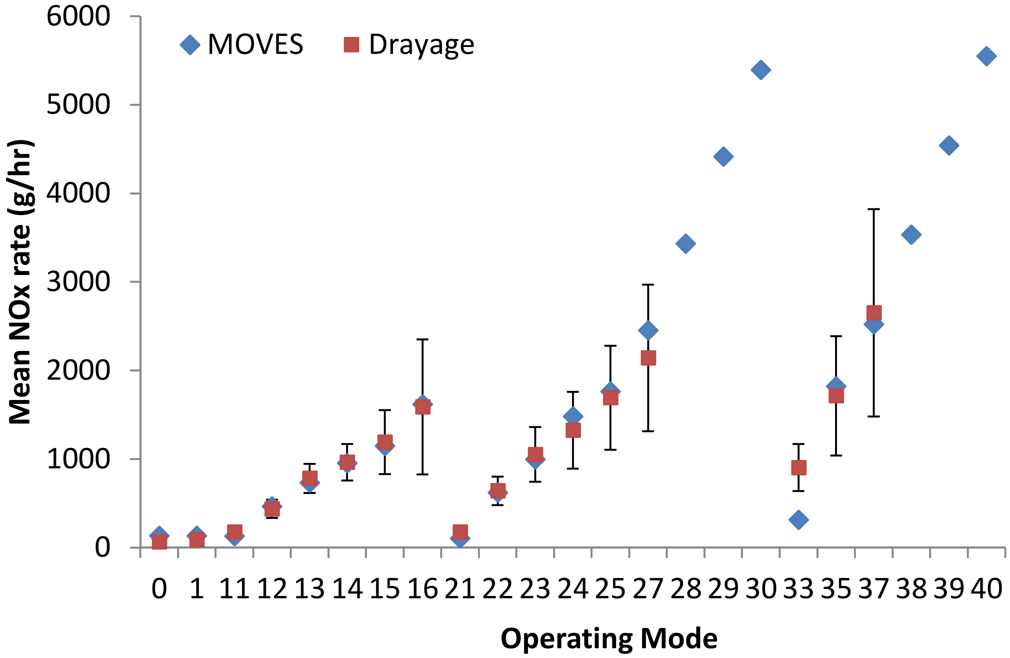


Figure 2-11. Comparison of Means: MOVES2010 emission rates vs. Houston Drayage Data (n=1) for model year 1998 HHD trucks. Error bars represent the 95% confidence interval of the mean.

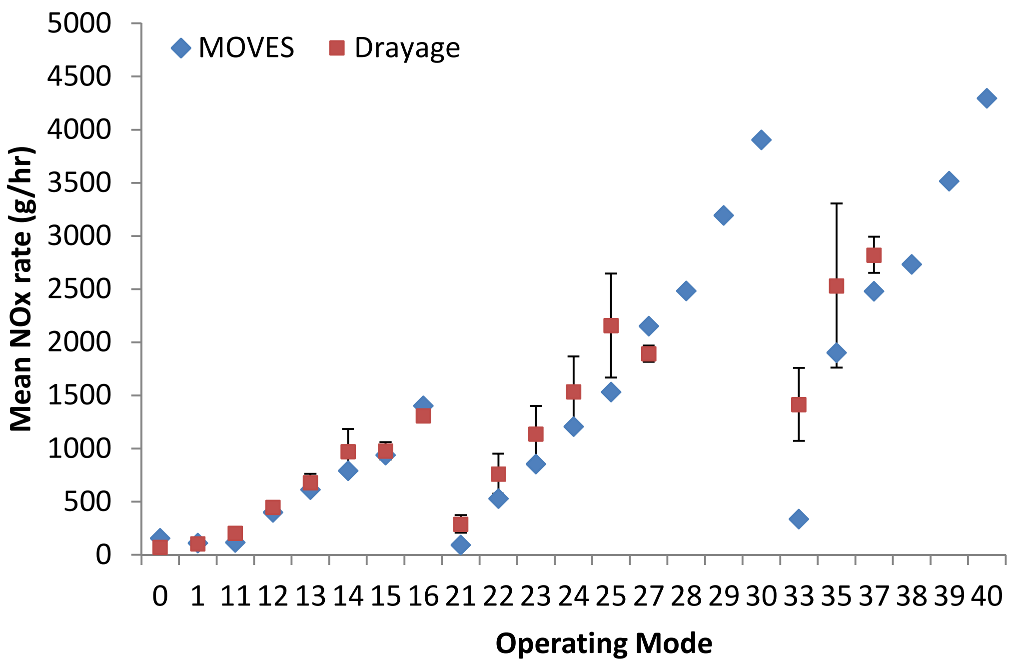
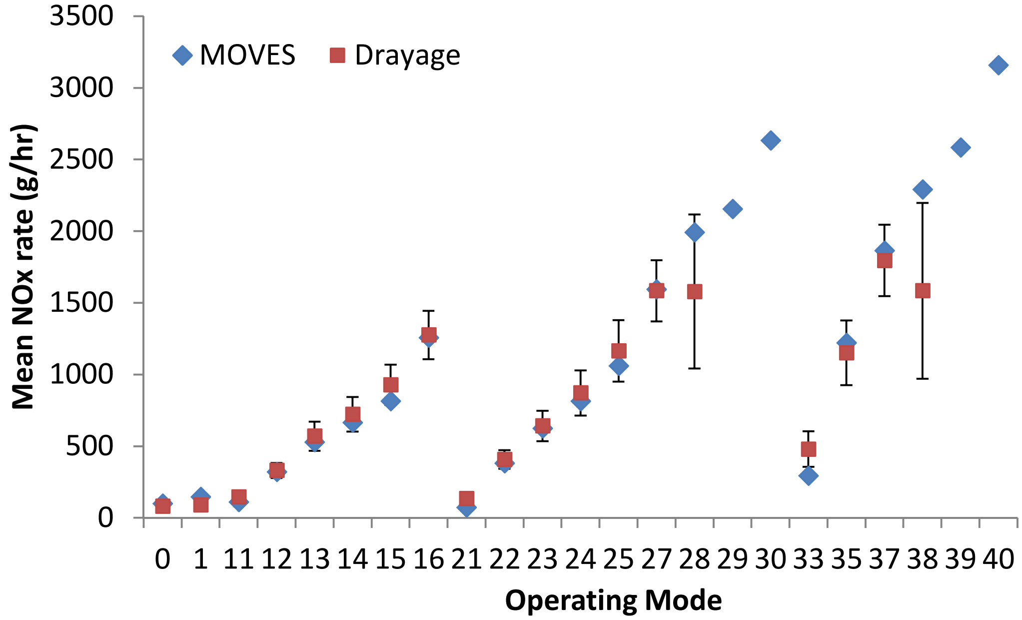


Figure 2-12. Comparison of Means: MOVES2010 emission rates vs. Houston Drayage Data (n=10) for model year 1999-2002 HHD trucks. Error bars represent the 95% confidence interval of the mean.



In Figure 2-13 and Figure 2-14, 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% confidence intervals of the mean of Houston Drayage data in Figure 2-13. When compared to HDIU data in Figure 2-14, 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 2-13. Comparison of Means: MOVES2010 emission rates vs. Houston Drayage Data (n=8) for model year 2003-2006 HHD trucks. Error bars represent the 95% confidence interval of the mean.

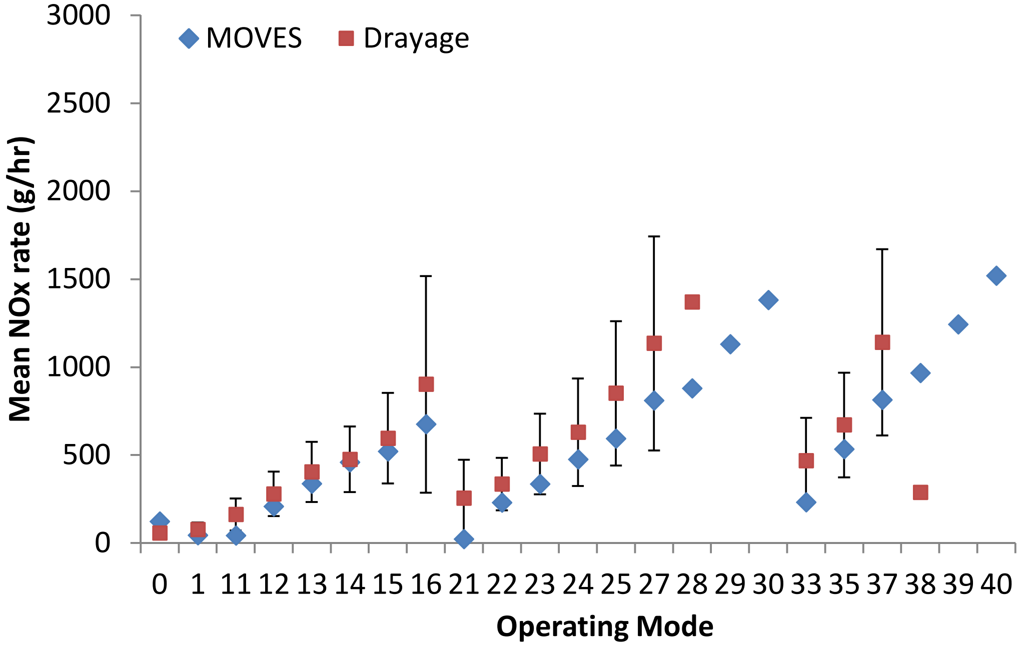
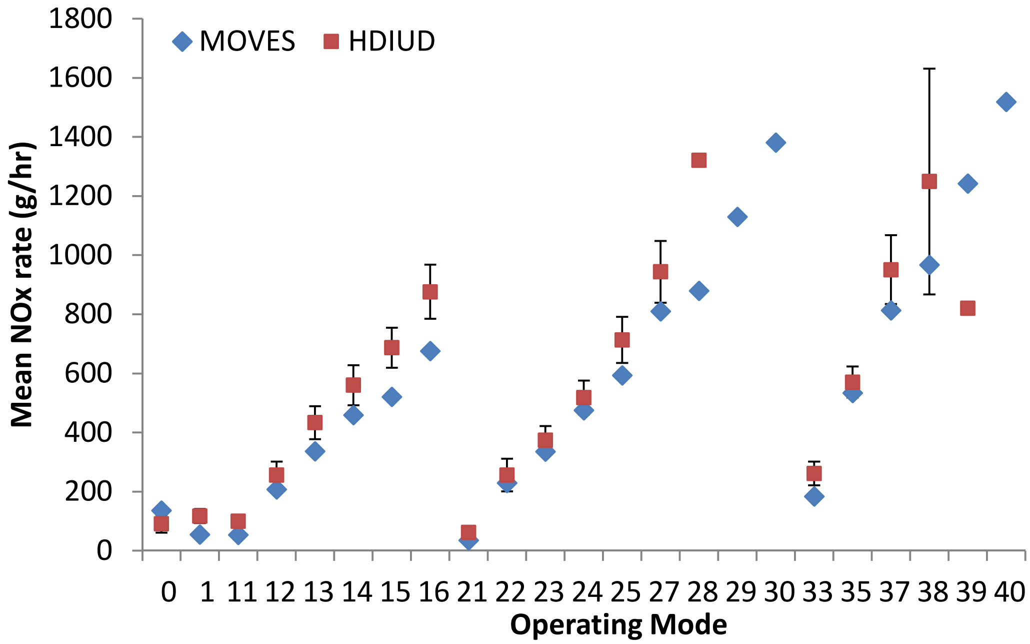
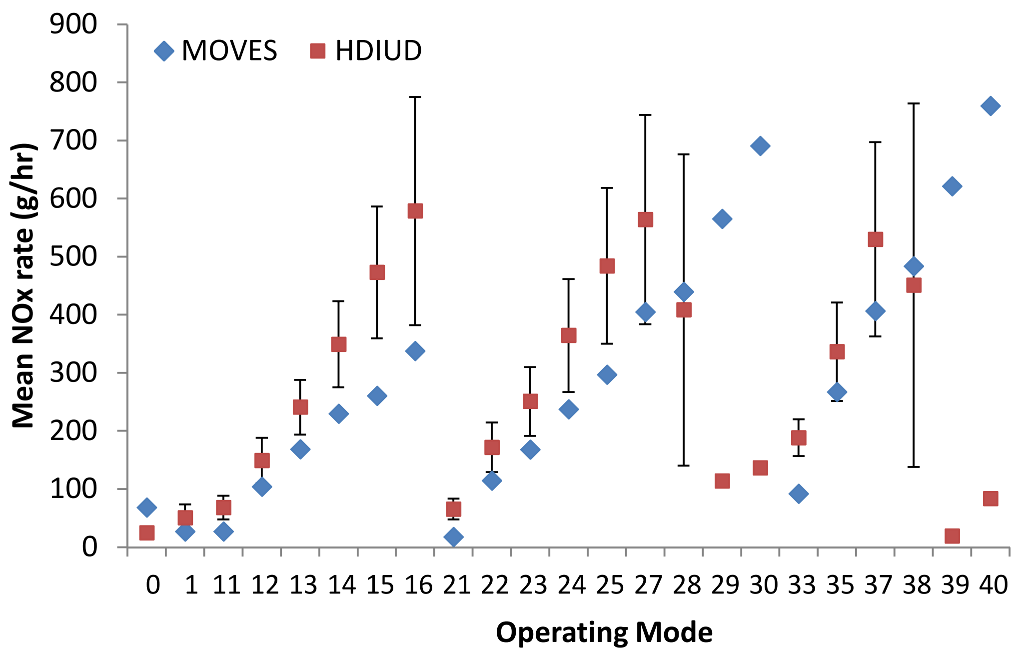


Figure 2-14. Comparison of Means: MOVES2010 rates vs. HDIU (n=40) for model years 2003-2006 HHD trucks. Error bars represent the 95% confidence interval of the mean.



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 0. 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 2-15 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 2-15. Comparison of Means: MOVES rates vs. HDIU (n=68) for model years 2007-2009 HHD trucks. Error bars represent the 95% confidence interval of the mean.



2.1.1.8.2 Medium-Heavy Duty Trucks

Figure 2-16 and Figure 2-17 show that MOVES2010 rates for MHD trucks compare well with the HDIU data for both model years groups 2003-2006 and 2007-2009. The data is generally scarce in high-power operation modes, and thus, no 95% confidence interval was calculated. The comparisons validated the MOVES2010 rates for MHD trucks, and no change was made in MOVES2014.

Figure 2-16. Comparison of Means: MOVES2010 rates vs. HDIU (n=25) for model years 2003-2006 MHD trucks. Error bars represent the 95% confidence interval of the mean.

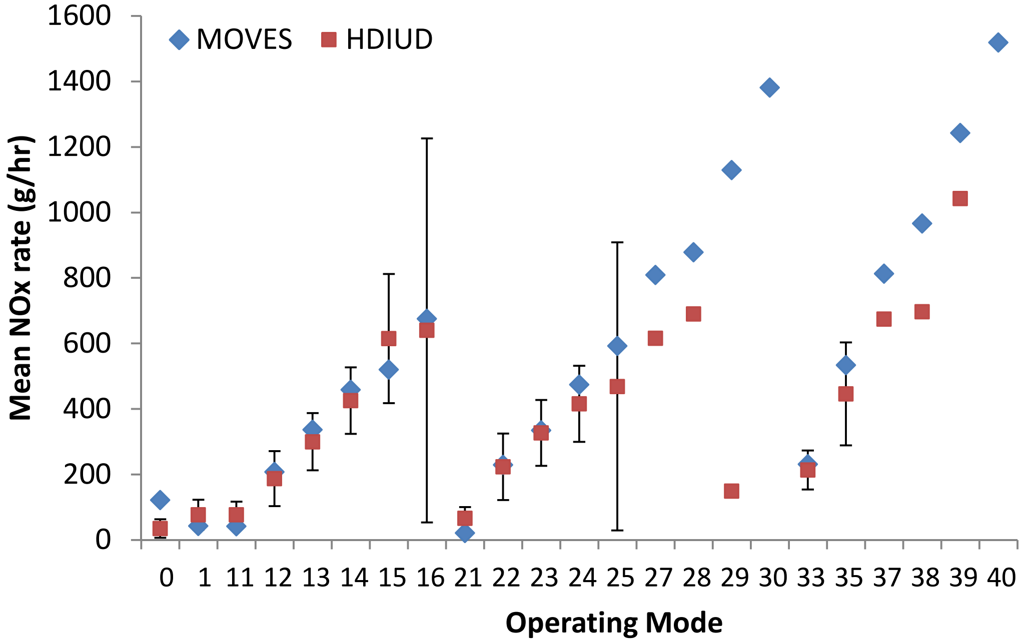
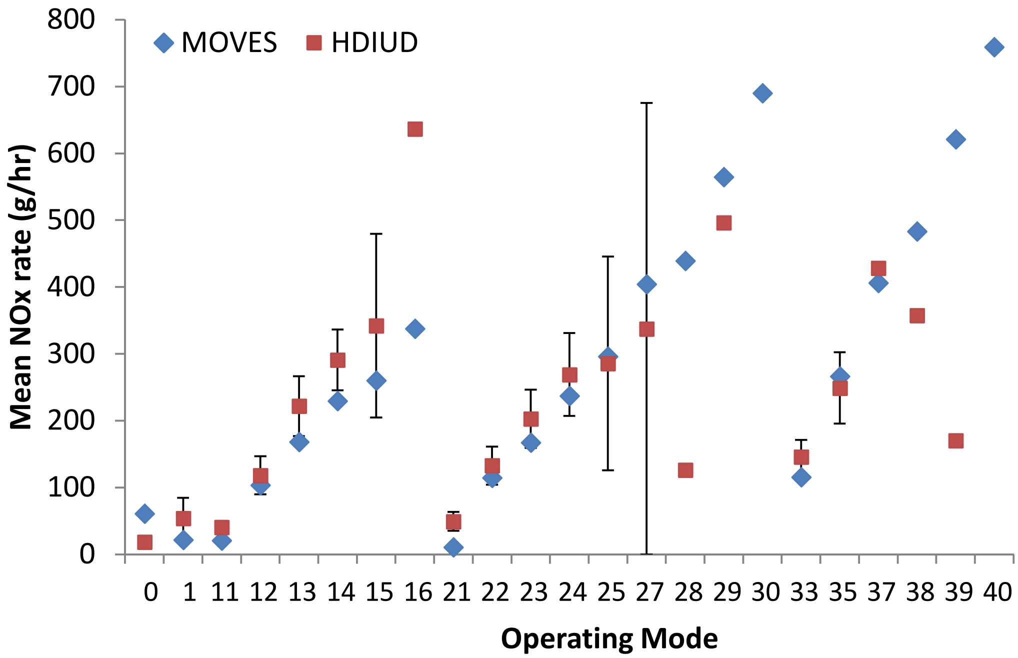


Figure 2-17. Comparison of Means: MOVES2010 rates vs. HDIU (n=71) for model years 2007-2009 MHD trucks. Error bars represent the 95% confidence interval of the mean.



2.1.1.8.3 Light-Heavy Duty Trucks

The comparisons of the MOVES2010 LHD45 rates to the corresponding LHD45 HDIU trucks for model years 2003-2006 (Figure 2-18) and 2007-2009 (Figure 2-19) show that MOVES2010 rates compare well with the HDIU data. Therefore, MOVES2010 rates for these model year groups were retained in MOVES2014.

Figure 2-18. Comparison of Means: MOVES2010 rates vs. HDIU (n=15) for model years 2003-2006 LHD45 trucks. Error bars represent the 95% confidence interval of the mean.

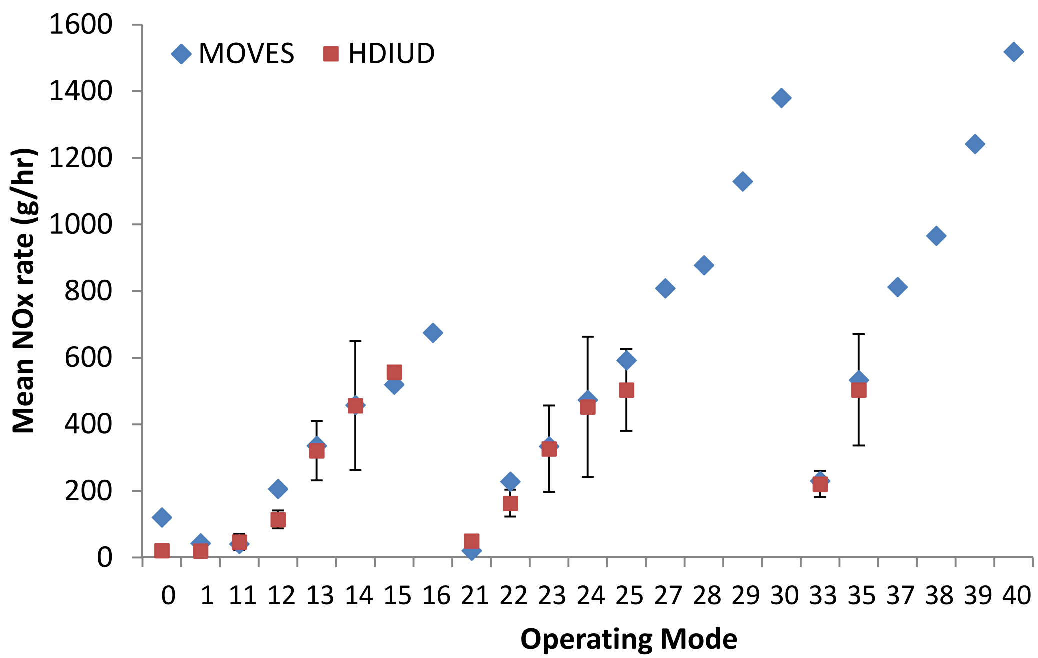
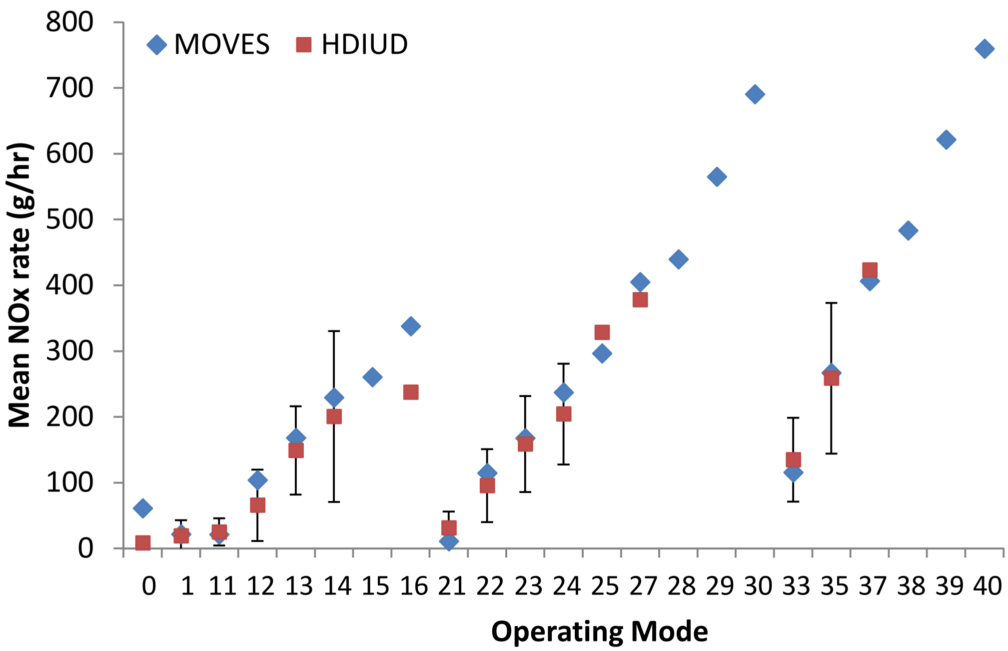


Figure 2-19. Comparison of Means: MOVES2010 rates vs. HDIU (n=24) for model years 2007-2009 LHD45 trucks. Error bars represent the 95% confidence interval of the mean.



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 NOx, 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 2-9 shows the model year group ranges and the applicable brake-specific emissions standards.

Table 2-9. 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 MOVES2014 $PM_{2.5}$ emission rates was generated in the CRC E-55/59 research program[33e]. The following description by Dr. Ying Hsu and Maureen Mullen of E. H. Pechan, in the "*Compilation of Diesel Emissions Speciation Data – Final Report*" 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

[e] The MOVES2014 $PM_{2.5}$ emission rates were originally developed in MOVES2010, and are largely unchanged for heavy-duty diesel vehicles.

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 proposed 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 proposed 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 2-10.

Table 2-10. 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 2-11.

Table 2-11. 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[34] 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 that 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 2-12 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 2-12. 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). The equation below shows the normalization process for a particular one second TEOM measurement.

$$PM_{\text{normalized},\,i,\,j} = \frac{PM_{\text{filter},\,j}}{\sum^{j} PM_{\text{TEOM},\,i}} PM_{\text{TEOM},\,j,\,i} \qquad \textbf{Equation 2-16}$$

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) [35] 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 by regulatory class, model-year group and the 23 operating modes. 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.

2.1.2.3 *Hole filling and Forecasting*

2.1.2.3.1 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 NOx rates, emission rates were extrapolated for the highest STP operating modes.

2.1.2.3.2 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.[f]

The emission rates of LHD≤ 10K (regClassID 40) need to be compatible with VSP-based operating modes as discussed in Section 1.1. In Draft MOVES2009, heavy-duty emission rates were VSP-based.[36] The PM emission rates for LHD≤10K in MOVES2014 are equivalent to the PM emission rates for LHD2b3 from MOVES2009. The LHD2b3 emission rates in MOVES2009 were derived by applying a factor to the VSP-based MHD PM emission factors derived from the E55/59 TEOM data. A factor of 0.46 was 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

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[f] In MOVES2010, the LHD45 and LHD2b3 were both estimated based on VSP-based emission rates, using a similar methodology as the current LHD≤10K emission rates. In MOVES2014, we replaced the LHD≤14K and LHD45 emission rates with MHD emission rates because they now use the same mass scaling factor.

trucks. The equation used to derive the PM emission rates for regulatory class LHD≤10K (RegClassID 40) is shown below:

$$LHD \leq 10K\ emission\ rate = 0.46\ \times MHD\ (VSP\_based) emission\ rate \qquad \textbf{Equation 2-17}$$

Where the MHD VSP-based emission rate is obtained from MOVES2009.[36]

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 2-13 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.6.

Table 2-13. 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
[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.			

2.1.2.3.3 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, we expect 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 2-14 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 limited results from these studies demonstrate that the effectiveness of working particulate traps is very high. The interested reader can review the ACES report.[38]

Table 2-14. The average certification results for model years 2003-2007. Average ratio from MYs 2003-2006 to MY 2007 is 27.7

Certification Model Year	Mean (g/bhp-hr)	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

2.1.2.3.4 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 2-15 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 – 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 NOx, 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 2-15. 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% value for 2013+ is driven by the assumed full-implementation of the OBD in 2013 and later trucks, which assumes a 33% decrease in tampering and mal-maintenance emission effects.

Table 2-15. 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

2.1.2.3.5 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[39]. 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 EC emissions explicitly at the operating mode level, because of the availability of EC emission measurements at the operating mode level, and the importance of mode in determining the composition of PM emissions.

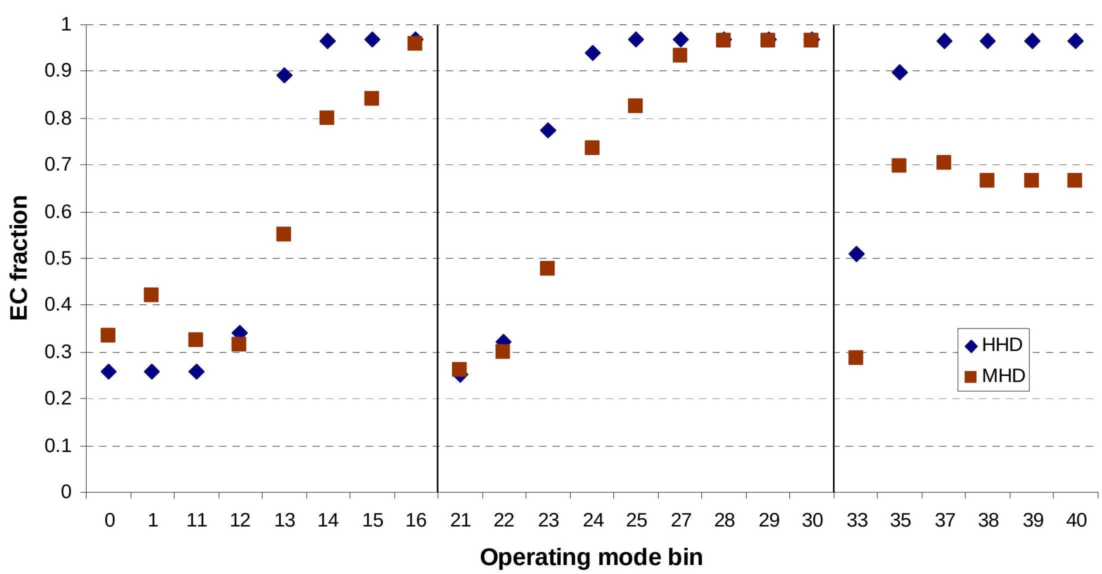
MOVES models Total $PM_{2.5}$ emissions by vehicle operating mode using elemental carbon (EC) and non-elemental particulate matter carbon (NonECPM), as shown in Equation 2-18.

$$PM_{2.5} = EC + NonECPM \quad \textbf{Equation 2-18}$$

The EC fractions used in MOVES for pre-2007 model year trucks (i.e. before diesel particulate filters (DPFs) were standard) are shown in Figure 2-20. These vary according to regulatory class and MOVES operating mode. They typically range from 25 percent at low loads (low STP) to over 90 percent at highly loaded modes. All of the EC fractions were developed in a separate analysis from which the Total $PM_{2.5}$ emission rates were developed, and are documented in Appendix E. The primary dataset used in the analysis came from Kweon et al. (2004) where particulate composition and mass rate data were collected on a Cummins N14 series test engine over the CARB eight-mode engine test cycle. The EPA PERE model and a Monte Carlo approach were used to simulate and develop operating mode-specific EC/PM fractions. The EC and NonECPM emission rates in the MOVES database were calculated by multiplying the Total $PM_{2.5}$ emission rates developed from E-55/59 by the EC/PM and NonECPM/$PM_{2.5}$ fractions developed in Appendix E. Comparisons between the EC/PM fraction used in MOVES and reported by other test programs program are displayed in the MOVES2014 TOG and PM Speciation Report: Appendix C.2[42]. The NonECPM fraction of PM is simply calculated as the remainder of $PM_{2.5}$ that is not EC as shown in Equation 2-19.

$$\frac{NonECPM}{PM_{2.5}} = 1.0 - \frac{EC}{PM_{2.5}} \quad \textbf{Equation 2-19}$$

Figure 2-20. Elemental Carbon fraction by operating mode for pre-DPF-equipped trucks



For 2007 and later model year DPF-equipped diesel engines, we used the elemental carbon fraction of 9.98% measured in Phase 1 of the Advanced Collaborative Emissions Study (ACES) Report[40]. 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% EC/PM fraction across all operating modes for the 2007+ diesel emissions rates.

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 MOVES2014 Fuel Adjustment Report[41]. MOVES uses speciation profiles to estimate the composition of organic carbon, ions, and elements in NonECPM as discussed in the MOVES2014 TOG and PM Speciation Report[42].

2.1.2.4 *Sample results*

Figure 2-21 and Figure 2-22 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. 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 2-21. Particulate matter rates by operating mode representing heavy heavy-duty vehicles (model year 2002 at age 0-3 years)

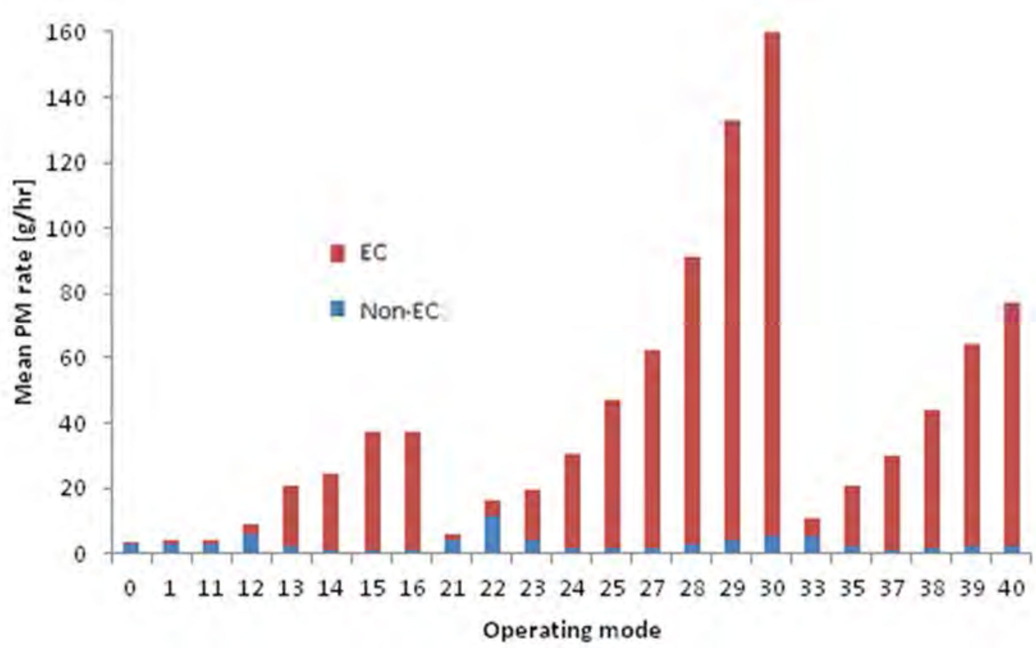


Figure 2-22. Particulate matter rates by operating mode for heavy heavy-duty vehicles (model year 2007 at age 0-3 years)

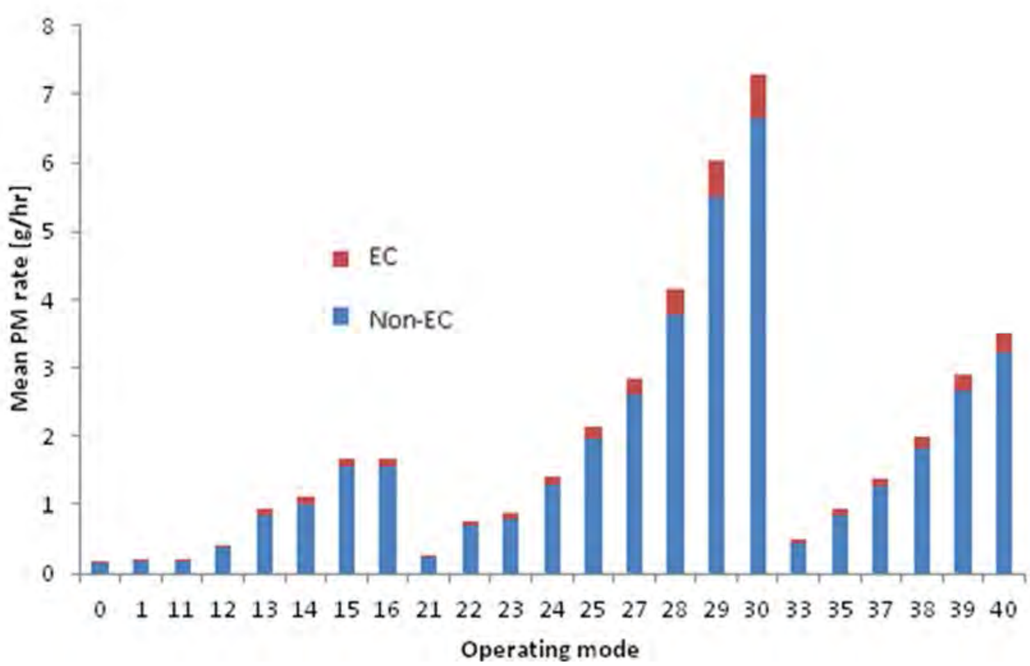


Figure 2-23 shows an example of how tampering and mal-maintenance estimates increase PM with age. The EC/PM proportion does not change by age, but the overall rate increases and levels off after the end of useful life. This figure shows the age effect for MHD. The rate at which emissions increase toward their maximum depends on regulatory class.

Figure 2-23. Particulate matter rates by age group for medium heavy-duty vehicles (model year 2002, operating mode 24)

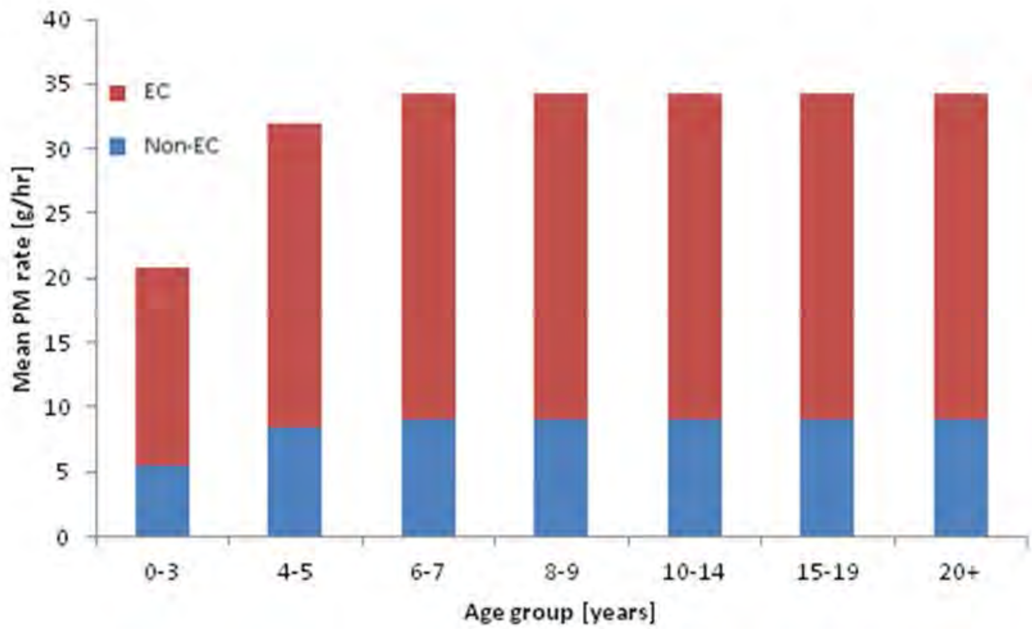
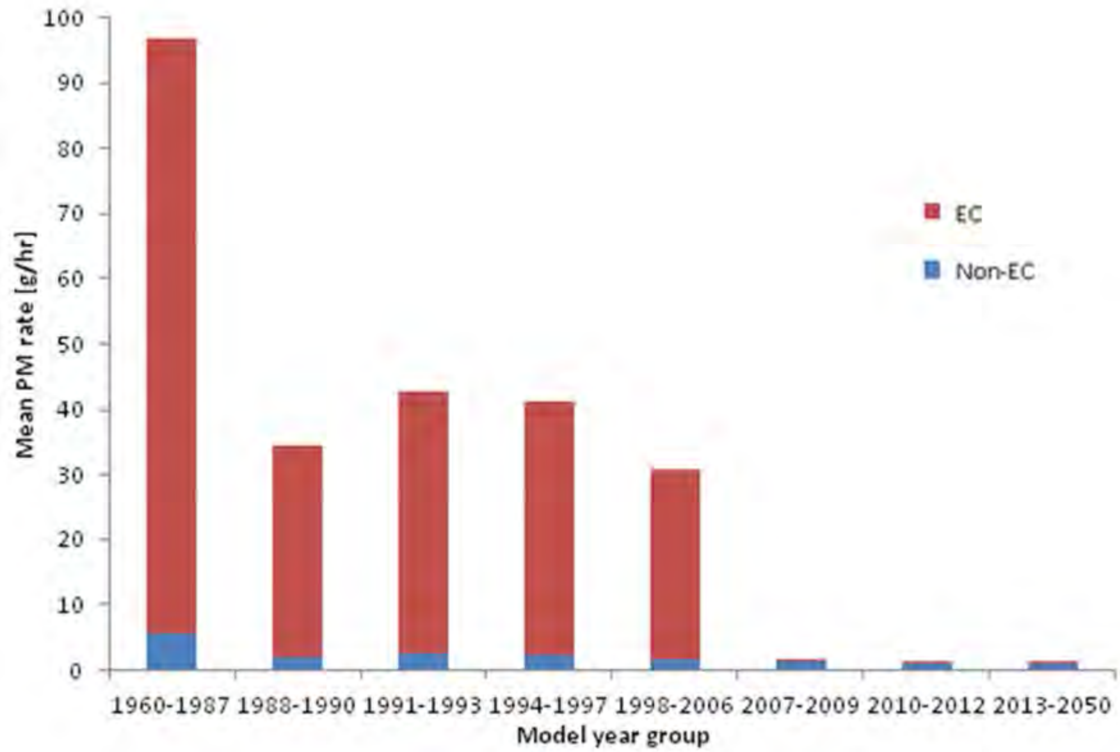


Figure 2-24. shows the effect of model year on emission rates. Emissions generally decrease with new PM standards. The EC fraction stays constant until model year 2007, when it is reduced to less than ~10% due the implementation of diesel particle filters. The overall PM level is substantially lower 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 2-24. Particulate matter rates for heavy 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. Recent regulations on non-methane hydrocarbons (NMHC) (sometimes in conjunction with NOx) combined with the common use of diesel oxidation catalysts will yield reductions in both HC and CO emissions from 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 NOx and PM. The HC/CO model year groups are:

- 1960-1989
- 1990-2006
- 2007+

2.1.3.1 *Data Sources*

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]:** 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)[43]:** 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)[44]:** 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 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 on-road data used for the NOx 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. The numbers of vehicles in the data sets are shown in Table 2-16.

Table 2-16. 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
	Bus	26			1	3		
	LHD45	2			1			
	LHD2b3	6						
2003-2006	**HHD**	6						

2.1.3.2 *Analysis*

As for PM emission rates, 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[4] that were used in the PM analysis.

Using a method similar to that used in the NOx 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 2.1.1.3.2 Instead of using our results to directly populate all the emission rates, we directly populated only the age group that was most prevalent in each regulatory class and model year group combination. These age groups are shown in Table 2-17. We used the MHD to represent the LHD45 and LHD≤14K emission rates.[g]

[g] 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 2-17. Age groups used directly in MOVES emission rate inputs for each regulatory class and model year group present in the data

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

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.9. We applied the same tampering and mal-maintenance effects for CO as HC, which are shown in Table 2-18.

Table 2-18. Tampering and mal-maintenance effects for HC and CO over the useful life of trucks

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.6 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 on 2007 and later 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 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 NOx.

In Figure 2-25 and Figure 2-26, we see that HC and CO mean emission rates increase with STP, though there is much higher uncertainty than for the NOx 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 2-25. THC emission rates [g/hr] by operating mode for model year 2002 and age group 0-3. Error bars represent the 95% confidence interval of the mean.

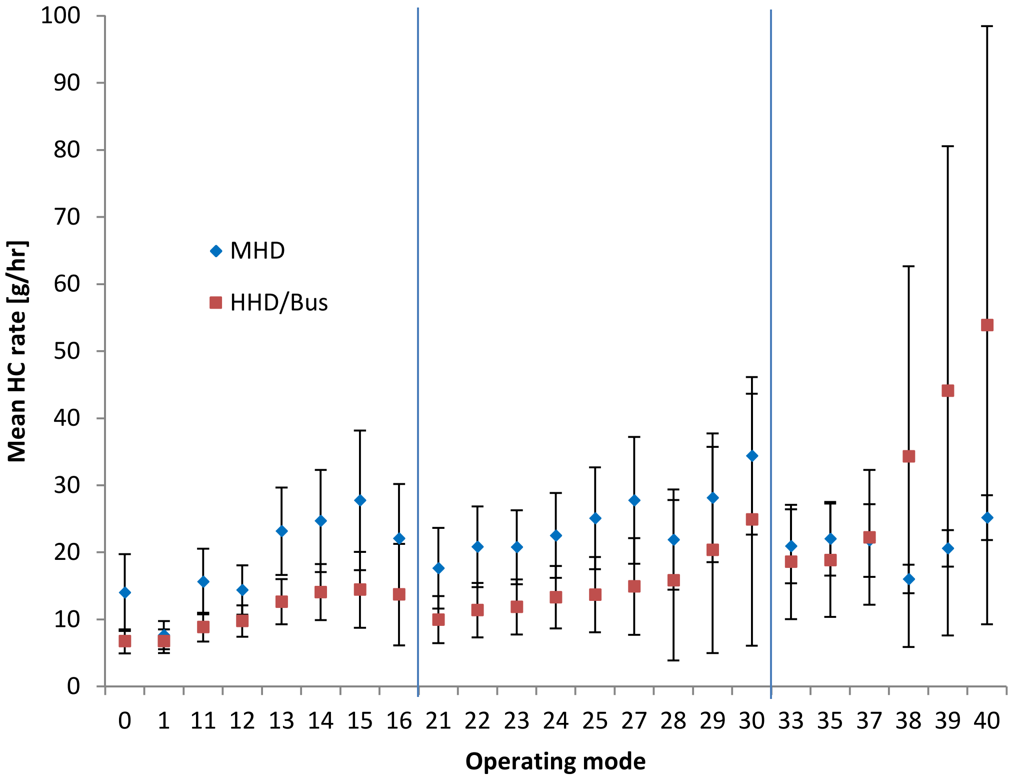


Figure 2-26. CO emission rates [g/hr] by operating mode for model year 2002 and age group 0-3. Error bars represent the 95% confidence interval of the mean.

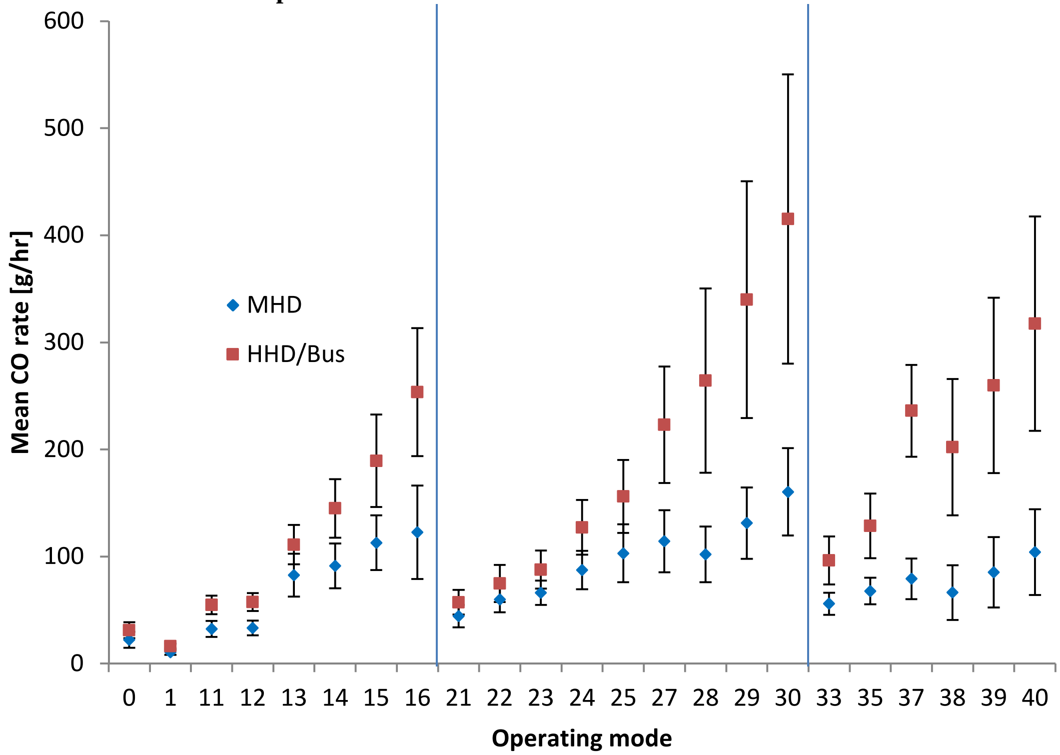


Figure 2-27 and Figure 2-28 show HC and CO emission rates by age group. Due to our projections of T&M effects, there are large increases as a function of age. Additional data collection would be valuable to determine if real-world deterioration effects are consistent with those in the model, especially in model years where diesel oxidation catalysts are most prevalent (2007 and later).

Figure 2-27. THC emission rates [g/hr] by age group for model year 2002 and operating mode 24. Error bars represent the 95% confidence interval of the mean.

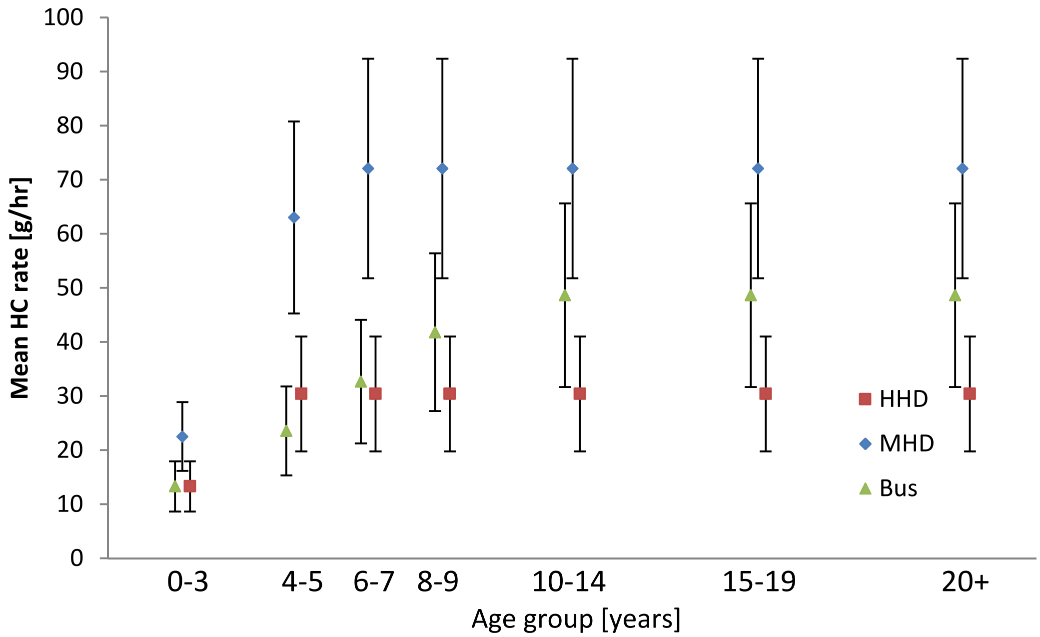


Figure 2-28. CO emission rates [g/hr] by age group for model year 2002 and operating mode 24. Error bars represent the 95% confidence interval of the mean.

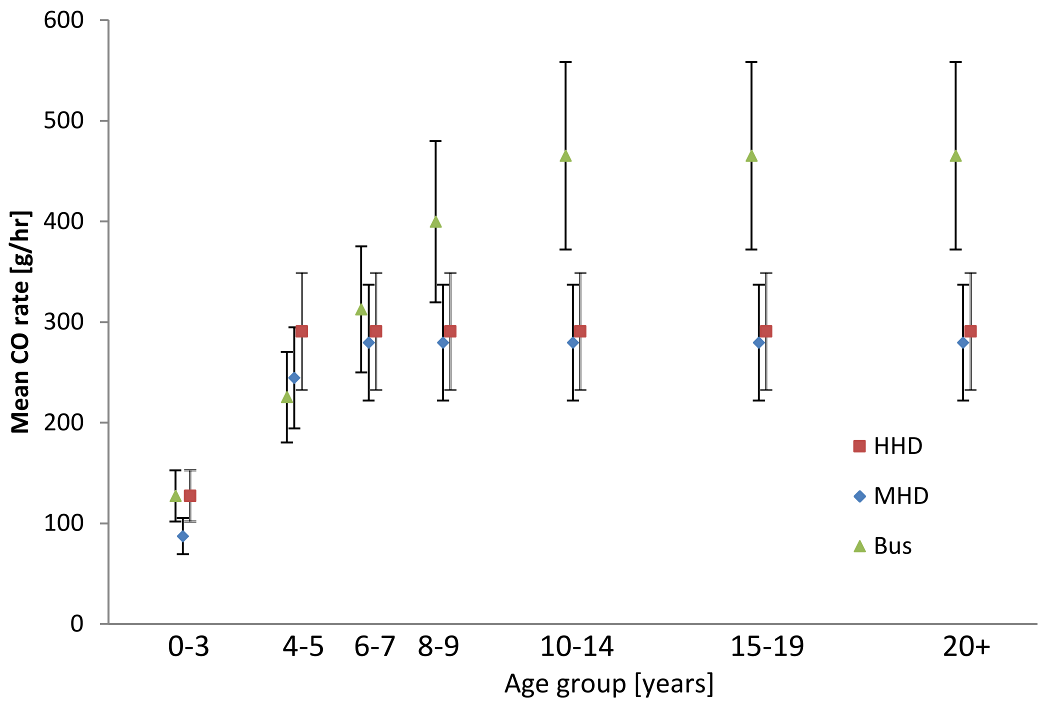


Figure 2-29 and Figure 2-30 show sample HC and CO emission rates by model year group. The two earlier model year groups are relatively similar. The rates in the 2007-2050 model year group reflect the use of diesel oxidation catalysts. Due to the sparseness of the data and the fact that HC and CO emissions do not correlate as well with STP (or power) as NOx and PM do, uncertainties are much greater.

We only analyzed data from vehicles within the HHD regulatory class within model year group 2003-2006. The zero-mile emission rates derived from for HHD regulatory class are used as the basis for the zero-mile emission rates for the other HD regulatory classes. As mentioned earlier, the 2007 and later emission rates are derived by reducing the CO and HC emissions in 2003-2006 by 80% and applying the model-year and regulatory class specific T&M adjustment factors.

Figure 2-29. THC emission rates by model year group for operating mode 24 and age group 0-3. Error bars represent the 95% confidence interval of the mean.

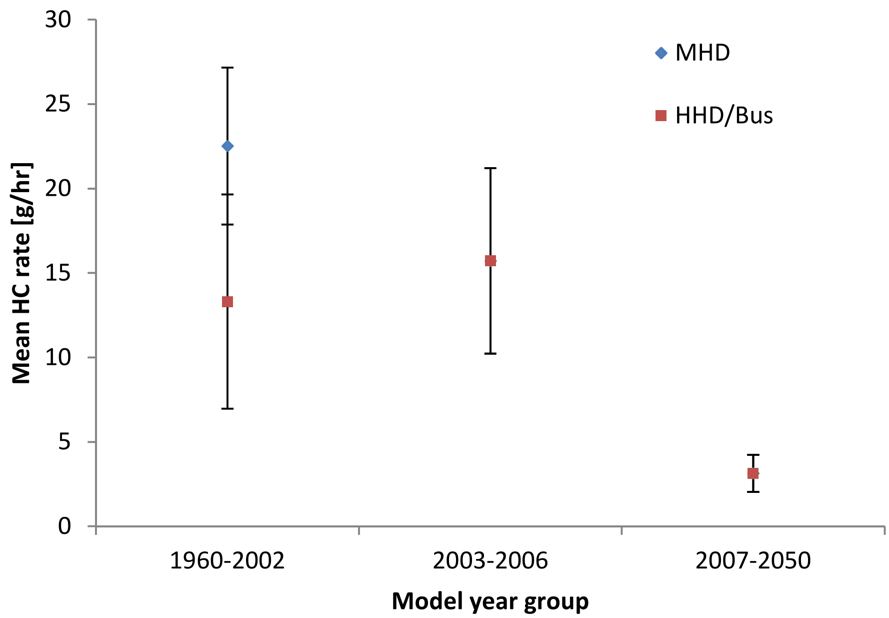
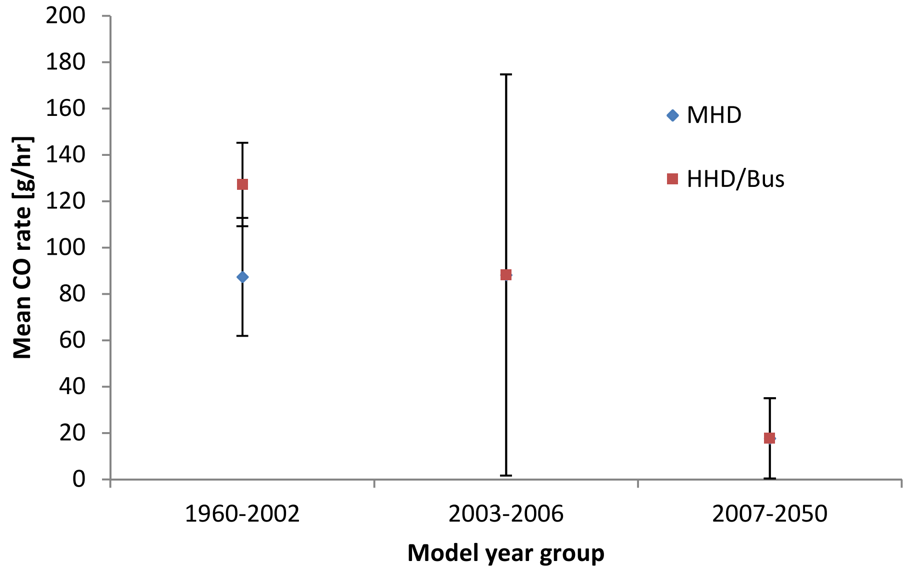


Figure 2-30. CO emission rates by model year group for operating mode 24 and age group 0-3. Error bars represent the 95% confidence interval of the mean.



2.1.4 Energy

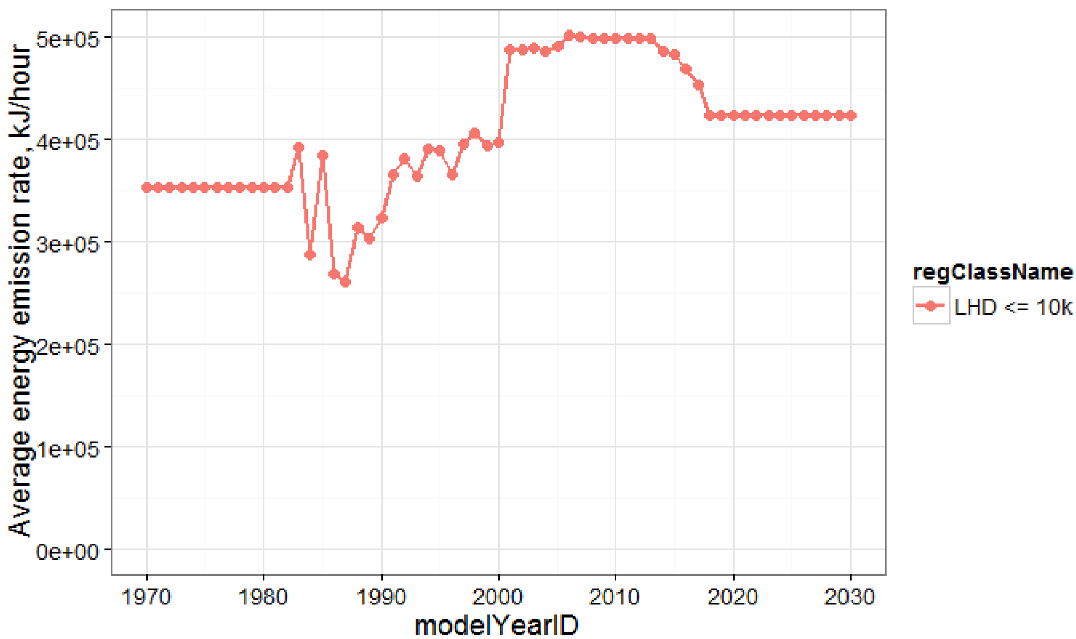
2.1.4.1 *LHD≤10K Energy Rates for Model Years 1960-2013*

In MOVES2014, the energy rates for LHD≤10K for pre-2007 diesel energy rates are unchanged from the LHD2b3 regulatory class rates in MOVES2010a. In MOVES2010a, the energy rates for this regulatory class, along with the light-duty regulatory classes, were consolidated across weight classes and engine technologies, as discussed in the MOVES2010 energy updates report.[45] As explained in the 2010 energy update report, the approach for modeling energy emission rates changed significantly in MOVES2010a. Earlier MOVES versions significantly more detail in the energy rates, which varied by engine technologies, engine size and more refined loaded weight classes. For MOVES2010a, the energy rates were simplified to be single energy rates for regulatory class, fuel type and model year combinations. This was done by aggregating the MOVES2010 energy rates 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 MOVES2010a and now in MOVES2014. The average of the emission rates (weighted equally across each operating mode) for these model years are shown in Figure 2-31. 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 2-31the emission rates from 1960-1983 are constant.

2.1.4.2 *LHD≤10K Energy Rates for Model Years 2014-2050*

For model years 2014 and later, 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 2.1.4.4. The CO_2 emission reductions for diesel 2b3 trucks in Table 2-20 were applied equally to the 2013 model year energy consumption rates in each running operating mode bins to derive 2014 and later energy consumption rates. Figure 2-31 displays the average energy consumption (across all running operating modes) for model years 1970 through 2030 The energy rates are constant going forward from 2018 to 2050.

Figure 2-31. Average Energy Consumption Rates for LHD≤10K diesel vehicles across all running operating modes[h]



2.1.4.3 *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, STP structure and calculation steps as in the NOx analysis; 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.

As for previous versions of MOVES, CO_2 emissions were used as the basis for calculating energy rates. To calculate energy rates [kJ/hour] from CO_2 emissions, 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[46] for diesel fuel, using Equation 2-20.

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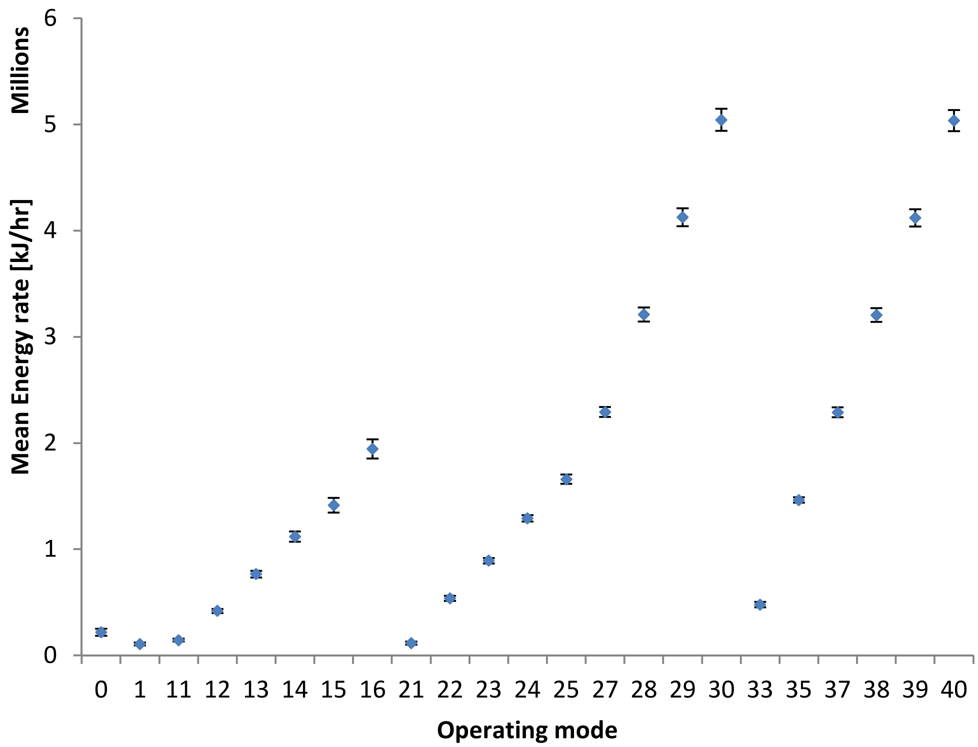
[h] *Note, this figure displays a straight average across all operating modes, and thus emphasizes the energy used in the operating modes with highest energy consumption. At run time MOVES actually computes emissions based on an operating mode distribution determined by VMT allocation by roadtype and speed as well as sourcetype mass. See the MOVES Vehicle Population and Activity report[4] for more information on operating mode distributions.*

$$\bar{r}_{energy} = \bar{r}_{CO_2} \frac{HV}{f_{CO_2}} \qquad \textbf{Equation 2-20}$$

Figure 2-32. Diesel running exhaust energy rates for LHD≤14K, LHD45, MHD, HHD, and Urban Buses for 1960-2013 model years. Error bars represent the 95% confidence interval of the mean.



The energy rates for these heavy-duty diesel vehicle classes are shown in Figure 2-32. 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.

Even though the emission rates by operating mode bin for the age range in Figure 2-32 are not classified by regulatory class, the distribution of operating mode bins differs significantly by regulatory class. The smaller heavy-duty regulatory classes operated in the lower power operating mode bins, and likely never reach the highest power operating mode bins. Thus, the aggregated energy rates (e.g. KJ/mile) calculated from MOVES will differ by regulatory class.

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

The energy rates are revised for 2014 and later model years, to reflect the impact of the 2014 Medium and Heavy Duty Greenhouse Gas Rule.[47] The medium and heavy duty greenhouse gas program begins with 2014 model year and increases in stringency through 2018. The standards continue indefinitely after 2018. The program breaks the diverse truck sector into 3 distinct categories, including

- Line haul tractors (largest heavy-duty tractors used to pull 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 program 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.[i]

In MOVES, the improved fuel consumption from the HD GHG Rule is implemented in two ways. First, the running emission rates for total energy 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.[4]

The revised running emission rates for total energy are drawn from the HDGHG rulemaking modeling.[47] The estimated reductions for heavy-duty diesel vehicles, including all rates are for include new running, start and extended idle rates, are shown in Table 2-19. These rates are for the 2014 and later model years, and reflect the improvements expected from improved energy efficiency in the powertrain. The reductions from the baseline were applied to the appropriate regulatory classes and model years in the MOVES emissionRate table.

Table 2-19 Estimated reductions in diesel and gasoline engine CO_2 Emission rate reductions from the HD GHG Program Phase 1

GVWR Class	Fuel	Model Years	CO_2 Reduction From Baseline
HHD (8a-8b)	Diesel	2014-2016	3%
		2017+	6%
LHD(4-5) and MHD (6-7)	Diesel	2014-2016	5%
		2017+	9%
	Gasoline	2016+	5%

Unlike the HHD standards, 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 estimated expected changes in CO_2 emissions due to improved engine and vehicle technologies. Since nearly all HD pickup trucks and vans will be certified on a chassis dynamometer, the CO_2 reductions for these vehicles are not represented as engine and road load reduction components, but total vehicle CO_2 reductions. MOVES2014 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≤10 and

[i] HFCs are not modeled in MOVES, and the N2O and CH4 standards are not considered forcing on emissions.

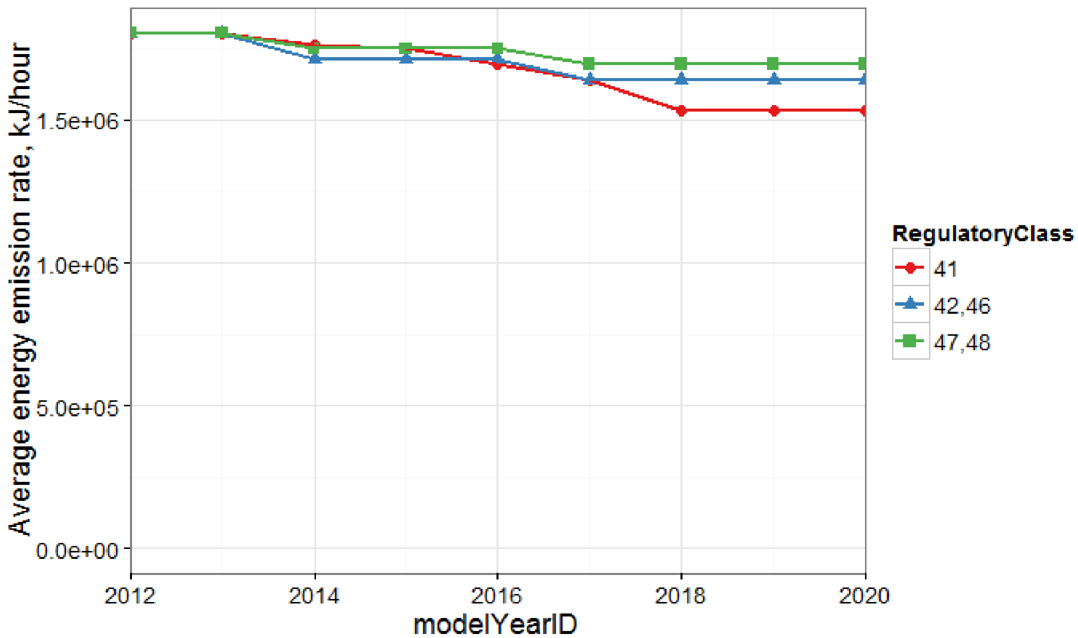
LHD≤14K were lowered by the percentages shown in Table 2-22 for the corresponding model years.

Table 2-20 Estimated total vehicle CO_2 reductions for HD diesel and gasoline pickup trucks and vans

GVWR class	Fuel	Model years	CO_2 Reduction from baseline
LHD 2b-3	Gasoline	2014	1.5%
		2015	2%
		2016	4%
		2017	6%
		2018+	10%
	Diesel	2014	2.3%
		2015	3%
		2016	6%
		2017	9%
		2018+	15%

Figure 2-33 displays the average energy consumption rates for the heavy-duty diesel source types that are modeled using Scaled Tractive Power (STP) with a fixed mass factor of 17.1. All the operating mode demonstrate the same relative trend as the average. 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 2-33, with separate reductions for the class 2b and 3 trucks (LHD≤14K), class 4-7 trucks (LHD45, MHD), and class 8 trucks (HHD).. The urban bus regulatory is by definition a heavy heavy-duty vehicle, and is treated the same as the other heavy-heavy duty vehicles (HHD). For LHD≤14K the energy rates are constant from 2018 going forward, for the other categories (LHD45, MHD, Urban Bus, HHD) the energy rates are constant going forward starting in model year 2017.

Figure 2-33. Average energy consumption rates for LHD≤14K (41), LHD45 (42), MHD (46), Urban Bus (48), and HHD (47) diesel vehicles across all operating modes[h]



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 ratedocument[8]. The impact of ambient temperature on cold starts is discussed in the Emission Adjustments MOVES report[48].

2.2.1 HC, CO, and NOx

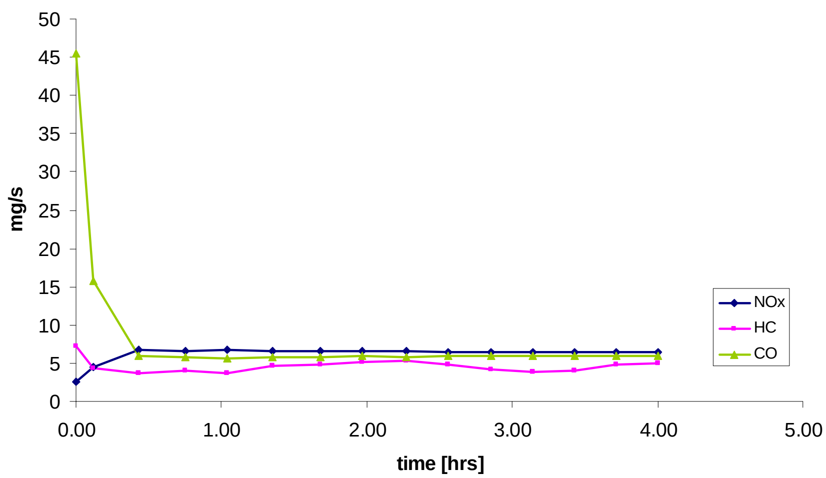
For light-duty diesel vehicles, start emissions are estimated by subtracting FTP bag 3 emissions from FTP bag 1 emissions. Bag 3 and Bag 1 are the same dynamometer cycle, except that Bag 1 starts with a cold start, and Bag 3 begins with a hot start. A similar approach was applied for LHD vehicles tested 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 NOx are shown in Table 2-21.

Table 2-21. The average start emissions increases for light-heavy duty diesel vehicles (g) for regulatory class LHD≤10K, LHD≤14K, and LHD45 (RegClassIDs 40, 41, and 42). No differentiation by model year or age.

	HC	CO	NOx
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 2-34. The biggest drop in emission rate through the test was with CO, whereas there was a slight increase in NOx (implying that cold start NOx is lower than runningNOx), and an insignificant change in HC.

Figure 2-34. Trends in the stabilization of idle emissions from a diesel engine following a cold start. Data were collected 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 2-22. The measured HC increment is zero. The NOx increment is negative since cold start emissions are lower than warm idle emissions.

Table 2-22. Cold-start emissions increases in grams on the 2007 Cummins ISB

HC	CO	NOx
0.0	16.0	-2.3

We also considered NOx data from University of Tennessee[49], 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 NOx emissions during cold start (similar to our own work described above), and several trucks produced higher NOx emissions during cold start. Due to these conflicting results, and the recognition that many factors affect NOx emission during start (e.g. air-fuel ratio, injection timing, etc), we set the default NOx cold-start increment to zero. Table 2-23 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 model years and ages.

Table 2-23. MOVES inputs for HHD and MHD diesel start emissions (grams/start) for regulatory class 46, 47, and 48. No differentiation by model year or age.

HC	CO	NOx
0.0	16.0	0.0

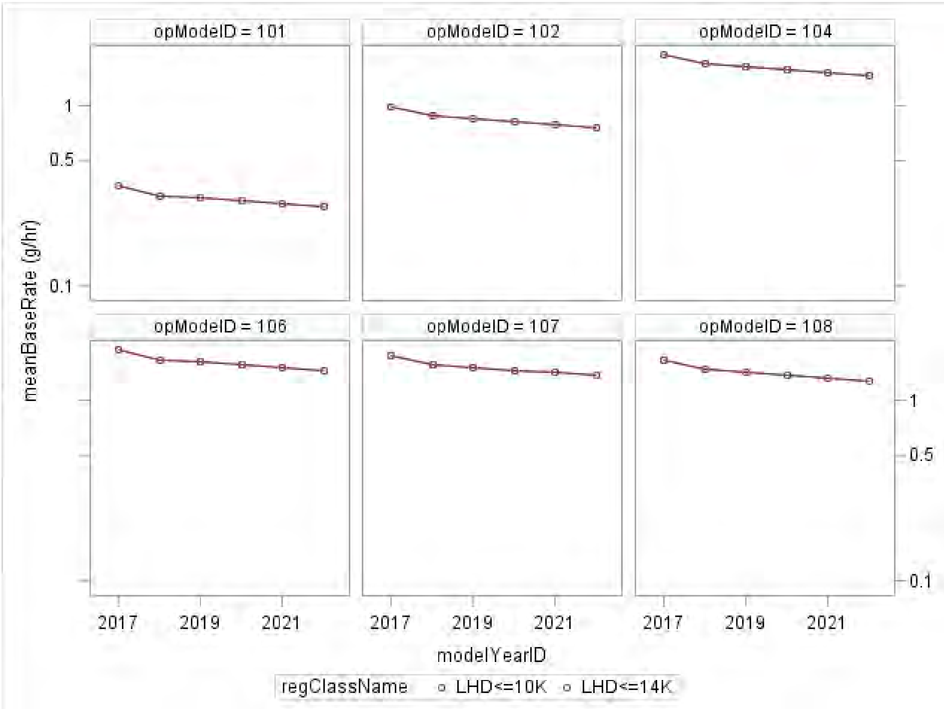
As discussed in the Emission Adjustments Report[48], MOVES2014 applies an additive adjustment to HC cold-start emissions to the diesel start emissions for ambient temperatures below 72 F. Thus, despite a baseline HC start emission rate of zero, MOVES2014 estimates positive HC start emissions from heavy-duty diesel vehicles at ambient temperatures below 72 F. No temperature adjustments are applied to CO, PM or NOx diesel start emissions.

2.2.1.1 *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 2-35. Note that start rates are identical for the two regulatory classes.

Figure 2-35. NO_x: Start emission rates in selected operating modes vs. model year for the two light-heavy duty regulatory classes (LOGARITHMIC SCALE).



2.2.2 Particulate Matter

Data for particulate matter start emissions from heavy-duty vehicles are rare. 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 and later 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. We plan to update this value when more data becomes available.

2.2.3 *Adjusting Start Rates for Soak Time*

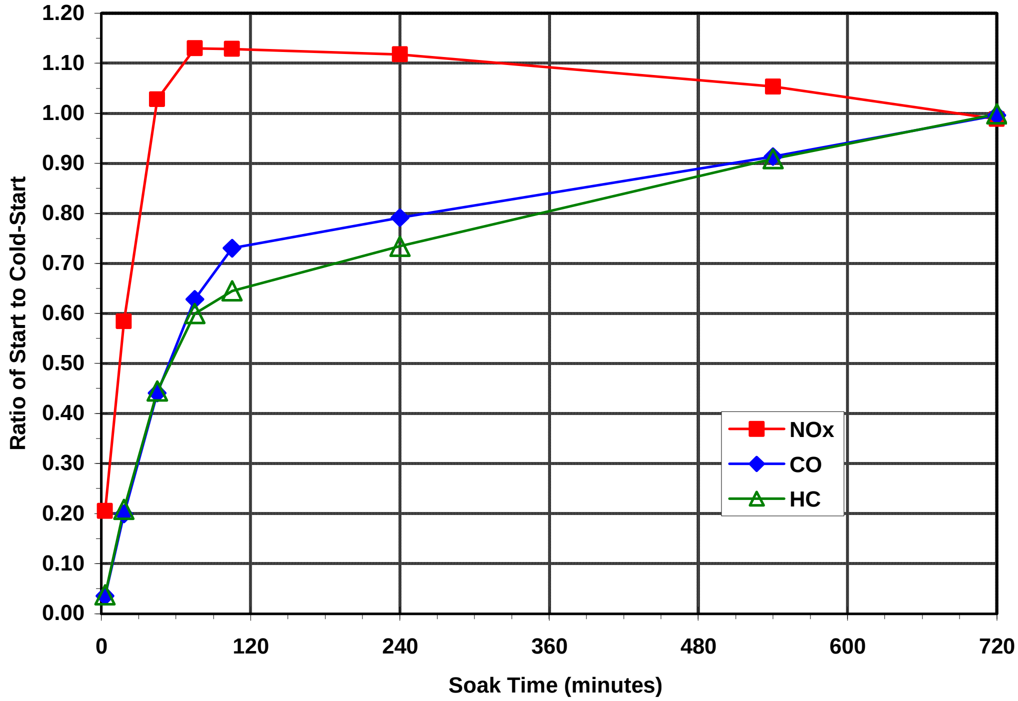
The discussion to this point has concerned the development of rates for cold-start emissions from heavy duty diesel vehicles. In addition, it was necessary to derive rates for additional operating modes that account for shorter soak times. As with light-duty vehicles, we accomplished this step by applying soak fractions. As no data are available for heavy-duty vehicles, we applied the same fractions used for light-duty emissions. Table 2-24 describes the different start-related operating modes in MOVES as a function of soak time. The value at 720 min (12 hours) represents cold start. These modes are not related to the operating modes defined in Table 1-4 which are for running exhaust emissions.

Table 2-24. 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 NOx are illustrated in Figure 2-36 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[8]. The soak fractions are taken from the non-catalyst soak fractions derived in a CARB report[50] and reproduced in a MOBILE6 report[51]. 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 NOx. For medium and heavy-heavy duty vehicles (regulatory classes MHD, HHD, and Urban Bus) only the CO soak fractions in Figure 2-36 are applied to the cold-start emissions, because the base cold start HC and NOx emission rates for medium and heavy-heavy duty emission rates are zero.

Figure 2-36. Soak Fractions Applied to Cold-Start Emissions (opModeID = 108) to Estimate Emissions for shorter Soak Periods (operating modes 101-107). This Figure is reproduced the Light-duty emissions Report[8]



The start emission rates used for heavy-duty vehicles, derived from applying the soak fractions are displayed in Table 2-25 for HC, CO, and NOx.

Table 2-25. Heavy-duty diesel HC, CO, and NOx Start emissions (g/start) by operating mode for all model year and all ages in MOVES.

	HC		CO		NOx	
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

[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, and 48)

The PM start rates by operating mode are given in Table 2-26 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 2-26. Particulate Matter Start Emission Rates by Operating Mode (soak fraction) for all HD vehicles (regClass ID 40 through 48)

Operating Mode	$PM_{2.5}$ (grams per start) 1960-2006 MY	$PM_{2.5}$ (grams per start) 2007+ 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

2.2.3.1 *Adjusting Start Rates for Ambient Temperature*

The emission adjustments report discusses the impact of ambient temperature on cold start emission rates (opModeID 108)[48]. 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 to obtain cold start temperature adjustments for opModeID 101 through 107. The additive cold start adjustment for HC emission factors are displayed in Table 2-27, 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 NOx.

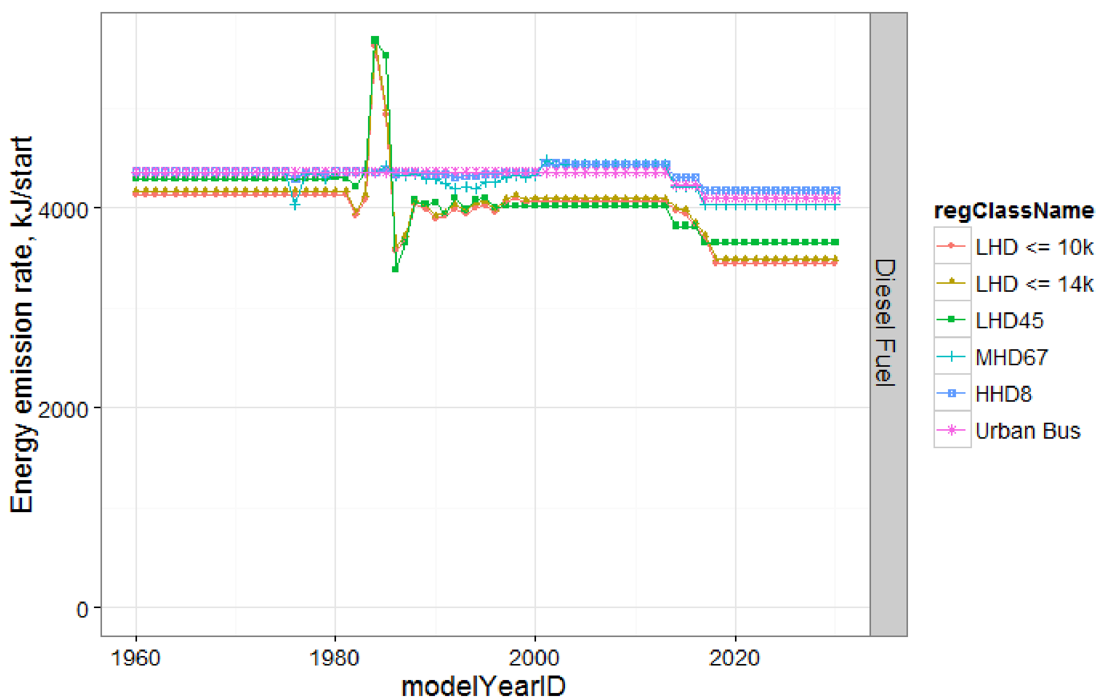
Table 2-27. HC Diesel Start Temperature Adjustment by opModeID.

opModeID	Start Temp Adjustment	Soak fraction
101	-0.0153×(Temp – 75)	0.38
102	-0.0152×(Temp – 75)	0.37
103	-0.0180×(Temp – 75)	0.44
104	-0.0201×(Temp – 75)	0.50
105	-0.0211×(Temp – 75)	0.52
106	-0.0254×(Temp – 75)	0.62
107	-0.0349×(Temp – 75)	0.86
108	-0.0406×(Temp – 75)	1.00

2.2.4 Start Energy Rates

The MOVES start energy rates for the heavy-duty diesel regulatory classes are shown in Figure 2-37. The energy start rates were developed for MOVES2004[52], and updated in MOVES2010 as documented in the MOVES2010a energy updates report[45]. 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 begin phase-in in 2014 and have the same reductions as the running energy rates as presented in Table 2-19.

Figure 2-37. 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 2004 Energy Report.[52] Additionally, the energy consumption is reduced for starts that occur when the vehicles is 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 2-28. These fractions are used for all model years and regulatory classes of diesel vehicles.

Table 2-28. 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 2-29 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 2-29. 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, and is sometimes referred to as "hotelling." The use of accessories such as air conditioning systems or heating systems will affect emissions emitted by the engine during idling. Extended idling by vehicles also allows cool-down of the vehicle's catalytic converter system or other exhaust emission after-treatments, when these controls are present. Extended idle is treated as a separate emission process in MOVES.

Extended idling does not include the vehicle idle operation which occurs during normal road operation, such as the idle operation which a vehicle experiences while waiting at a traffic signal or during a relatively short stop, such as idle operation during a delivery. Although frequent stops and idling can contribute to overall emissions, these modes are already 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 are the only source type assumed to have any significant extended idling activity. As a result, an estimate for the extended idling emission rate has not been made for any of the other source types modeled in MOVES.

While the MOVES2014 emission rates for extended idling are the same as the rates in MOVES2010, the extended idling activity in MOVES2014 has been reduced to account for the anticipated growing use of Auxiliary Power Units and the impact of the HDGHG rule as discussed below in Section 2.3.5.

2.3.1 Data Sources

The data used in the analysis of extended idling emission rates includes idle emission results from several test programs conducted by a variety of researchers at different times. Not all of the studies included all the pollutants of interest. The references contain more detailed descriptions of the data and how the data was obtained.

Testing was conducted on 12 heavy-duty diesel trucks and 12 transit buses in Colorado by McCormick et al.[53]. 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.)[54]. 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)[55]. 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.)[56]. 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 [57].

The National Cooperative Highway Research Program (NCHRP)[58] 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.)[59]. 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 on-road emissions testing trailer based in Research Triangle Park, North Carolina (Broderick)[60]. 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 NOx emissions under a variety of conditions at Oak Ridge Laboratories (Story et al.)[61]. 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)[49].

2.3.2 Analysis

EPA estimated mean emission rates during extended idling operation for particulate matter (PM), oxides of nitrogen (NOx), hydrocarbons (HC), and carbon monoxide (CO using all the data sources referenced above. 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 factors affecting engine load, such as accessory use, and engine idle speed are the important parameters in estimating the emission rates of extended idling. The impacts of most other factors, such as engine size, altitude, model year within MOVES groups, and test cycle are negligible. This makes the behavior of truck operators very important in estimating the emission rates to assign to periods of extended idling.

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 process assume both accessory use and engine idle speeds set higher than used for "curb" (non-discretionary) idling.

The studies focused on three types of idle conditions. The first is considered a curb idle, with low engine speed (<1,000 rpm) and no air conditioning. The second is representative of an extended idle condition 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.

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. The only data available represents a curb idle condition. No data was available to develop the elevated NOx emission rates characteristic of higher engine speed and accessory loading, therefore, the percent increase developed from the 1991-2006 trucks was used.

Extended idle emission rates for 1991-2006 model year heavy duty diesel trucks are based on several studies and 184 tests detailed in Appendix C. The increase in NOx emissions due to higher idle speed and air conditioning was estimated based on three studies that included 26 tests. The average emissions from these trucks using the high idle engine speed and with accessory loading was used for the emission rates for extended idling.

The rates for 2007-and-later were calculated before these vehicles were available and have not been updated for MOVES2014. The 2007 heavy duty diesel emission standards were expected to result in the widespread use of PM filters and exhaust gas recirculation (EGR) and 2010 standards to result in after-treatment technologies. However, since there is no requirement to address extended idling emissions in the emission certification procedure, EPA anticipated little effect on HC, CO, and NOx emissions after hours of idling due to cool-down effects on EGR and most aftertreatment systems. However, we did not expect DPFs to lose much effectiveness during extended idling. As a result, we projected that idle NOx emissions would be reduced 12 percent and HC and CO emissions will be reduced 9 percent from the extended idle emission rates used for 1988-2006 model year trucks. The reduction estimates are based on a ratio of the 2007 standard to the previous standard and assuming that the emission control of the new standard will only last for the first hour of an eight hour idle. For PM, we assumed an extended idling emission rate equal to the curb idling rate (operating mode 1 from the running exhaust analysis). Detailed equations are included in Appendix C.

2.3.3 Results

Table 2-30 shows the resulting NOx, HC, and CO emission rates estimated for heavy-duty diesel trucks from the data analysis. Extended idling measurements have large variability due to low engine loads.

Table 2-30. Mean extended idle emission rates from data analysis (g/hour)

Model Year Groups	NOx	HC	CO	PM
Pre-1990	112	108	84	8.4
1990-2006	227	56	91	4.0
2007 and later	201	53	91	0.2

2.3.4 MOVES Extended Idle Emission Rates

Table 2-31 shows the emission rates used in MOVES for extended idle for diesel MHD and HHD trucks. These are the only regulatory classes in MOVES for diesel combination trucks, which are the only types of trucks with extended idle vehicle activity in MOVES. The emission rates for regulatory class HHD (RegClassID 47) are equal to the mean extended emission rates from Table 2-30 for HC, CO, and NOx. Due to limited data we calculated the MHD (RegClassID 46) extended idle emission rates as half of the extended idle emission rates of the HHD emission rates for HC, CO and NOx. There are no age effects modeled for extended idle emissions in MOVES.

Table 2-31. Extended idle emission rates in MOVES by pollutant and regulatory class (g/hour)

Model Year Groups	HC		CO		NOx	
	MHD	HHD	MHD	HHD	MHD	HHD
1960-1990	54	108	42	84	56	112
1991-2006	28	56	45.5	91	113.5	227
2007+	26.5	53	45.5	91	100.5	201

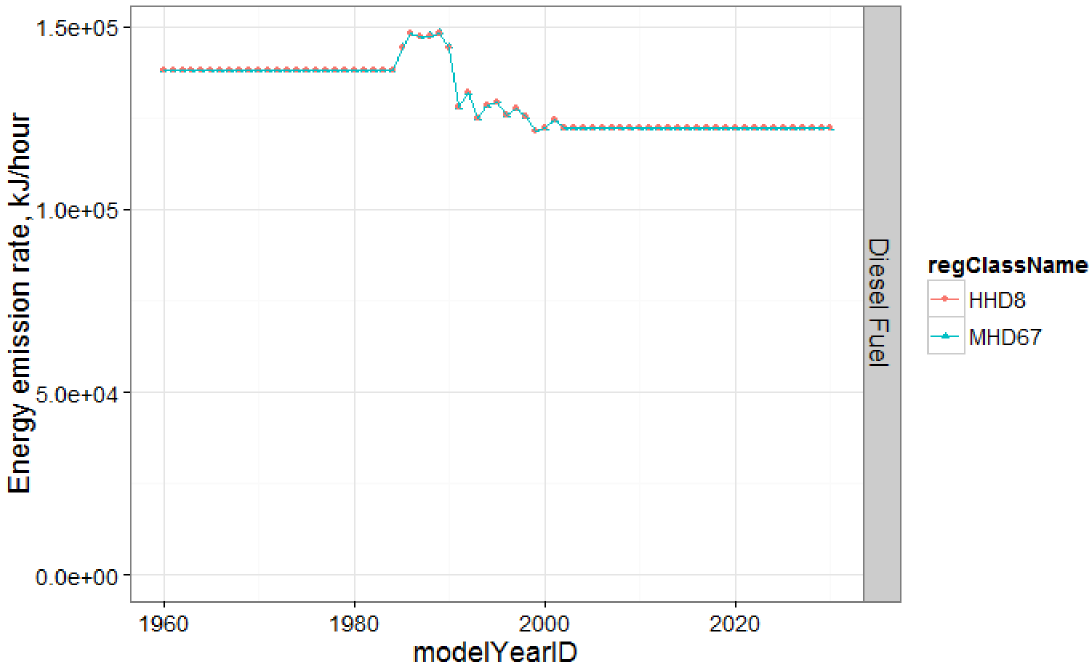
Table 2-32 shows the extended idle PM emission rates in MOVES. MOVES stores PM emission rates according to EC and NonECPM, but the total PM, and EC/PM fraction are reported in Table 2-32 as well. As mentioned previously, the PM2.5 extended idle emission rates are based on curb idle emission rate (operating mode 1 from the running process). Thus, the model year groups for PM are the same model year groups used for running PM emission rates. However, despite the different sources, the PM emission rates used in MOVES are similar in magnitude to the mean PM emission rates calculated from the extended idle studies shown in in Table 2-30.

Table 2-32. Particulate matter emission rates for extended idle emissions

Model Year Groups	Regulatory Class MHD			
	EC	NonECPM	PM	EC/PM
1960 - 1993	1.77	2.44	4.21	42.1%
1994 - 1997	3.07	4.21	7.28	42.1%
1998 - 2002	2.91	4.00	6.91	42.1%
2003 - 2006	2.63	3.60	6.23	42.1%
2007+	0.032	0.288	0.32	9.98%
	Regulatory Class HHD			
	EC	**NonECPM**	**PM**	**EC/PM**
1960 - 1993	1.08	3.13	4.21	25.7%
1994 - 1997	1.66	4.78	6.44	25.7%
1998 - 2002	1.58	4.57	6.16	25.7%
2003 - 2006	1.43	4.13	5.56	25.7%
2007+	0.03	0.31	0.35	9.98%

The extended idle energy emission rates are unchanged from those originally developed for MOVES2004 and are documented in the Energy and Emissions Report[52], and are displayed in Figure 2-38. The extended idle energy consumption rates are the same for both regulatory class MHD67 and HHD diesel vehicles.

Figure 2-38. Extended idle energy emission rates for regulatory class HHD and MHD diesel trucks.



As shown in Table 2-29 above, extended idle is estimated to contribute 1.3% and 4.7% of the energy consumption from regulatory class MHD and HHD diesel vehicles in the United States in calendar year 2011.

2.3.5 Auxiliary Power Unit Exhaust

In MOVES2014, we added a new emission process for auxiliary power unit (APU) exhaust. 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 MOVES default activity assumes APU's are used for 30% hotelling activity for model year 2010 and later trucks[j], with extended idling occurring for the remaining 70% of hotelling activity.[4] Users can

[j] The 2014 Medium and Heavy-duty Greenhouse Gas rulemaking assumed a 30% APU penetration in model years 2010-2014, and 100% APU penetration for 2015 and later. The assumption for APU penetration for 2015 and later was revised in MOVES2014 to continue at 30%.

update the fraction of hotelling activity spent in extended idling, APU usage, and engine off activity as discussed in the MOVES2014 User Guide[62]

The APUs in MOVES are assumed to be Tier 4-compliant, small (<8 kW) nonroad compression-ignition engines. We use the THC, CO, NOx, and $PM_{2.5}$ emission rates from the NONROAD2008 model for this category of nonroad engine to develop the APU emissions rates, as was done in the 2014 Medium and Heavy Duty Greenhouse Gas Rule[47]. The $PM_{2.5}$ emissions were divided into EC (25%) and 75% (nonEC) using fractions similar to the EC/PM split for conventional extended idling exhaust from HHD trucks (Table 2-32). The APU emission rates are displayed in Table 2-33. The APU energy usage (per hour) is 22% of the MOVES extended idle emission rate for 2002 and later trucks, demonstrating the potential energy savings from using an auxiliary power unit.

Table 2-33 – APU emission rates

Pollutant	Emission Rate	Units
THC	6.72	g/hr
CO	36	g/hr
NOx	26.88	g/hr
EC	0.45	g/hr
NonEC	1.35	g/hr
$EC/PM_{2.5}$	25%	%
Total Energy	27171.336	KJ/hr

3 Heavy-Duty Gasoline Vehicles

In MOVES2014, the exhaust emission rates for the MHD and HHD regulatory classes of heavy-duty gasoline vehicles were largely unchanged from MOVES2010. The exhaust emission rates changed for LHD emission rates, to incorporate new data, as well as to develop the appropriate emission rates for the new regulatory classes LHD≤10K (RegClassID 40) and LHD≤14K (RegClassID 41). Also, we updated exhaust and energy rates to account for the impact of new Tier 3 and Heavy-Duty Greenhouse Gas regulations which impacted all the heavy-duty gasoline source types

3.1 Running Exhaust Emissions

3.1.1 HC, CO, and NOx

3.1.1.1 *Data and Analysis for 1960-2007 Model Year Trucks*

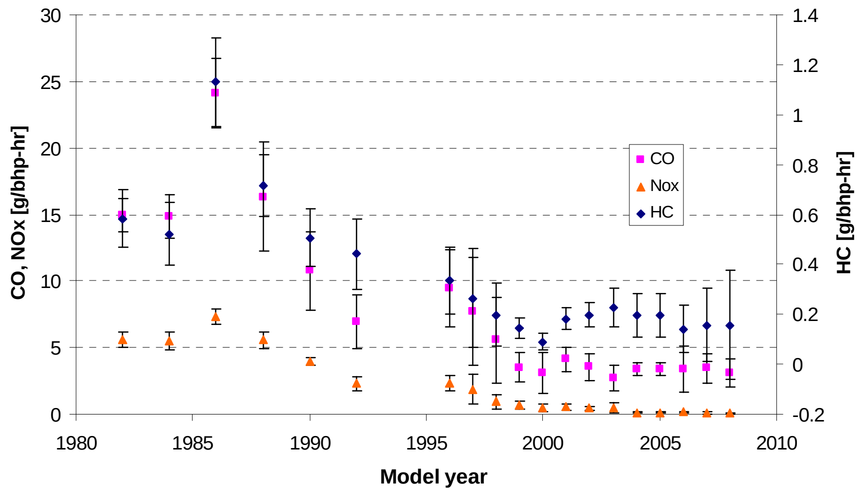
As gasoline-fueled vehicles are a small percentage of the heavy-duty vehicle fleet, the amount of data available for analysis was small. We relied on four medium-heavy duty gasoline trucks from the CRC E-55 program and historical data from EPA's Mobile Source Observation Database (MSOD), which has results 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 meager 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 3.1.1.6.

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, NOx 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

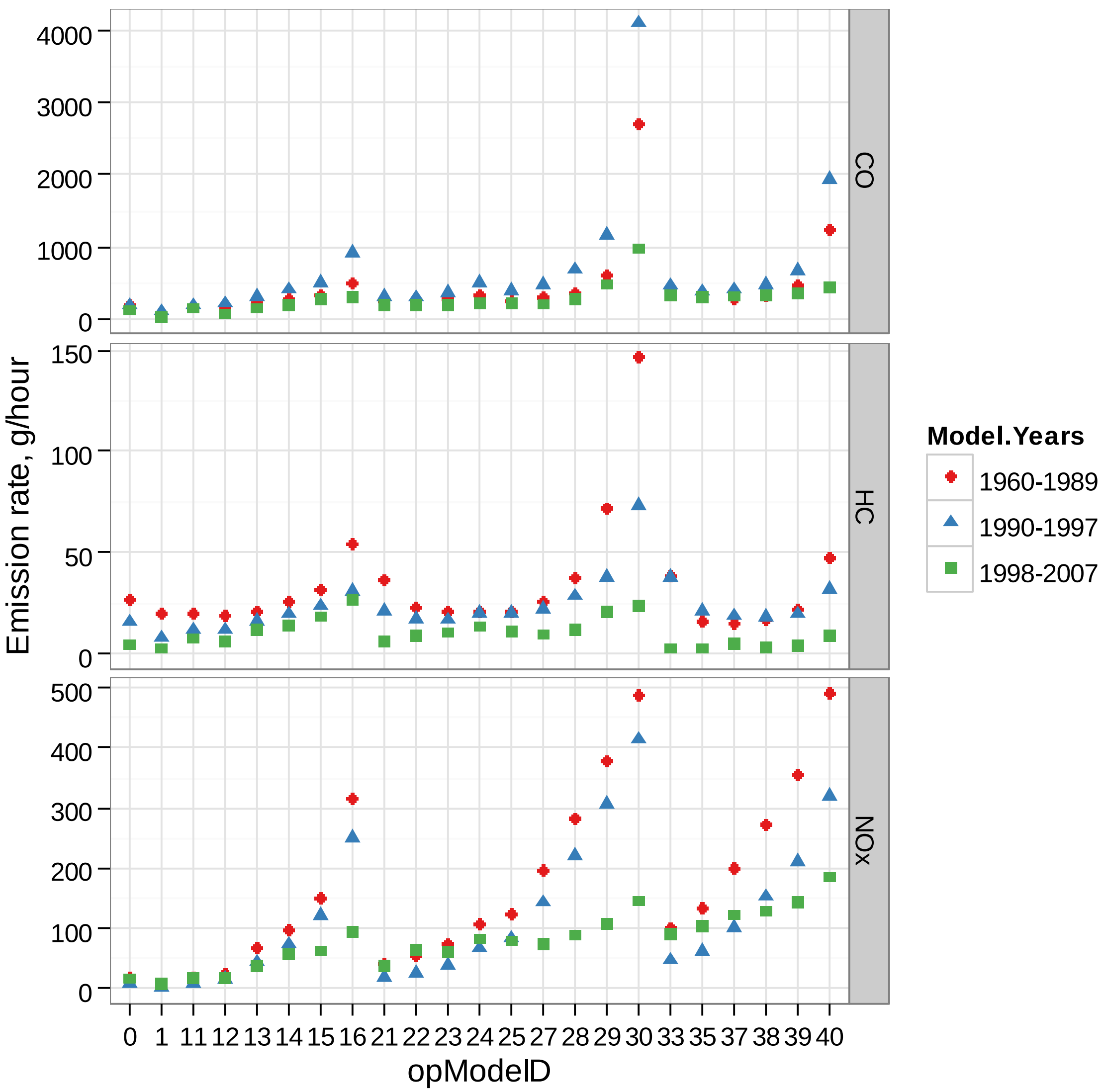


Figure 3-3 shows the emissions trends by age group. Since we did not use the tampering and mal-maintenance methodology as we did for diesels, the age trends reflect our coarse binning with age. For each pollutant, only two distinct rates exist – one for ages 0-5 and another for age 6 and older.

Figure 3-3. Emission rates by operating mode and age group for MY 1998-2007 vehicles in regulatory class LHD ≤10K

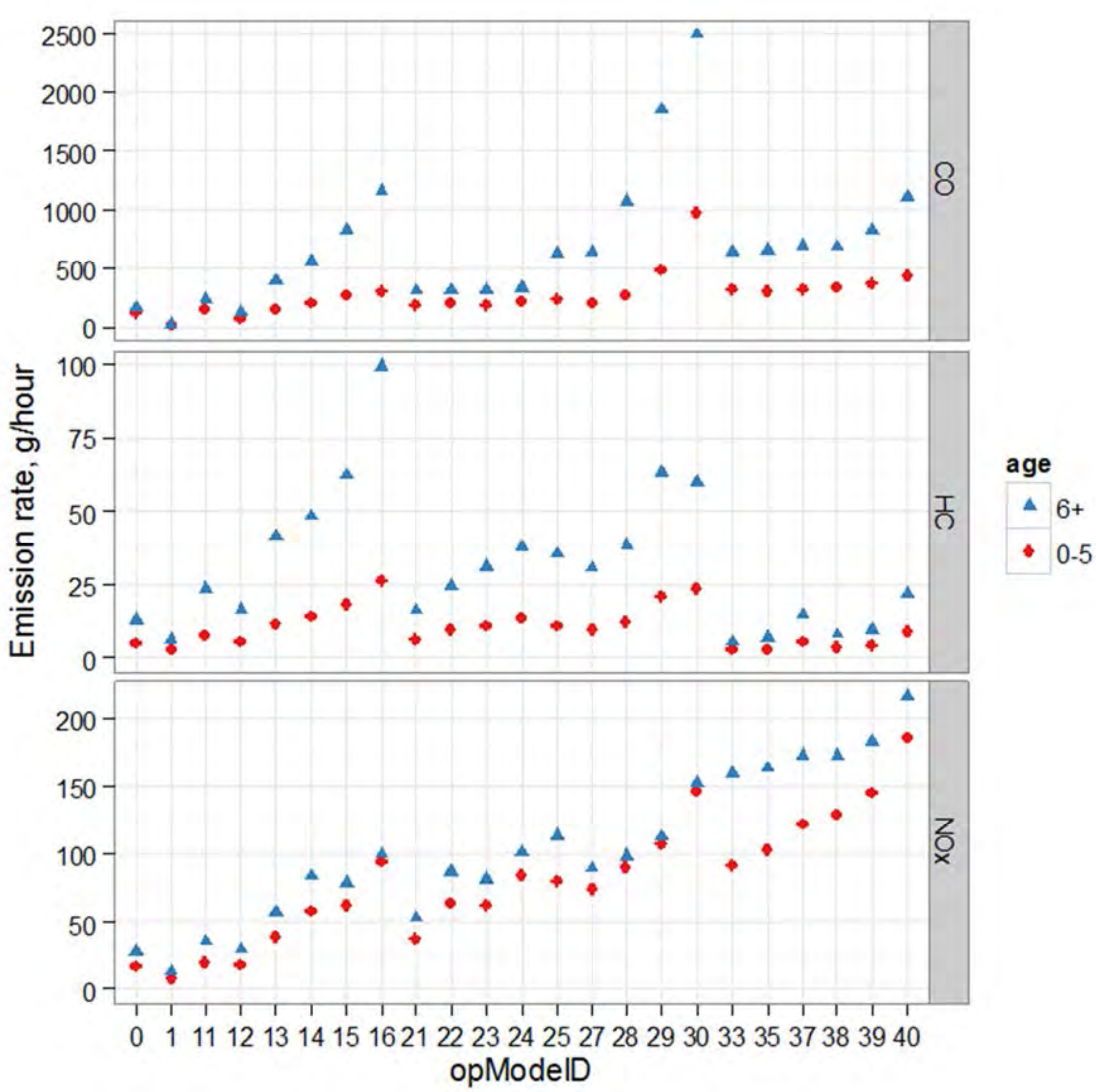


Table 3-2 displays the multiplicative age effects by operating mode for Regulatory Class LHD≤10K vehicles. The relative age effects are derived from the sample of vehicle tests summarized in Table 3-1. The multiplicative age effects are used to estimate the aged emission rates (ages 6+) years from the base emission rates (ages 0-5) for HC, CO, and NOx. 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	NOx
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).[k]

Table 3-3. Useful Life FTP Standards from the Tier 2[63] and 2007 Heavy-Duty Highway[64] Rules

	MDPV (Tier 2 Bin 5)	8.5k – 10K (Class 2B)	10K-14K (Class 3)	Engine Certified[l]
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
NOx	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% of the gasoline 8,500 to 10,000 truck class.[65] In MOVES2014, we project that MDPVs are 15% of total MOVES LHD2b3 regulatory class in MYs 2008 and later. The MOBILE6 document also states that more than 95% of class 2B trucks are chassis certified.[65] Thus, we estimate that 5% 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.[66] This is roughly consistent with recent model year sales totals. [67] Combining these assumptions, we get the sales fractions shown below (Table 3-4).

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[k] This mixture of vehicles was not explicitly considered during the development of MOVES2010.

[l] The FTP differs between engine and chassis certified vehicles. We used adjustment factors described in the MOBILE 6 documentation to convert from g/bhp-hr to g/mile (1.2x), but these adjustment factors may vary in their utility. The small proportion of engine certified vehicles within the population of LHD2b3 trucks dilutes their impact.

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.[m] While the model produces estimates of on-road emissions rather than certification emissions, the weighted certification standard is a useful benchmark for the modeled rates (Table 3-5).[n]

Table 3-5. Aggregate useful life FTP 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),[34] 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.

[m] The engine standard was converted to a g/mile standard using a factor of 1.2 as described in the MOBILE6 report

[n] 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 3-6. 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,[o] 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,[p] 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.

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
NOx	2.04	0.22	9.28

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

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

3.1.1.3.2 Validation against In-Use Verification Program Data

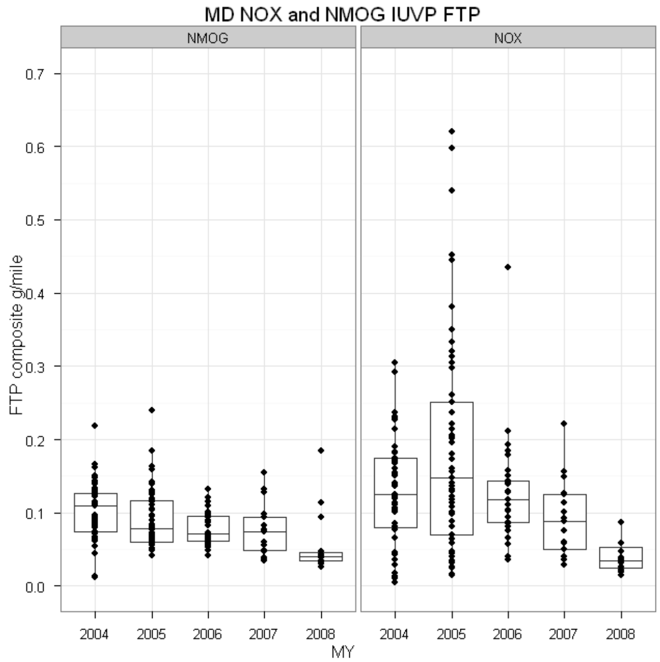
We reviewed In Use Verification Program (IUVP) data for MYs 2004-2008 vehicles (estimated test weights of 7,500 pounds to 10,000 pounds) to determine the appropriateness of the MOVES2010 emission rates.[q] We evaluated whether vehicles during these MYGS were achieving the standard, or if alternate methods 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 3-5) of 0.42 (NMOG) and 0.23 (NOx) in Table 3-8 & Figure 3-4. These ratios indicate that vehicles typically comply with the standard, with a significant amount of headroom.

Table 3-8. Average compliance margin and headroom for LHD2b3 trucks

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

[q] 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.[r] 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

Given that (a) the MOVES2010 LHD2b3 emission rates are significantly above the calculated aggregate standard, and (b) the IUVP data shows that most light-heavy 2b trucks achieve the standard, we calculated new MOVES2014 HC/CO/NOx emission rates for regulatory Class LHD≤10K (RegClassID 40) vehicles in 2008 and later MYs.

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.[8] 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.[8] Because we are basing the emission rates on light-duty emission rates

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

(which are also VSP-based), the emission rate update is limited to regulatory class LHD≤10K (RegClassID 40) vehicles.

We scaled the modal data from Tier 2 Bin 8 vehicles by the ratio of FTP standards[s] so that the rates would be consistent with the higher emission rates of regulatory class LHD≤10K (RegClassID 40) vehicles.

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
NOx	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.[8] 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	NOx
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.

[s] 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%, 28%, and 25% 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.

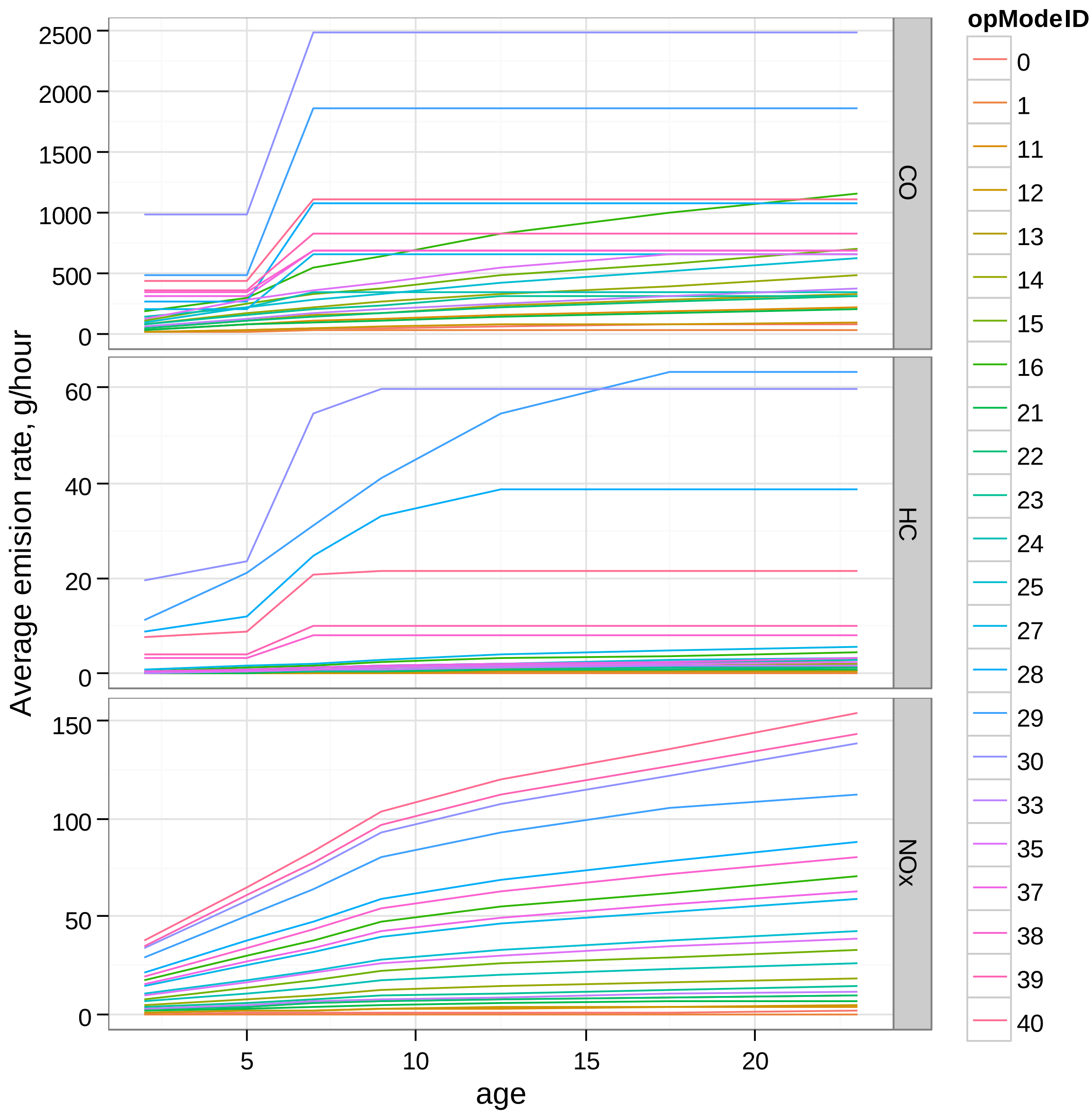
Table 3-11. Multiplicative age effect used for running emissions for regulatory class LHD≤10K (RegClassID 40) 2008+ model years.

ageGroupID	HC	CO	NOx
3	1	1	1
405	1.95	2.31	1.73
607	2.80	3.08	2.21
809	3.71	3.62	2.76
1014	4.94	4.63	3.20
1519	5.97	5.62	3.63
2099	7.20	6.81	4.11

After applying the 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. 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 NOx emission rates were impacted by this step. Figure 3-5 shows the regulatory class LHD≤10K (RegClassID 40) model year 2008-2017 emission rates for CO, HC, and NOx. 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 NOx 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 NOx 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 NOx, 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%
NOx	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% 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.

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

Table 3-13. Composite FTP NMOG+NOx 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.

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

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.[t] The rates for MY2022 were estimated as equivalent to light-duty rates, assuming a fleet composition of 10% Bin 8 and 90% 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 3-2 was performed for all rates across all operating modes and ageGroups.

Resulting rates for HC, CO and NOx are shown in Figure 3-6, Figure 3-7, and Figure 3-8 respectively.

[t] The database version used was MOVESt3DB20110331.

Figure 3-6. THC: running-exhaust emission rates for vehicles in the LHD≤10K regulatory class (regClassID 40), during the Tier-3 phase-in.

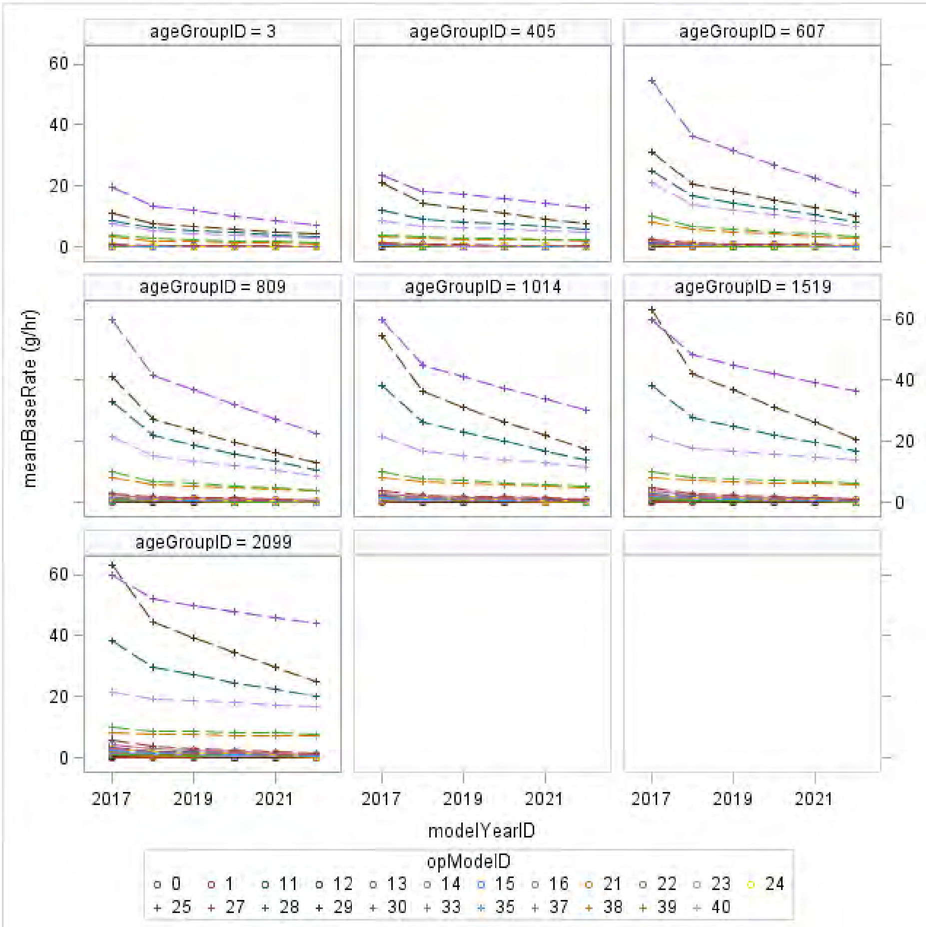


Figure 3-7. CO: running-exhaust emission rates for vehicles in the LHD≤10K regulatory class (regClassID 40), during the Tier-3 phase-in.

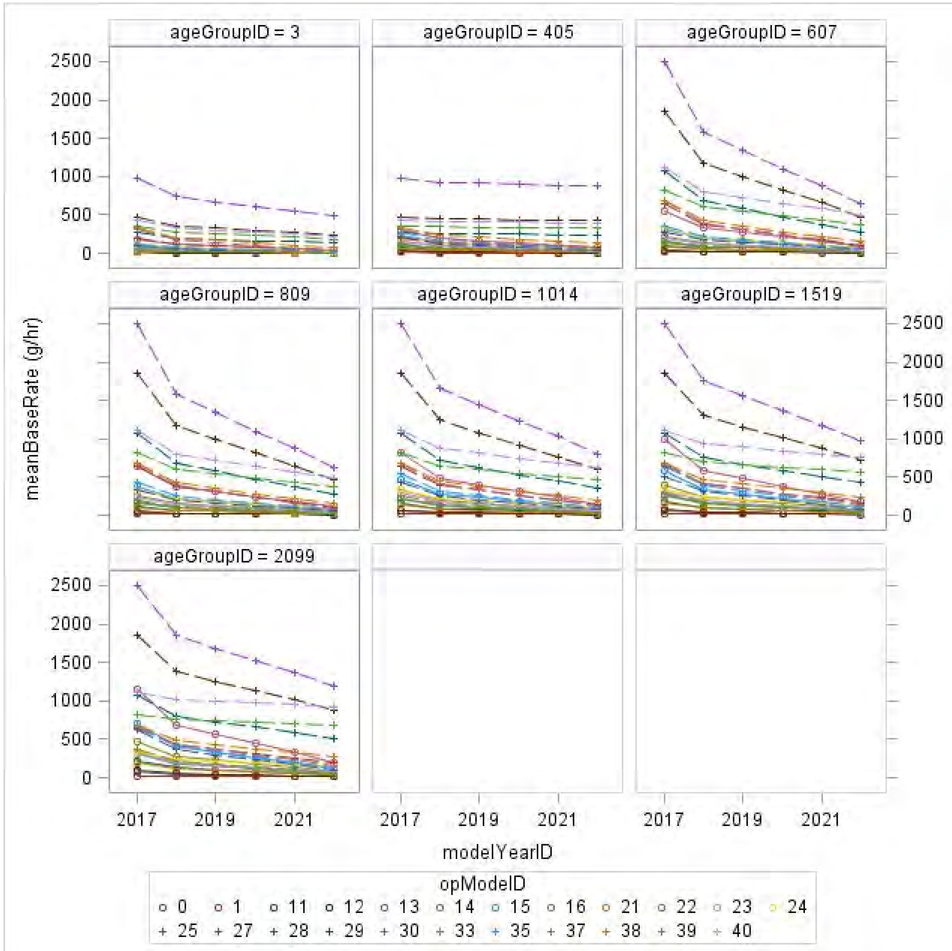


Figure 3-8. NO_x: running-exhaust emission rates for vehicles in the LHD≤10K regulatory class (regClassID 40), during the Tier-3 phase-in.

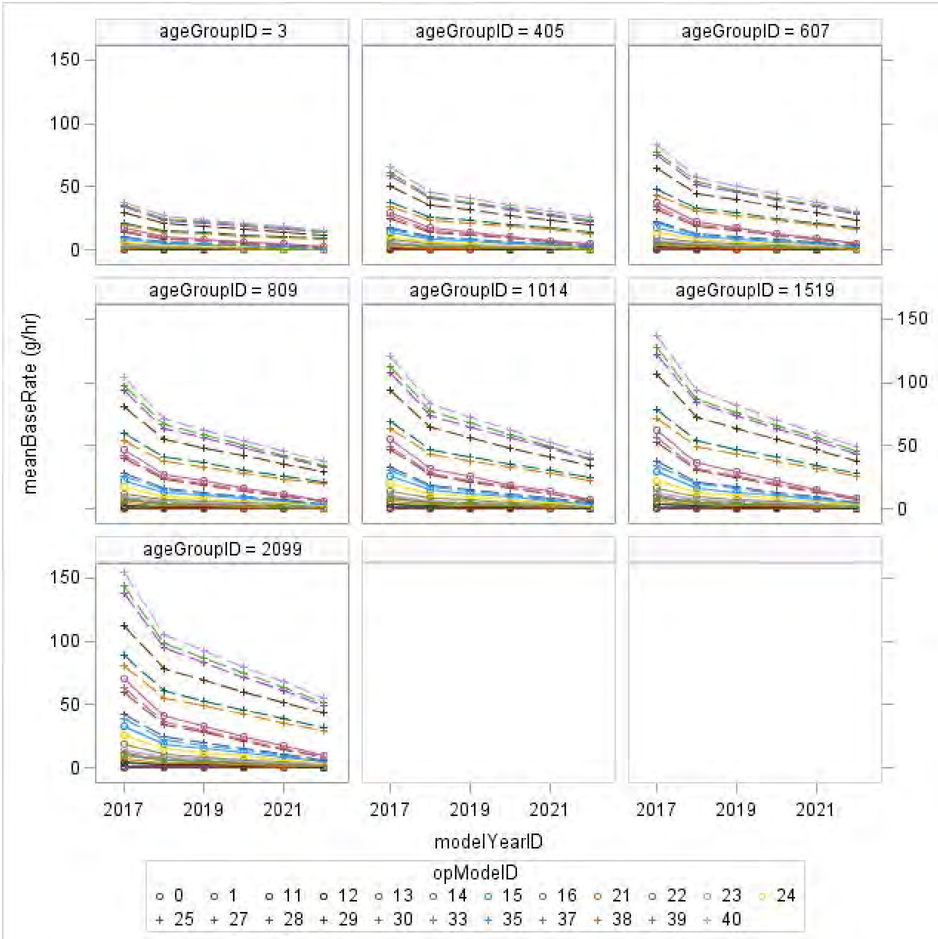
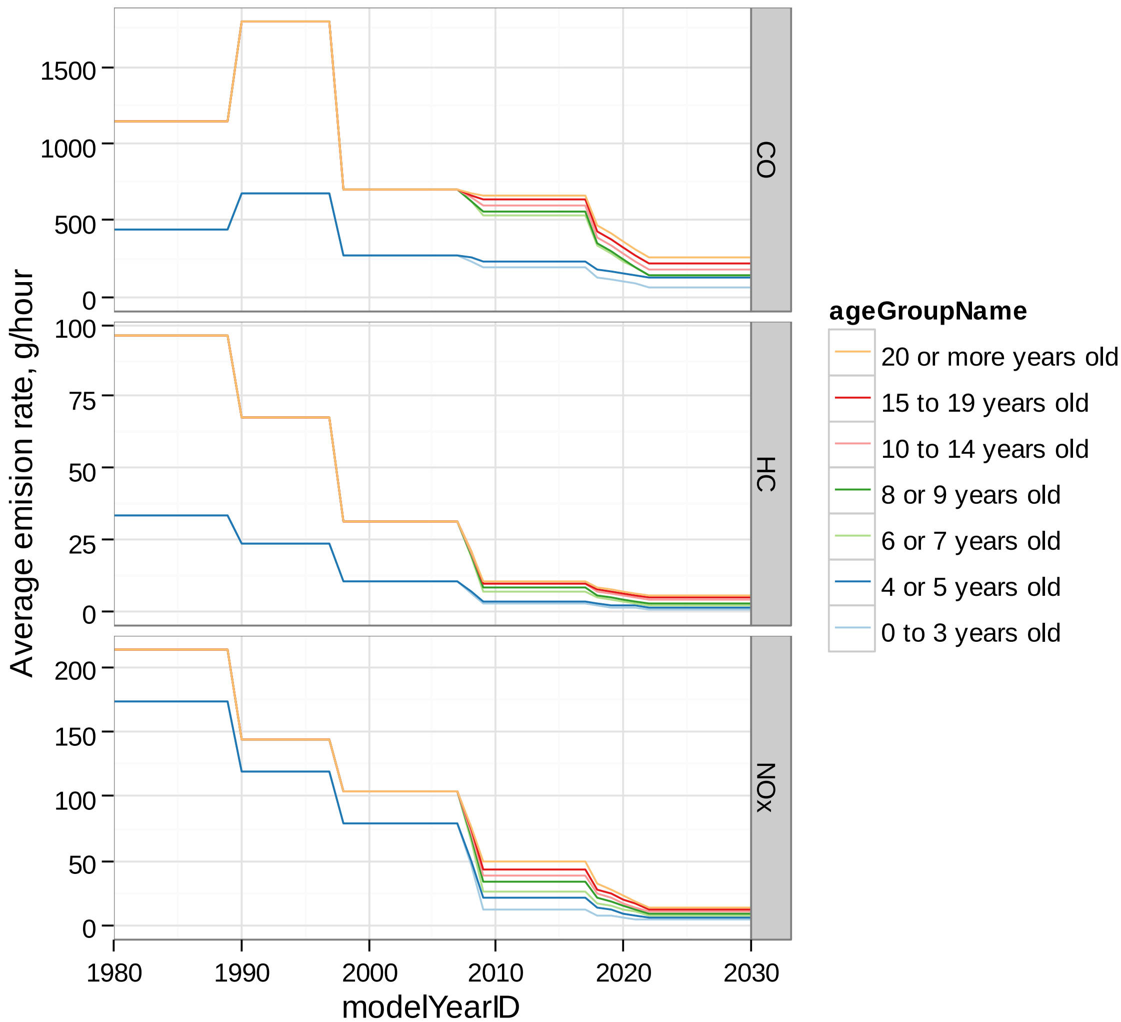


Figure 3-9 summarizes the decreasing trend in emissions from the analysis documented in this chapter, showing the average emission rates (across all operating modes) for CO, HC, and NOx for the 1980 to 2007 model years for LHD≤10K vehicles. Note that the 1980 rates are used for all model years 1960-1980, 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 NOx. 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 3-1. 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 NOx 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

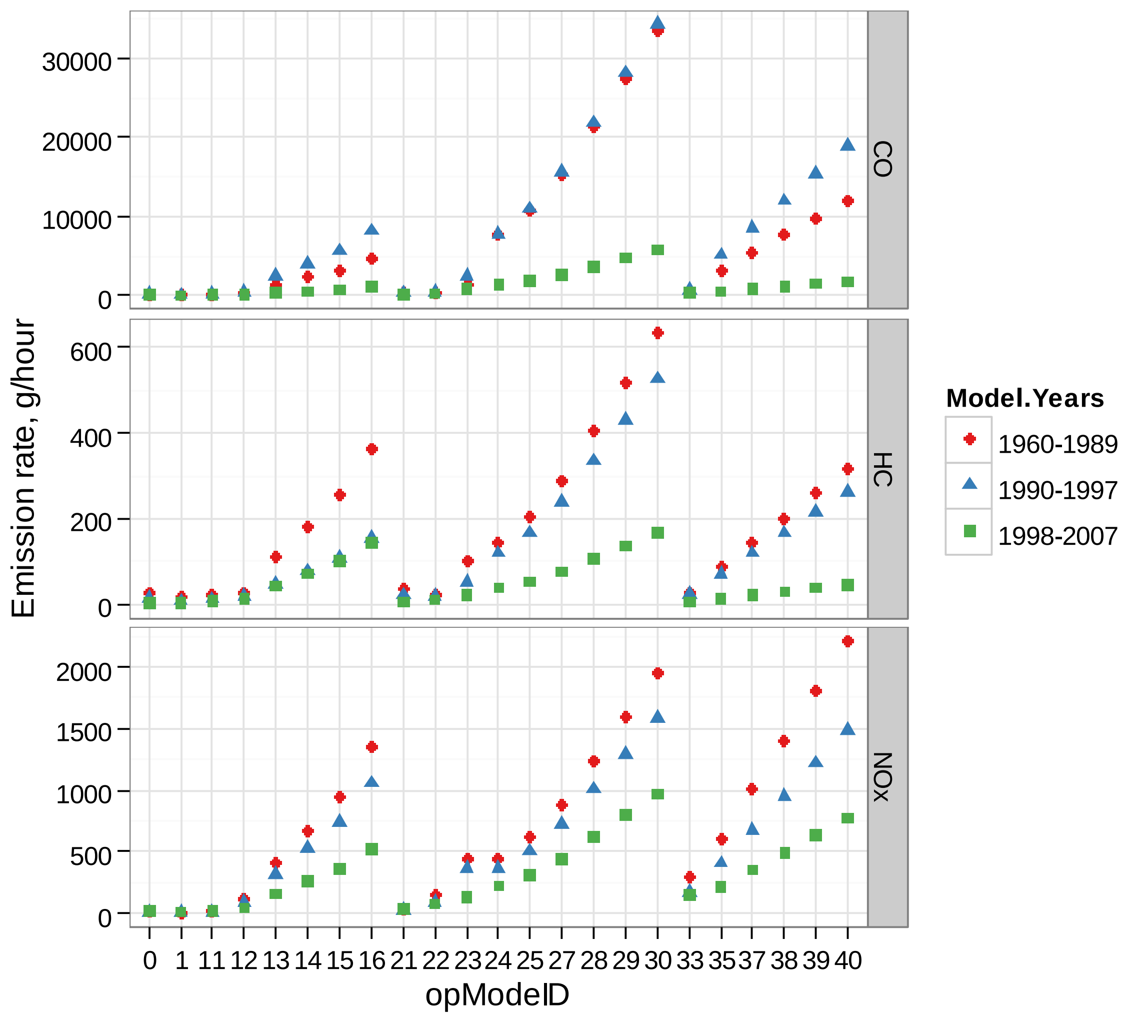


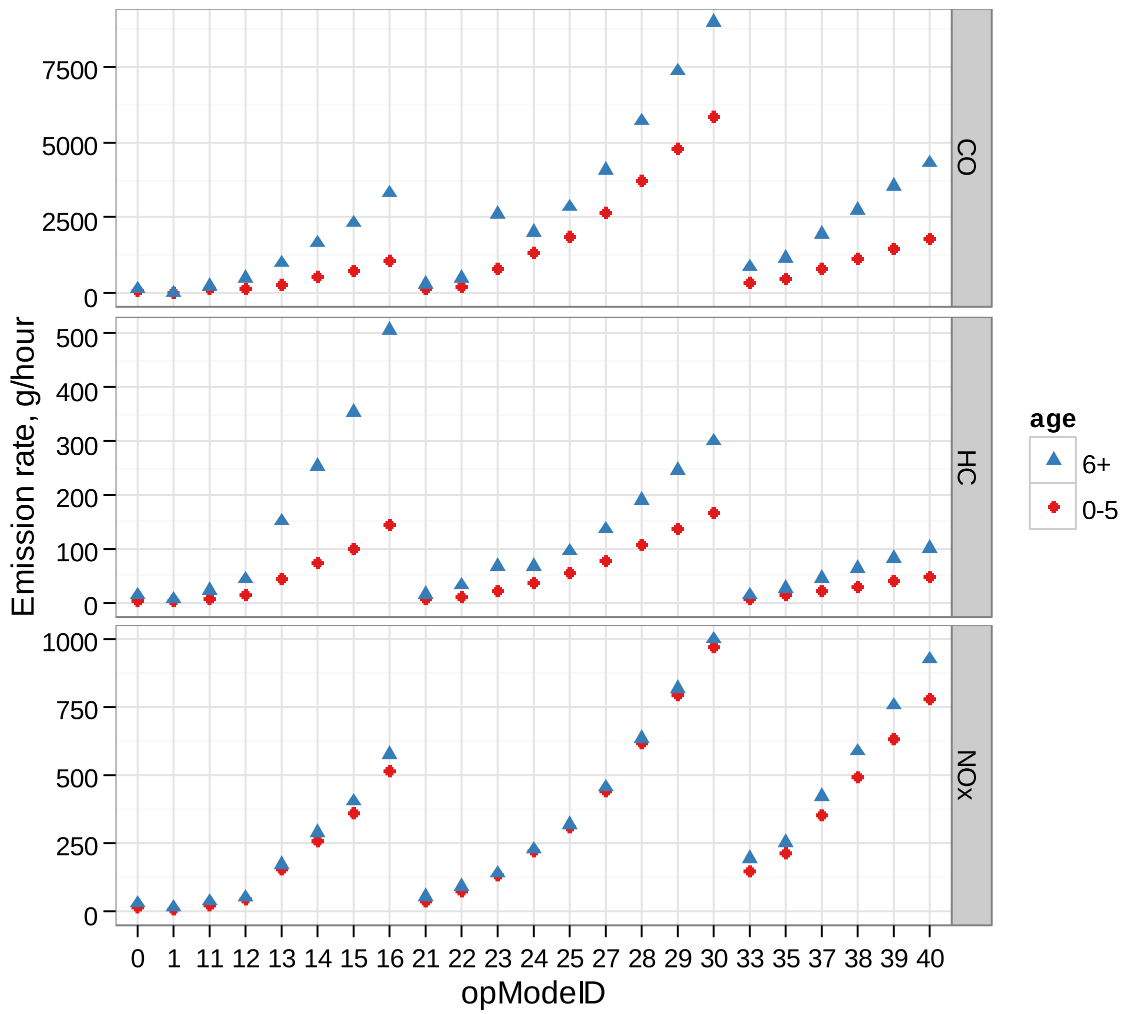
Table 3-17 displays the multiplicative age effects by operating mode for LHD<14K, LHD45, MHD, and HHD gasoline vehicles. While these age effects were derived from the same data as those for the LHD≤10K vehicles, these heavy-duty age effects are slightly different for these vehicles, because the operating 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	NOx
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 on-road heavy duty vehicles GVW class 4 and above, a relatively small fraction are powered by gasoline: about 15% are gasoline, as opposed to 85% diesel.[u] 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[68] The 2008 and later model years are modeled with a 70% reduction in the running rates starting in MY 2008, which is consistent with the emission standard reduction with the "Heavy-duty 2007 Rule".[69] 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% 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 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. Note also that start rates for the two regulatory classes are identical, as they are not defined in terms of STP.

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[u] 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).

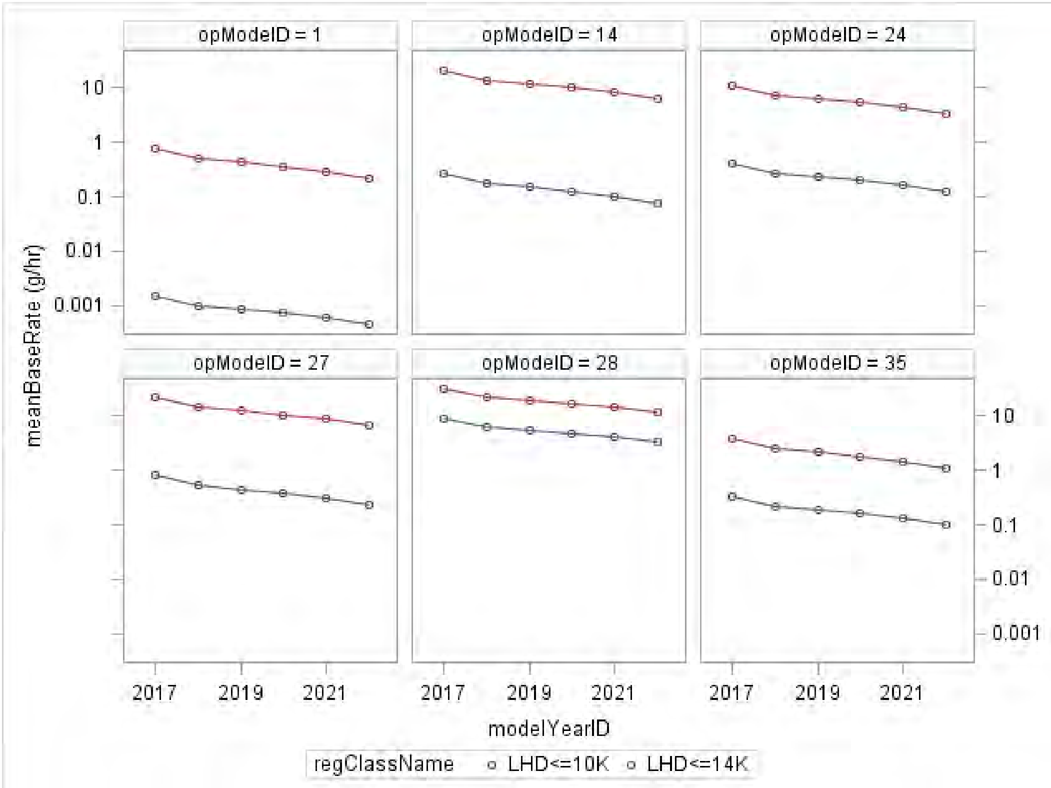


Figure 3-13. NO_x emission rates vs. model year for regulatory classes LHD≤10K and LHD≤14K, showing selected operating modes for the running exhaust process (Note the logarithmic scale).

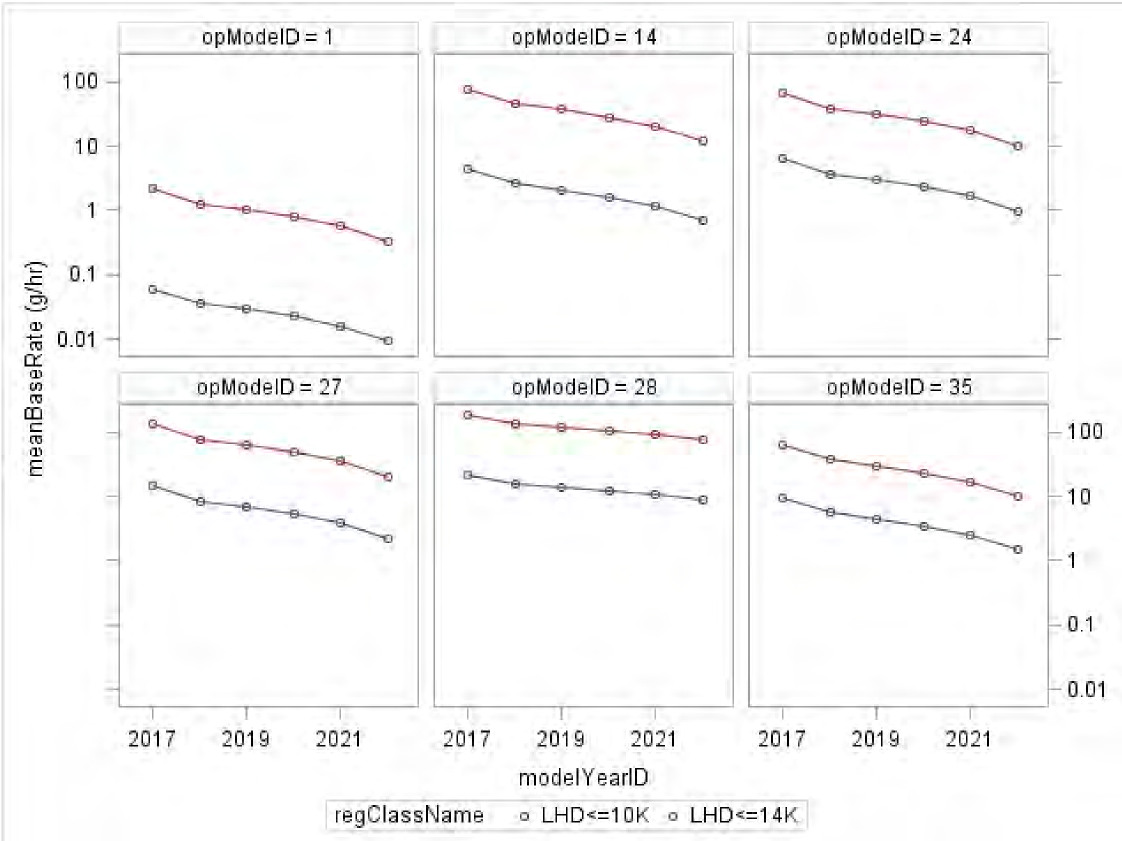
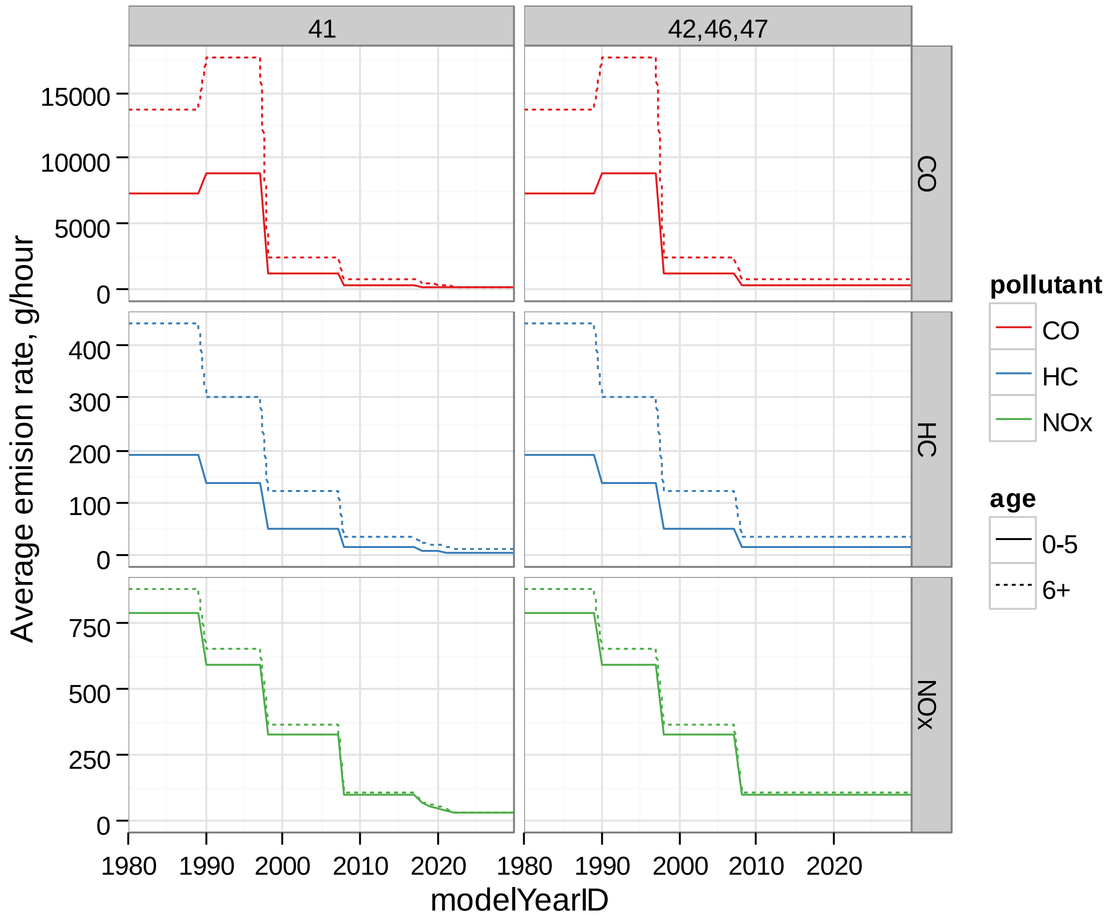


Figure 3-14. Average emission rate (across all operating modes) for regulatory class LHD≤14K, LHD45, MHD and HHD (RegClassIDs 41,42,46 and 47) for CO, HC, and NOx. Emission rates for 1960-1989, and 2022 – 2050 are constant.



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 MOVES2010 and MOVES2014, 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, because the HD 2007 Rule PM standards are not expected to change in-use emissions for medium and heavy-duty gasoline vehicles. As presented in the next section, the MOVES2014 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[69].

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 MOVES 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:

$$Ratio_{final} = Ratio_{older} WtFrac + Ratio_{newer}(1 - WtFrac)$$

$$= 1.679\times0.75 + 0.578\times0.25 = \mathbf{1.40}$$

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[8] , the PM emission rates for light-duty vehicles were revised in MOVES2014. 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. Hence, a comparison of PM emission rates in MOVES2014 between light-duty, and LHD≤ 10K, will yield a different ratio than the 1.4 derived for MOVES2010b.

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.

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

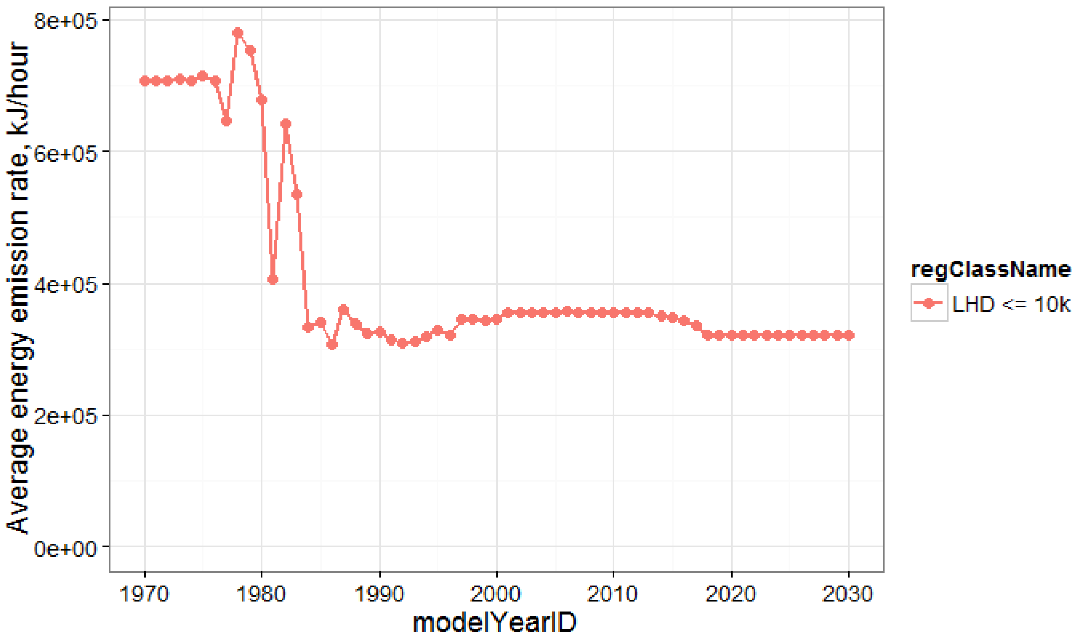
3.1.3.1 *LHD≤10K Energy Rates for Model Years 1960-2013*

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[45].

3.1.3.2 *LHD≤10K Energy Rates for Model Years 2014-2050*

For model years 2014 and later, 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 2.1.4.4. The CO_2 emission reductions for gasoline 2b trucks in Table 2-20 were applied to the 2013 model year energy consumption rates in each running operating mode bin to derive 2014 and later energy consumption rates. Figure 2-31 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 2018 to 2050.

Figure 3-15. Average Energy Consumption Rates for LHD≤10K gasoline vehicles across all running operating modes[v]

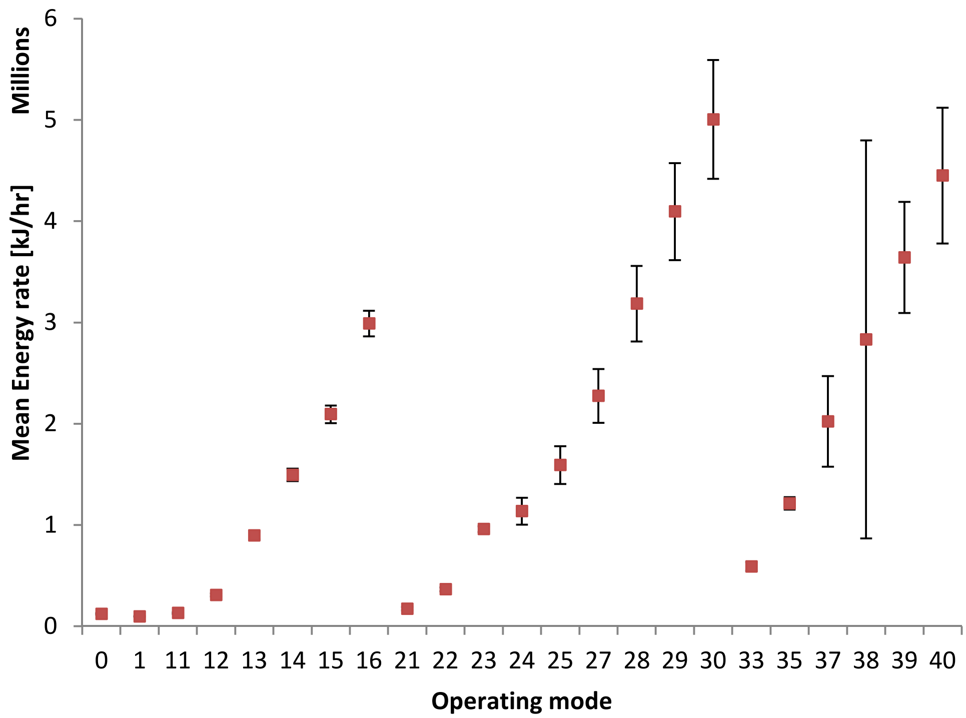


[v] *Note, this figure displays a straight average across all operating modes, and thus emphasizes the energy used in the operating modes with highest energy consumption. At run time MOVES actually computes emissions based on an operating mode distribution determined by VMT allocation by roadtype and speed as well as sourcetype mass. See the MOVES Vehicle Population and Activity report[4] 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 heavy-duty running exhaust gasoline rates were the same as those used for HC, CO, and NO_x. However, new energy rates were only developed for LHD≤14K, LHD45, MHD, and HHD regulatory classes. 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 2-20). 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)



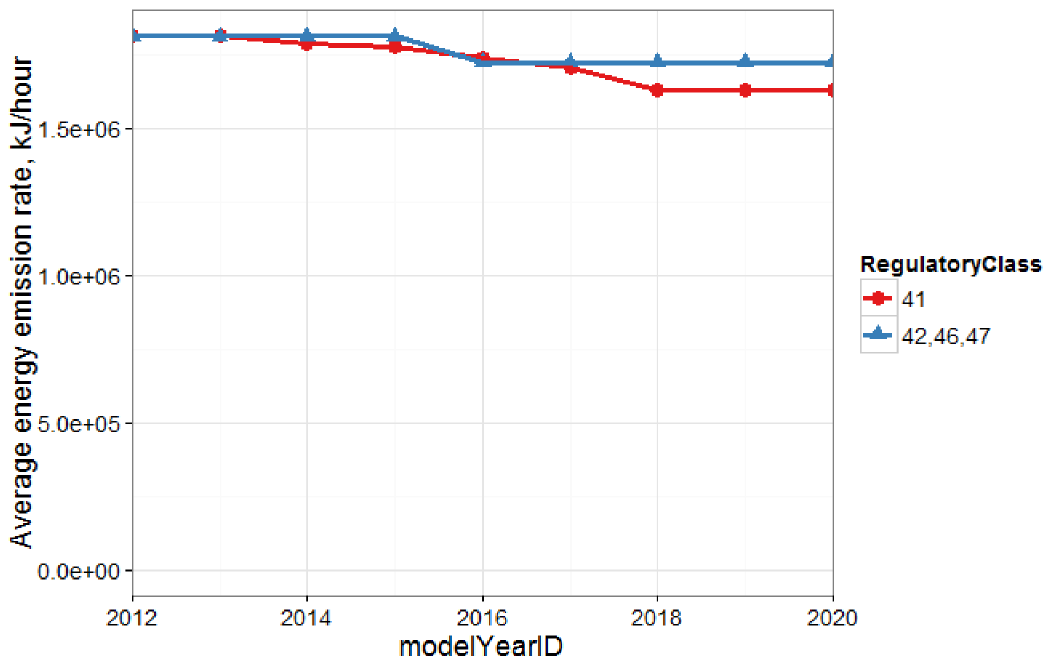
A linear extrapolation to determine rates at the highest operating modes in each speed range was performed analogously to diesel energy and NO_x rates (see Section 2.1.1.4.1).

3.1.3.4 *Energy Rates for LHD≤14K (2014-2050), LHD45, MHD, and HHD (2016-2050)*

Updates to the rates displayed in Figure 3-16 were made to the heavy-duty gasoline energy rates for model years 2014+ based on the 2014 Medium and Heavy-duty Greenhouse Gas Rule[47] as discussed in Section 2.1.4.4. 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). For LHD≤14K the energy rates are constant 2018 going forward, for the other categories (LHD45, MHD, HHD) the energy rates are constant going forward starting in model year 2017.

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[v]



3.2 Start Emissions

3.2.1 Emissions Standards

Emissions standards for the Federal Test Procedure (FTP) are shown in Table 3-20 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 3-20. 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.

3.2.2 Available Data

To develop start emission rates for heavy-duty gasoline-fueled vehicles, we extracted data available in the USEPA Mobile-Source Observation Database (MSOD). 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 lb, placing all trucks in the MOVES2010b LHD2b3 regulatory class. In MOVES2014, 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 3-21 shows the model-year by age classification for the data. The model year groups in the table were designed based on the progression in NOx standards between MY 1990 and 2004. Standards for CO and HC are stable over this period, until MY 2004, when a combined NMHC+ NOx standard was introduced. However, no measurements for gasoline HD trucks were available for MY2004 or later.

Start emissions are not dependent on power, and 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 3-21. Availability of emissions start data by model-year group and age group. NOTE: this table represents vehicles with GVWR < 14,000 lb.

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

3.2.3 Estimation of Mean Rates

As with light-duty vehicles, we estimated the "cold-start" as the mass from the cold-start phase of the FTP (bag 1) less the "hot-start" phase (Bag 3). As a preliminary exploration of the data, we averaged by model year group and age group and produced the graphs shown in Appendix F.

Sample sizes are small overall and very small in some cases (e.g. 1990, age 6-7) and the behavior of the averages is somewhat erratic. In contrast to light-duty vehicle emissions, strong model-year effects are not apparent. This may not be surprising for CO or HC, given the uniformity of standards throughout. This result is more surprising for NOx but model year trends are no more evident for NOx than for the other two. Broadly speaking, it appears 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

$$\bar{x}_g = e^{\ln \bar{x}_l} \quad \textbf{Equation 3-3}$$

This measure is not appropriate for use as an emission rate, but is useful in that it represents the "center" of the skewed parent distribution. As such, it is 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 suggests that emissions distributions should be strongly skewed, this result implies that these data are not representative of "real-world" emissions for these vehicles. This conclusion appears to be reinforced by the values in Figure F-3 which represent the "logarithmic standard deviation" calculated by model-year and age groups. This measure (s_l), is the standard deviation of natural logarithm of emissions (x_l). The values of s_l are highly variable, and generally less than 0.8, showing that the degree of skew in the data is 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 confirms 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 allows 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.

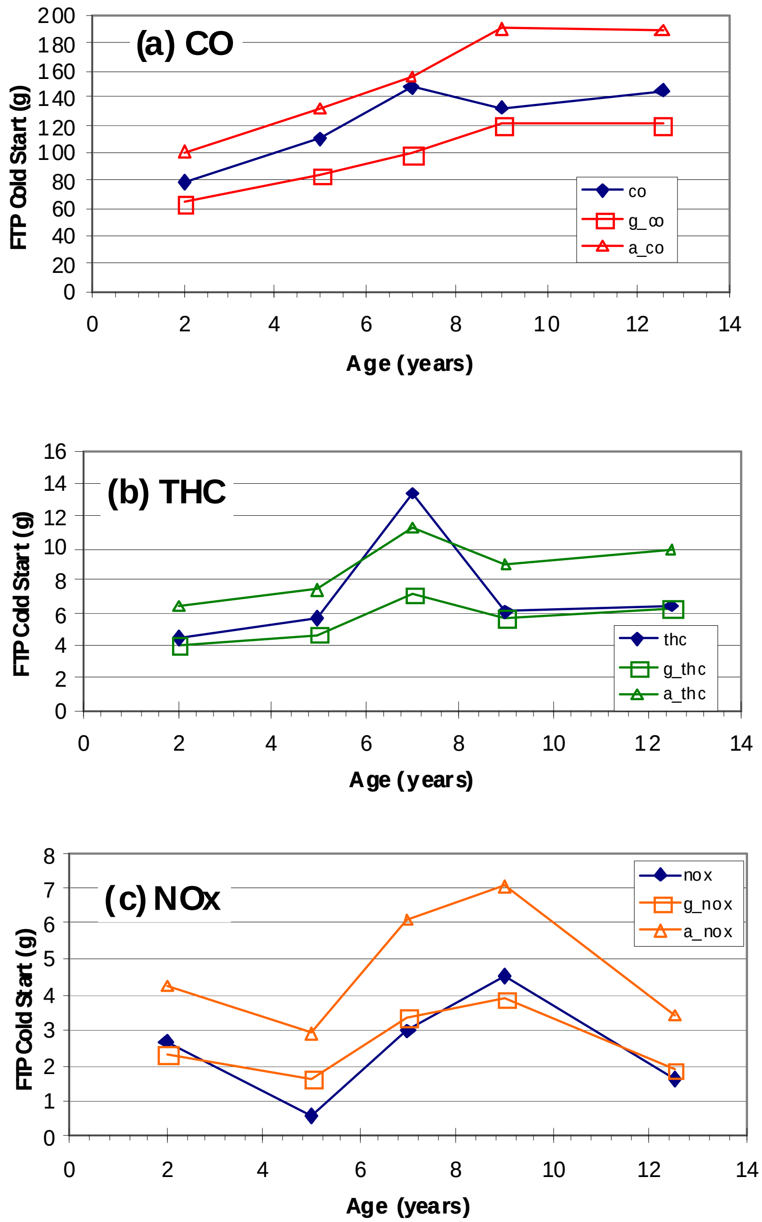
The re-estimated arithmetic means are calculated from the geometric means, by adding a term that represents the influence of the "dirtier" or "higher-emitting" vehicles, or the "upper tail of the distribution," as shown in Figure F-4.

$$\bar{x}_a = \bar{x}_g e^{\frac{s_l^2}{2}}$$ **Equation 3-4**

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)



3.2.4 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 3-5.

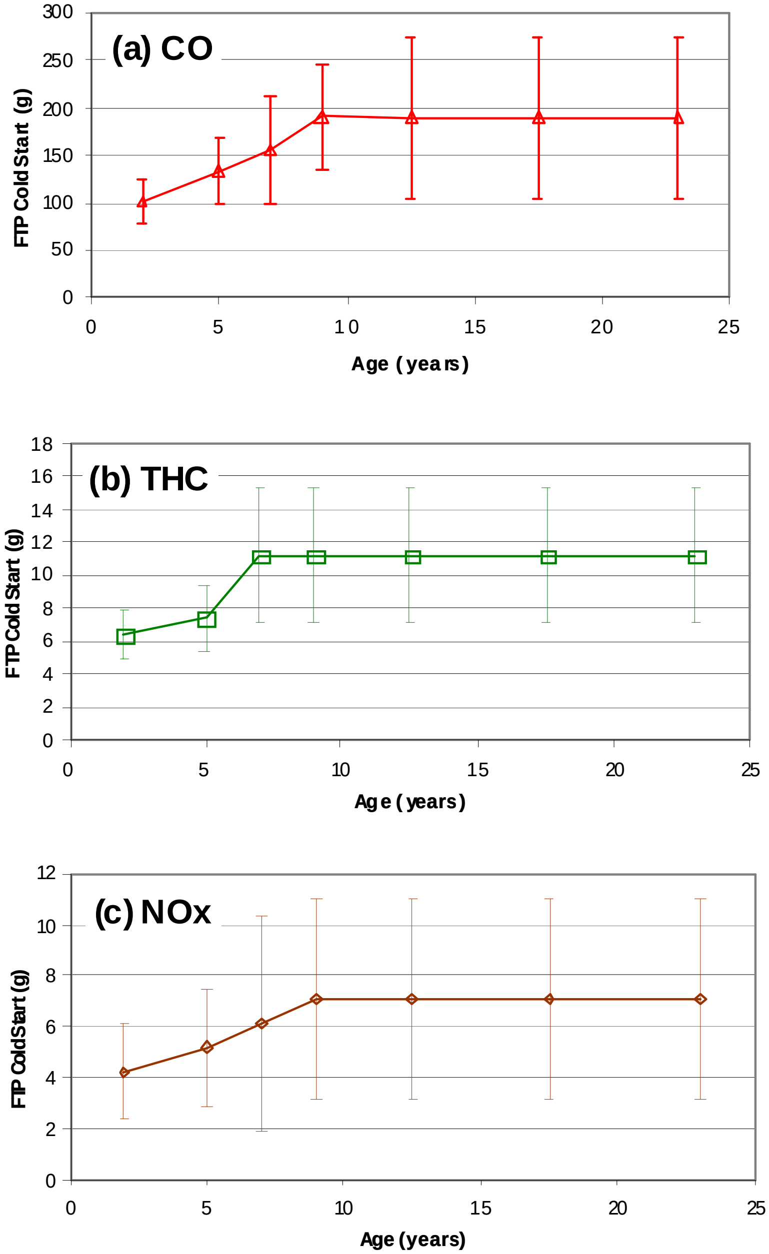
$$s = \sqrt{x_g^2 \, e^{s^2} (e^{s^2} - 1)}$$ **Equation 3-5**

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 3-22 and in Figure 3-19. Note that these results represent only "cold-start" rates (opModeID 108).

Table 3-22. 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**	**NOx**
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% confidence intervals



3.2.5 Projecting Rates beyond the Available Data

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.

3.2.5.1 *Regulatory class LHD≤10K and LHD≤14K (RegClassID 40 and 41)*

For CO the approach was simple. We applied the values in Table 3-22 to all model-year 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 NOx we imputed values for the 2005-07 and 2008-2017 model-year groups by multiplying the values in Table 3-22 by ratios expressed in terms of the applicable standards. Starting in 2005, a combined HC+NOx standard was introduced. It was necessary for modeling purposes to partition the standard into HC and NOx components. We assumed that the proportions of NMHC and NOx would be similar to those in the 2008 standards, which separate NMHC and NOx while reducing both.

We calculated the HC value by multiplying the 1960-2004 value by the fraction f_{HC}, where

$$f_{HC} = \frac{\left(\frac{0.14\ \text{g/hp-hr}}{(0.14+0.20)\ \text{g/hp-hr}}\right)(1.0\ \text{g/hp-hr})}{1.1\ \text{g/hp-hr}} = 0.37 \qquad \textbf{Equation 3-6}$$

This ratio represents the component of the 2005 combined standard attributed to NMHC. We calculated the corresponding value for NO_x as

$$f_{NOx} = \frac{\left(\frac{0.20\ \text{g/hp}-\text{hr}}{(0.14+0.20)\ \text{g/hp}-\text{hr}}\right)1.0\ \text{g/hp-hr}}{4.0\ \text{g/hp-hr}} = 0.147 \qquad \textbf{Equation 3-7}$$

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 3-23.

Table 3-23. 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 vehicles from the Light-Duty Emission Rate Report.[8]

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

3.2.5.2 *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 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.

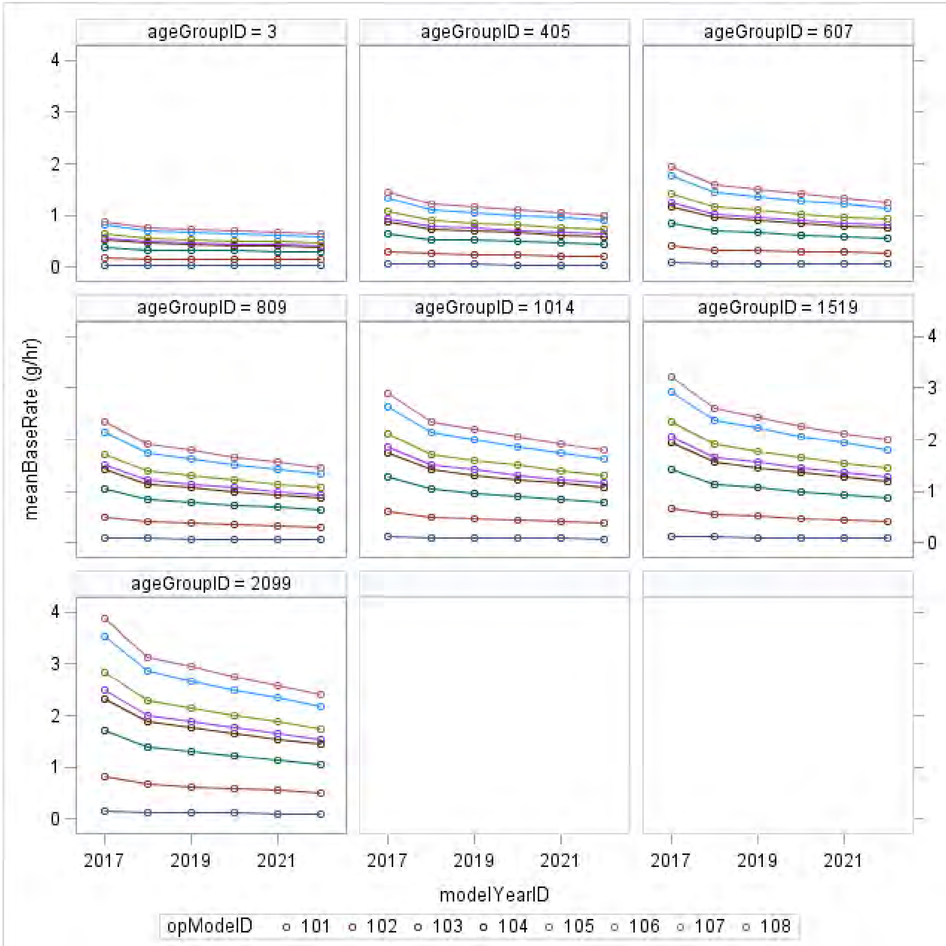


Figure 3-21. CO: Emission rates for the cold start-exhaust process, for the LHD≤10K (RegClassID 40) and the LHD≤14K (RegClassID 41) regulatory classes, by operating mode and age group, during the Tier-3 phase-in.

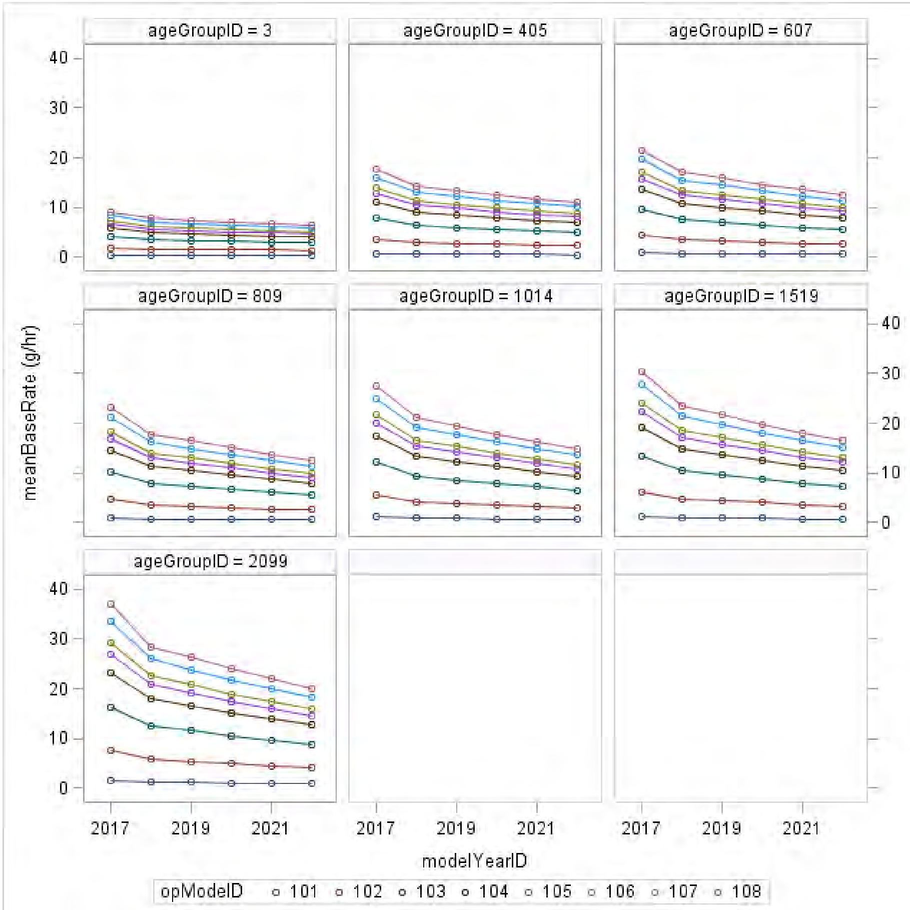
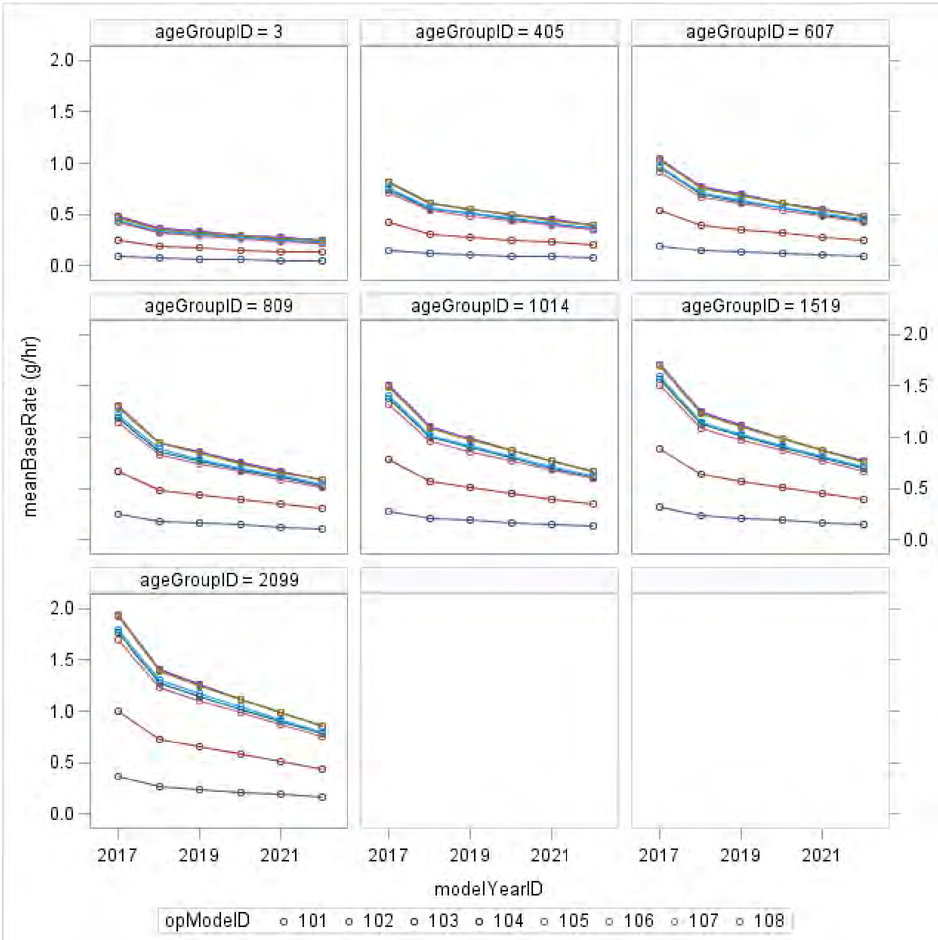


Figure 3-22. NO$_x$: Emission rates for the cold start-exhaust process, for the LHD≤10K (RegClassID 40) and the LHD≤14K (RegClassID 41) regulatory classes, by operating mode and age group, during the Tier-3 phase-in.



3.2.5.3 *Regulatory classes LHD45, MHD, and HHD*

Since continuous data were lacking for vehicles in classes LHD45 and MHD, we estimated cold start values relative to the LHD2b3 start emission rates estimated in MOVES2010.

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

$$f_{CO} = \frac{37.1 \text{ g/hp - hr}}{14.4 \text{ g/hp - hr}} = 2.58 \qquad \textbf{Equation 3-8}$$

and the corresponding ratio for HC for 1990-2004 model year vehicles is 1.73.

$$f_{HC} = \frac{1.9 \text{ g/hp - hr}}{1.1 \text{ g/hp - hr}} = 1.73 \qquad \textbf{Equation 3-9}$$

The ratios derived in the previous two equations (2.58 and 1.73) are applied to estimate the start emission rates for the first three model year groups for the LHD45, MHD, and HHD gasoline vehicles (Table 3-24). Note that the ratios for CO and HC do not vary by model year group because the standards do not; See Table 3-20 (page 119).

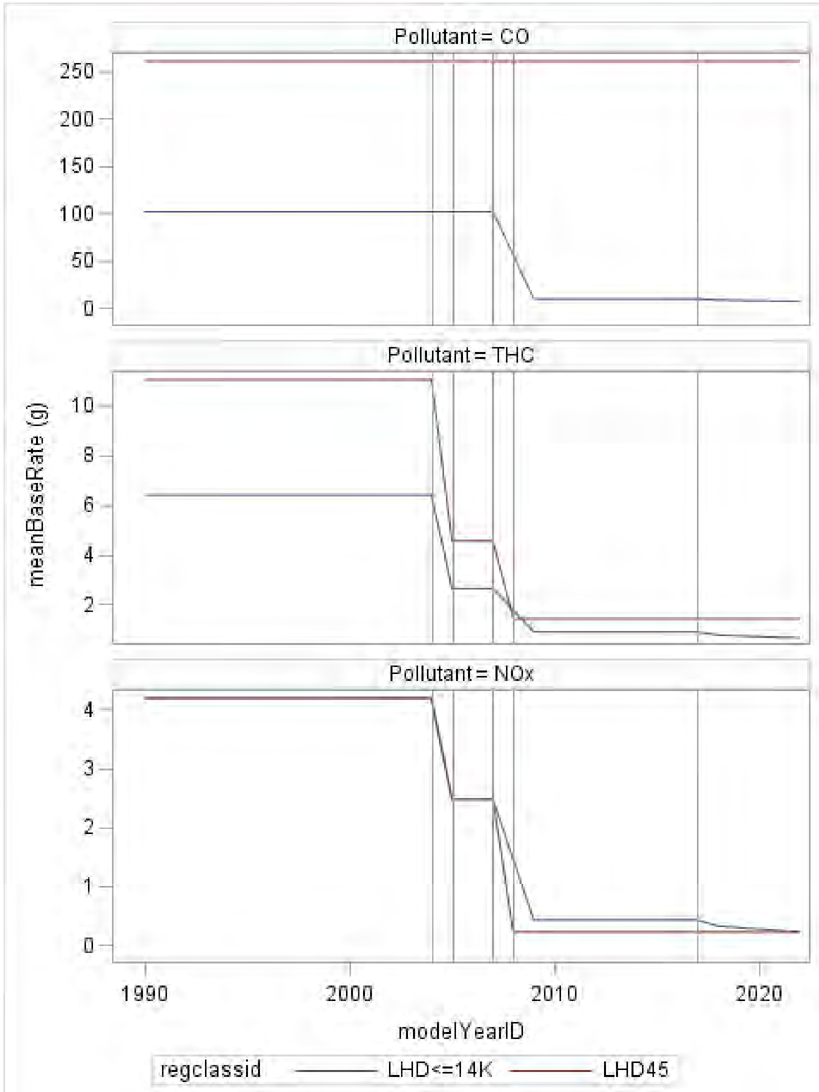
For NO_x, all MOVES2014 start emissions for medium and heavy-duty vehicles are equal to the MOVES2010 LHD2b3 start emission rates, because the same standards apply to both classes throughout. The approaches for all three regulatory classes in all three model years are summarized in Table 3-24.

The outcomes of the methods described in the table are summarized graphically in Figure 3-24 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 lb.

Table 3-24. 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 3-22	Values from Table 3-22	Values from Table 3-22
	2005-2007	Values from Table 3-22	Reduce in proportion to standards from 1960-2004	Reduce in proportion to standards from 1960-2004
	2008 - 2017	Values from Table 3-22	Section 3.2.5.1	Section 3.2.5.1
	2018 +	Section 3.2.5.2	Section 3.2.5.2	Section 3.2.5.2
LHD45, MHD, HHD	1960-2004	Increase in proportion to standards	Increase in proportion to standards from LHD2b3	Same values as LHD2b3
	2005-2007	Increase in proportion to standards	Increase in proportion to standards from LHD2b3	Same values as LHD2b3
	2008 +	Increase in proportion to standards from LHD2b3	Increase in proportion to standards from LHD2b3	Same values as LHD2b3

Figure 3-23. Cold-Start rates (opModeID 108) vs. model year, by pollutant, for heavy-duty gasoline vehicles in two regulatory classes. NOTE: the reference lines indicate the model years 2004, 2005, 2007, 2008 and 2017, respectively.



As we did for heavy-duty diesel and light-duty vehicles we applied the curve in Figure 2-36 to adjust the start emission rates for varying soak times. The rates described in this section were for cold starts (soak time > 720 minutes).

3.2.5.4 *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 to scale up start emission rates for light-duty trucks (RegClassID 30) for model years 1960-2017 (Section 3.1.2.2). For 2018 and later model years, the start PM emissions for heavy-duty gasoline are estimated to be the same as the rates in 2017.[w] As such, 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.

3.2.6 Start Energy Rates

The MOVES2014 energy rates are displayed in Figure 3-24. The heavy-duty gasoline start energy rates were originally derived in MOVES2004, and updated in MOVES2010a as described in the corresponding reports.[45] 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 3-25 displays the relative contribution of running and start operation to total energy consumption from the heavy-duty gasoline regulatory classes from a national MOVES run for calendar year 2011. 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 3-25. Relative contribution of total energy consumption from each pollutant process by regulatory class for heavy-duty gasoline vehicles in calendar year 2011.

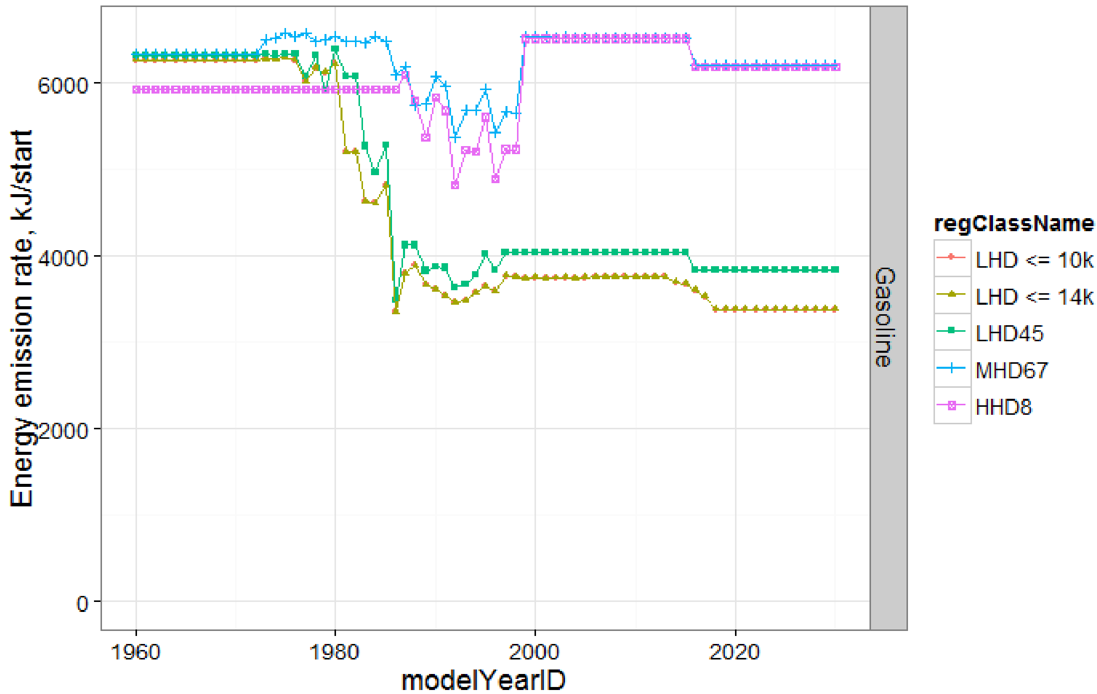
processID	processName	LHD≤10K	LHD≤14K	LHD45	MHD	HHD
1	Running Exhaust	96.3%	98.9%	99.0%	98.1%	98.1%
2	Start Exhaust	3.7%	1.1%	1.0%	1.9%	1.9%

The start energy rates are reduced for shorter soak times using the same factors for diesel vehicles, as presented in Table 2-28. The energy rates also increase with cold temperatures using the temperature effects documented in the 2004 Energy Report.[52]

The only changes to the start energy rates between MOVES2010b and MOVES2014 is the projected impact of the Phase 1 Heavy-duty GHG standards, which begin phase-in in 2014 and have the same reductions as the running energy rates, as presented in Table 2-19.

[w] The light-duty PM start rates are projected to decrease in model year 2018 with the implementation of the Tier-3Vehicle 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. MOVES2014 does not model a reduction in HD PM start emissions from the Tier 3 program, so the 1.4 scaled ratio is not applicable for 2018 and later model years.

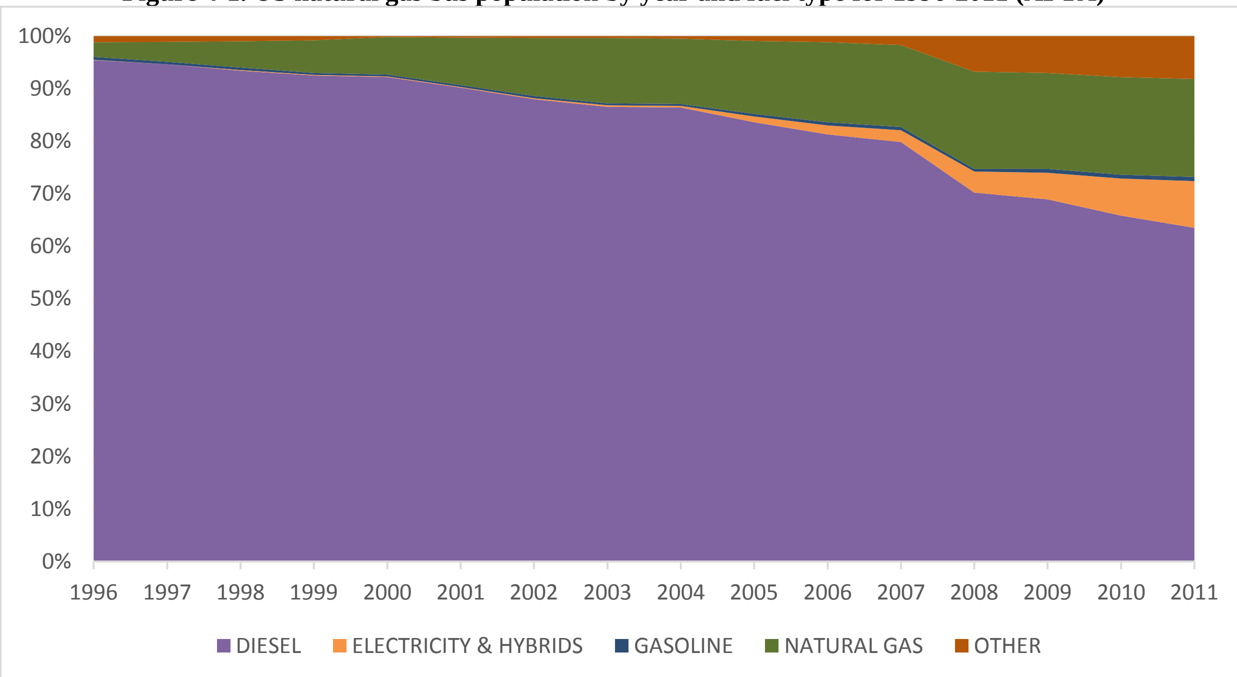
Figure 3-24. Heavy-duty gasoline cold start energy rates (opModeID 108) by model year and regulatory class.



4 Heavy Duty Compressed Natural Gas Transit Bus Emissions

While natural gas lacks the ubiquitous fueling infrastructure of gasoline, compressed natural gas (CNG) has grown as a transportation fuel for public transit, government, and corporate fleets. Such fleets typically utilize centralized, privately-owned refueling stations. 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.[70]

Figure 4-1. US natural gas bus population by year and fuel type for 1996-2011 (APTA) [71]



MOVES2010b and earlier versions can model emissions from CNG bus fleets. However, in absence of better data, MOVES2010b used the emission rates originally developed for medium heavy-duty gasoline trucks (regulatory class 46). These rates were used for hydrocarbon (HC), nitrogen oxides (NOx), carbon monoxide (CO), and particulate matter (PM) emission rates.[72] Medium HD gasoline trucks are reasonable proxies in terms of vehicle weight and engine size, but as this report shows, there are substantial differences between the MOVES2010b emissions rates and real-world measurements of CNG transit buses. This section describes MOVES2014 updates to the CNG bus emission rates in MOVES based on measurements from CNG buses and future projections.

4.1 Transit Bus Driving Cycles and Operating Mode Distributions

4.1.1 Heavy-Duty Transit Bus Driving Cycles

To evaluate whether the existing MOVES2010b rates for gasoline vehicles were appropriate surrogates for buses powered with CNG, we generated test cycle simulations using MOVES and compared the simulated results against chassis dynamometer measurements from published test programs. This process involved using MOVES to determine the distribution of operating modes for each drive cycle, and then multiplying the time spent in each mode by the corresponding emission rates in the EmissionRateByAge table. As in a transient emissions test, the sum of the emissions at each second over the duration of the test yields the total mass of emissions over the test cycle. Dividing the total by distance yields the emission rate over the test. These test programs included only running emissions and were based on a variety of heavy-duty and transit bus driving cycles. We configured MOVES to simulate the drive cycles by importing each drive cycle into MOVES using the Link Driving Schedules template in the Project Data Manager tool. As these were dynamometer measurements, we set the grade to “0” over the duration of each cycle. We imported two driving cycles: 1) the Central Business District (CBD), and 2) Washington Metropolitan Area Transit Authority (WMATA).

The CBD cycle is defined as a driving pattern with constant acceleration from rest to 20 mph, a short cruise period at 20 mph, and constant deceleration back to rest, repeated for 600 seconds (see Figure 4-2).[73] 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).[75]

Figure 4-2. Driving schedule trace of the Central Business District (CBD) cycle [74]

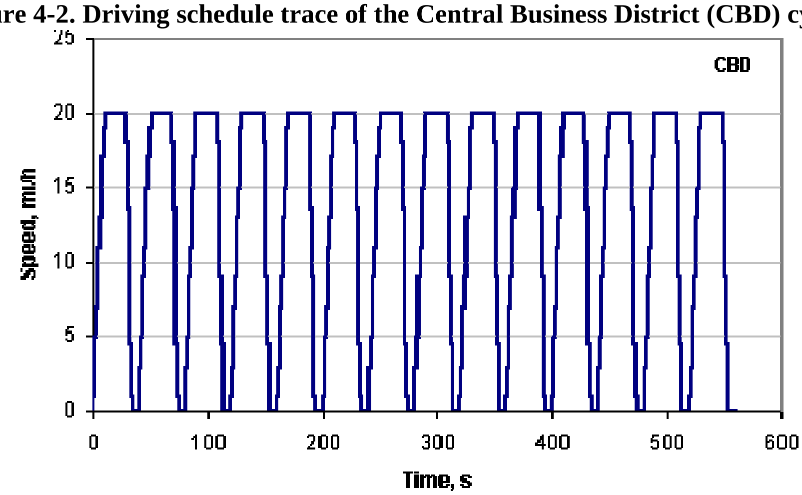
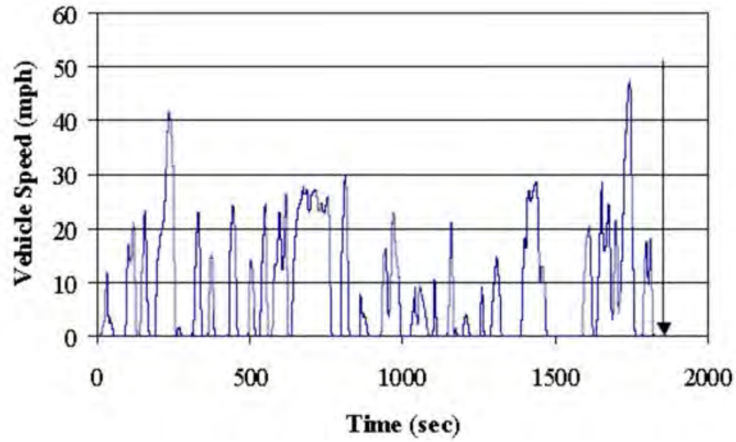


Figure 4-3 Driving schedule trace of the Washington Metropolitan Area Transit Authority (WMATA) cycle [75]



4.1.2 Transit Bus Operating Mode Distributions

The MOVES 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 MOVES 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.

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

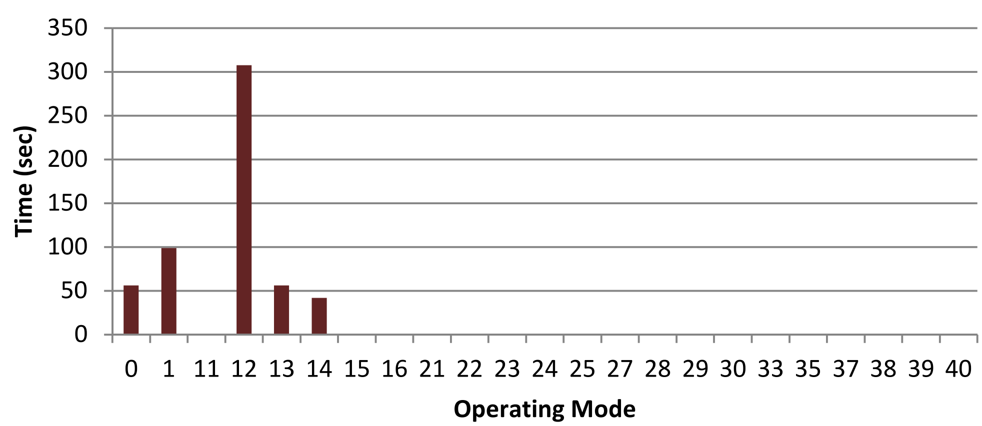
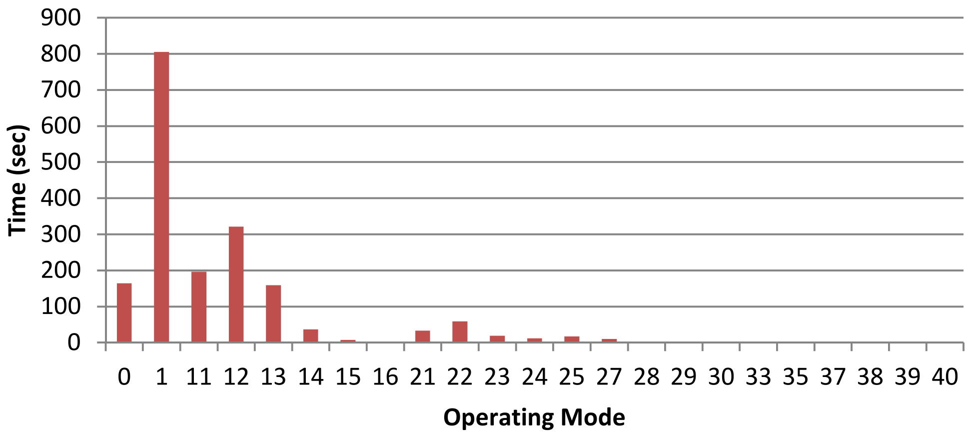


Figure 4-5. Operating mode distribution for the WMATA cycle



4.2 Comparison of Simulated Rates and Real-World Measurements

4.2.1 Simulating Cycle Emission Aggregates from MOVES2010b Rates

Having determined the total amount time spent in each operating mode over the course of each drive cycle, using the emission rates in the MOVES database (DB), we were able to simulate emissions over each cycle. 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.

We simulated a distance-specific emission factor (EF_{sim}, g/mile) for each pollutant for each cycle based on the operating mode distributions, existing MOVES emission rates, and the distance of the drive cycle, using the equation below:

$$EF_{sim,p,cycle} = \frac{\sum_{OM} t_{OM,cycle} r_{p,OM}}{d_{cycle}} \qquad \textbf{Equation 4-1}$$

where

$t_{OM,cycle}$ = cycle's total time spend in operating mode *OM*,

d_{cycle} = distance of the cycle,

$r_{p,OM}$ = time-specific emission rate of pollutant p in operating mode *OM*.

We compared the published test measurements to simulations using the MOVES2010b CNG transit bus rates from Equation 4-1. We also specified the age group and model year to match individual vehicles in the testing programs from the literature on CNG transit buses.

4.2.2 Published Chassis Dynamometer Measurements

The real-world data was collected from programs that were conducted at several research locations around the country on different heavy-duty chassis dynamometer equipment. In our analysis, we collected 35 unique dynamometer measurements—which consisted of running emissions rates in mass per unit distance for each of the pollutants and total energy below:

1. total hydrocarbons (THC),
2. methane (CH_4),
3. carbon monoxide (CO),
4. oxides of nitrogen (NOx),
5. particulate matter (EC + non-EC), and
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)[76] discussed later in this section. All other conversion factors to energy were taken from Melendez et al. (2005).[75]

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.[77]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)[78] and Ayala et al. (2003).[76] In the Ayala et al. (2002) study the 2000 model year CNG bus was tested and then retested after approximately two months of service,[78] 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[75]	National Renewable Energy Laboratory (NREL)	WMATA	2001 (4), 2004 (3)
Ayala 2002[78]	California Air Resources Board (CARB)	CBD	2000 (2)
Ayala 2003[76]	CARB	CBD	2000 (4), 2001 (2)
Lanni 2003[79]	New York Department of Environmental Conservation	CBD	1999 (3)
McCormick 1999[80]	Colorado School of Mines	CBD	1994 (2)
LaTavec 2002[81]	ARCO (a BP Company)	CBD	2001 (1)
McKain 2000[82]	WVU	CBD	1999 (3)
Clark 1997[83]	WVU	CBD	1996 (10)
TOTAL			**34**

As seen above, the CBD driving cycle was applied in each study except for one. Since this cycle (a) had the largest sample size and (b) appeared to be representative of the data from other cycles, we focused our MOVES2010b comparisons on the CBD cycle results.

We approximated the vehicle's age by subtracting the year the study was conducted from the model year of the vehicle. Most vehicles tested were less than three years old (ageGroupID "3"), whereas 9 vehicles fell into the four to five year-old age group (ageGroupID "405"). In the CBD cycle, 5 out of 28 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.[x] Vehicle model years ranged from MY 2001 to MY 2004 for the WMATA cycle and from MY 1994 to MY 2001 for the CBD cycle.

[x] Note that for MY 1994 in Figure 4-6 through Figure 4-10, CNG (MHD gasoline) MOVES2010b rates are based on age group 405. All other MOVES2010b rates are based on age group 3.

4.2.3 Plots of Simulated Aggregates and Published Measurements

Below are graphs of the CBD measurements by model year for each pollutant compared to simulated MOVES2010b CNG (MHD gasoline) rates.

Figure 4-6. NOx emission comparisons of CNG transit bus dynamometer measurements and MOVES2010b simulated aggregates on the CBD cycle.

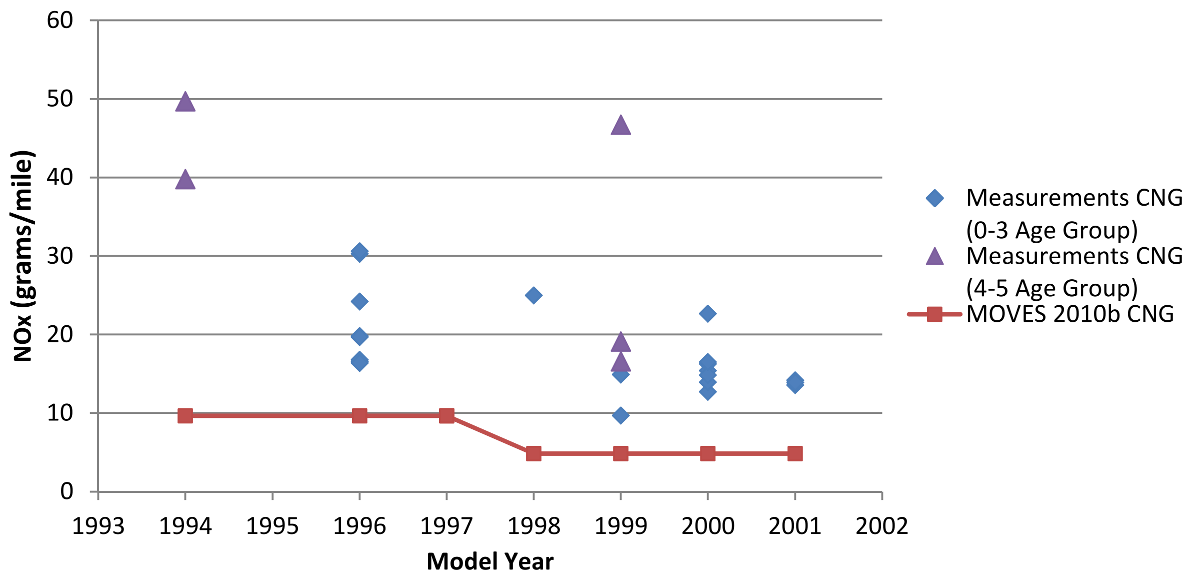


Figure 4-7. CO emission comparisons of CNG transit bus dynamometer measurements and MOVES2010b simulated aggregates on the CBD cycle.

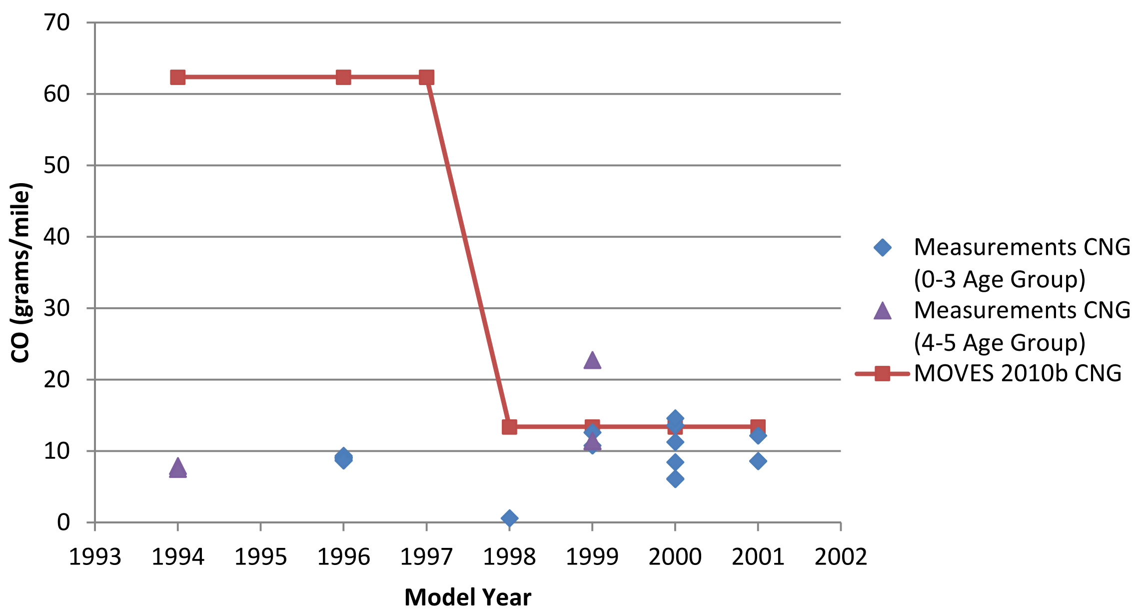


Figure 4-8. PM emission comparisons of CNG transit bus dynamometer measurements and MOVES2010b simulated aggregates on the CBD cycle.

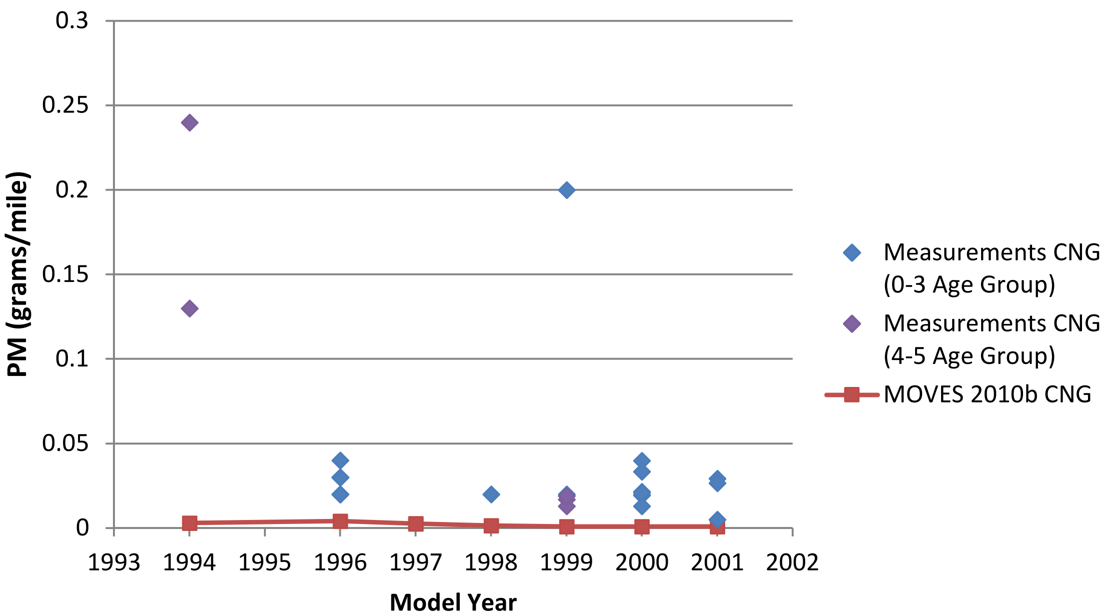


Figure 4-9. THC emission comparisons of CNG transit bus dynamometer measurements and MOVES2010b simulated aggregates on the CBD cycle.

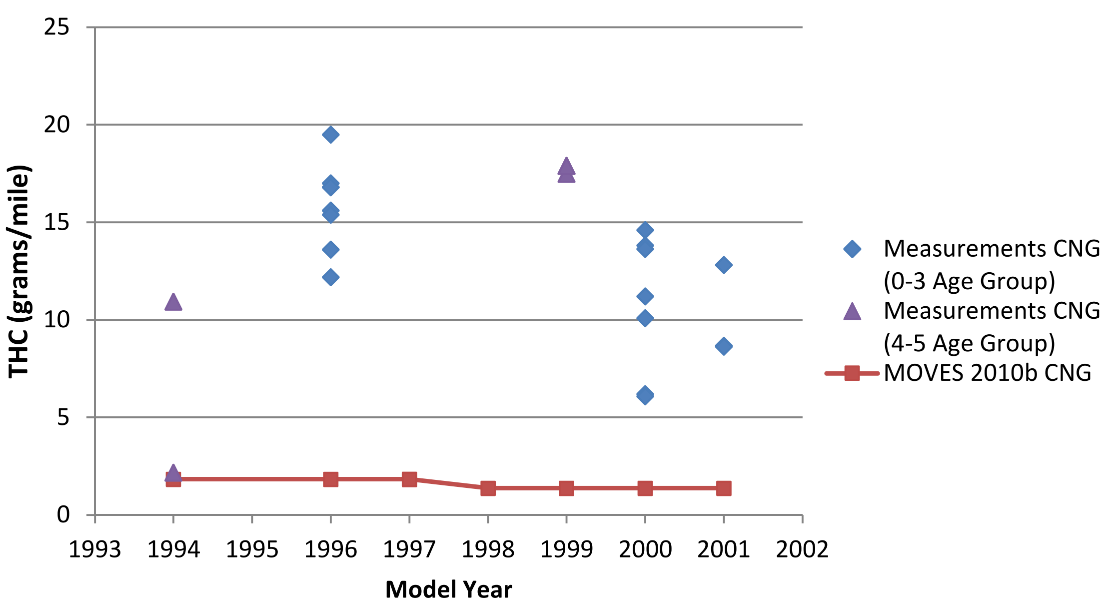


Figure 4-10. CH_4 emission comparisons of CNG transit bus dynamometer measurements and MOVES2010b simulated aggregates on the CBD cycle.

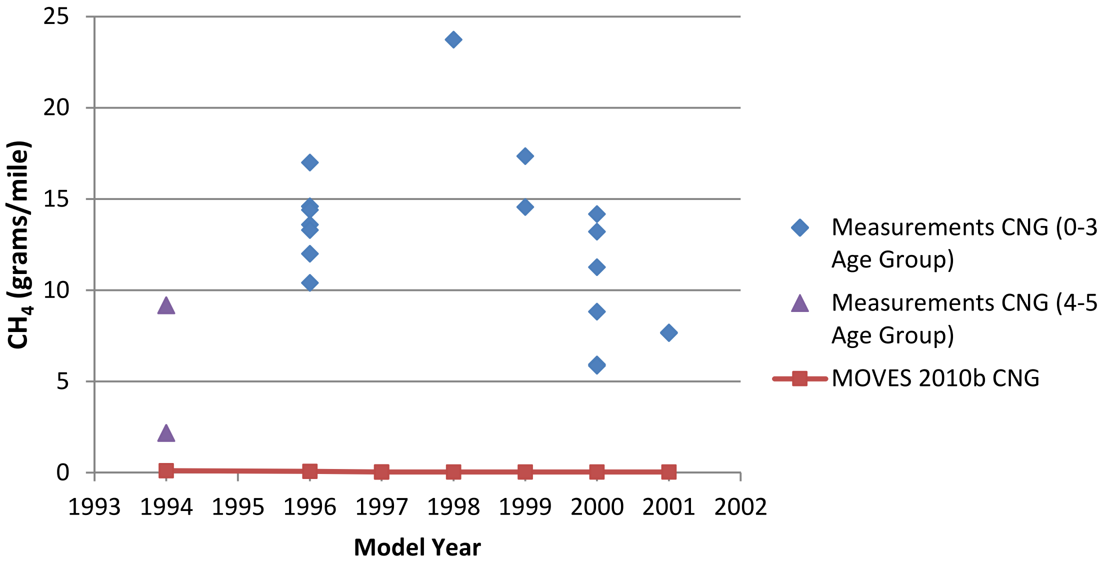
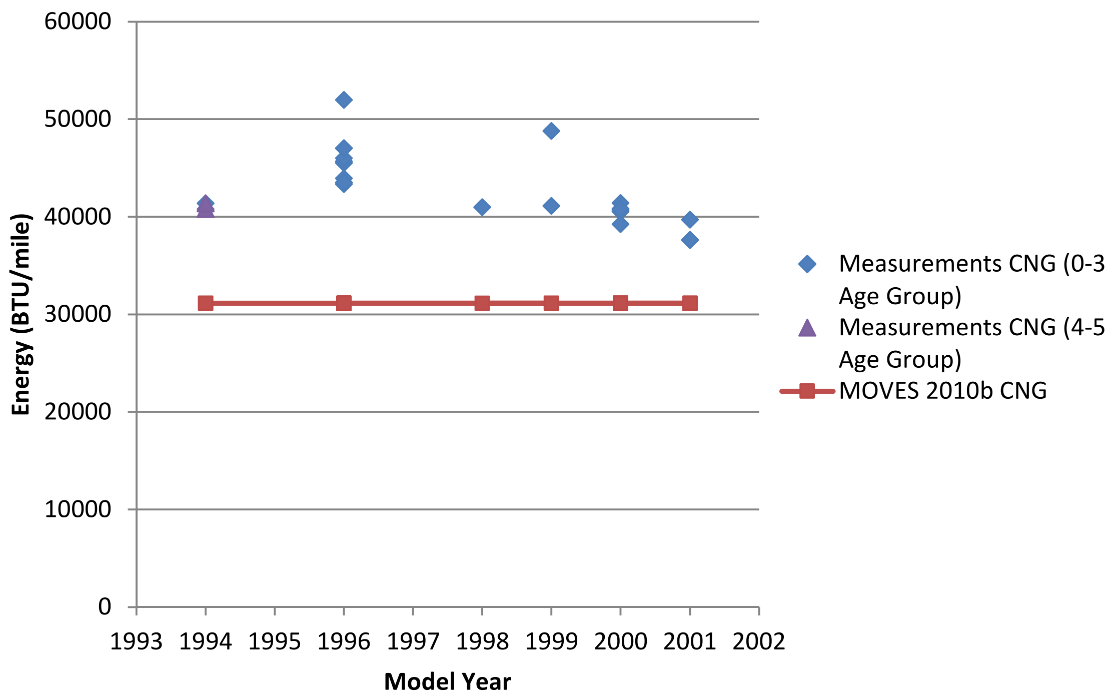


Figure 4-11. Total energy consumption comparisons of CNG transit bus dynamometer measurements and MOVES2010b simulated aggregates on the CBD cycle.



In Figure 4-6, the MOVES2010b CNG rates slightly under-predict the bus NOx measurements. As shown in Figure 4-7, MOVES2010b predictions for CO emissions are similar to the CNG measurements, particularly after 1999. Figure 4-8 shows that the MOVES2010b CNG predictions are lower for PM. As seen in Figure 4-9, MOVES2010b CNG predictions for THC emissions are lower than the measurements by an order of magnitude. As seen in Figure 4-10, this underestimate of THC is largely attributable to a significant underestimate of CNG related CH_4 in MOVES2010b. These relatively high 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.

Figure 4-11 shows that MOVES2010b under-predicts the total energy consumption seen in the literature. Thus, we concluded that the MOVES2010b CNG rates based on MHD gasoline truck rates were not adequate. As discussed in the next section, we developed new rates based on cycle averages from the dynamometer measurements.

4.3 Development of New Running Exhaust Emission Rates

Ideally, new MOVES emission rates are developed through analysis of second-by-second data of vehicles of the appropriate regulatory class, model year, and age. Unfortunately, such modal data was not readily available in this case. However, we substantially improved the CNG bus emission rates in MOVES2014 relative to MOVES2010b by raising or lowering the MY emission rates as a group (as opposed to individual adjustments by operating mode).

4.3.1 Determining Model Year Groups

First we evaluated the measured criteria pollutant rates (THC, CO, NOx and PM) to establish model year groups. Initially, we separated CNG buses equipped with aftertreatment (oxidation catalysts) and those not equipped, 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, there are both after-treatment equipped and non-equipped vehicles. Criteria emission improvements between the vehicles with after-treatment (AT) equipment and those without were primarily inconclusive and did not exhibit any clear trends.[y] Therefore, we chose to group all the CBD measurements from the literature into one model year group, spanning from MY 1994 to MY 2001. No data on CNG buses equipped with three-way catalysts (TWC) was readily available at the time of this analysis; we will look to incorporate data from buses that have TWCs and spark ignited, stoichiometric-burn engine technology as it becomes available.

Of the surveyed data, only one study had any vehicles newer than MY 2001.[z,84] This paper, a joint study between NREL and WMATA, had a small sample of vehicles from MY 2004. These vehicles have a visibly different emissions profile than the other vehicles.[75] While these buses were only tested on the WMATA driving cycle, they were all equipped with oxidation catalysts and had substantially lower emissions from the 1994-2001 buses, particularly for PM emissions. As a result, we created a second model year group from MY 2002 to MY 2006 based on the MY 2004 John Deere WMATA buses. This MY group ends before MY 2007 when a new series of stringent emission standards went into effect, as described below in Section 4.3.2.[85]

Note that the measured CO rate from the WMATA study for MY group 2002-2006 was not used. This vehicle's certification rate was a full order of magnitude lower than data from other 2004 certified models, and was not supported by additional test results. We adjusted the WMATA rate by the ratio between the sales-weighted average of the MY 2004 certification levels of all models and the certification level for that particular MY 2004 John Deere bus with the low CO rate.

4.3.2 Scaling Model Years After 2007

Without published data on in-use vehicles past MY 2004, we use emission certification levels as a proxies to estimate running emission rate changes since then. Certification levels are reported in grams per brake horsepower-hour and are not directly used in formulating MOVES emission rates because they do not include real-world effects such as deterioration.[86, aa] These real-world effects

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[y] The CNG studies do show that after-treatment has a large impact on several of the unregulated pollutants (e.g. formaldehyde). This impact is discussed later with PM and HC speciation in Section 4.6.

[z] A number of papers have discussed more recent vehicles. Examples include Clark et al. (2007).[84] 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.

[aa] As with other MOVES emission rate projections, we have used ratios to real-world measurements on tested technologies to estimate the real-world performance of new technologies. For diesel vehicles, we created ratios using emission standards as described above in Table 2-7. However, since standards for CNG and diesel buses are shared,

were present in the testing programs, so we created scaling factors that we could apply to the measured data from the testing programs to estimate rates after MY 2004.

Certification emission data for natural gas transit buses are publicly available by model year on the EPA's Office of Transportation and Air Quality website.[87] 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, NOx and PM levels have dropped dramatically over the past decade. This effect is largely attributable to increasingly strict emission standards, which have affected both diesel and CNG buses. To improve the accuracy of the scaling factor we weighted the emission levels with projected US sales figures for the certified CNG buses. These figures are confidential business information and cannot be shared publicly but have been incorporated as ratios to calculate the MY group 2007-2012 emission rates. The sales weighted average certification levels for MY group 2002-2006 and MY group 2007-2012 are shown in Table 4-2 below.

Table 4-2. Model year group 2002-2006 and 2007-2012 certification levels for CNG buses used for scaling of measured emission rate data

	Model Year Group	NOx	CO	PM	NMHC[1]
Certification (g/bhp-hr)	2002-2006	1.208	1.355	0.0078	0.147
Certification (g/bhp-hr)	2007-2012	0.2902	3.032	0.0033	0.057

1. Certification data has measurements of organic material non-methane hydrocarbon equivalent (OMNMHCE). For this analysis they were treated as NMHC values.[88]

While the sales figures cannot be shared, Table 4-3 below gives a sense of the CNG engine market by indicating the number of CNG transit bus models certified for each model year.

and the standards were primarily designed for diesel buses, we think ratios of certification levels are a better indicator for new CNG bus emissions.

Table 4-3. A summary of the number of certified CNG transit bus models by model year used in the sales-weighted calculations (USEPA OTAQ).

Model Year	Number of Vehicle Models
2002	4
2003	4
2004	4
2005	6
2006	4
2007	3
2008	1
2009	1
2010	2
2011	2
2012	2
TOTAL	**33**

Methane levels are not reported in the certification data, so we estimate CH_4 rates for MY group 2007-2012 through an analysis of the CH_4 to THC ratio by model year from the dynamometer measurements from the WMATA study. The CH_4/THC ratio for every model year fell within one standard deviation of the average ratio across all model years. The CH_4/THC ratios are calculated from averaged CH_4 and THC measurements on the respective CBD and WMATA cycles, as displayed in Table 4-4. We kept the CH_4/THC ratio constant from MY group 2002-2006 to MY group 2007-2012 and estimated the new CH_4 rate (given in Table 4-5) using this ratio.

Table 4-4 Summary of CH4/THC ratios for MOVES2014

Model Year	Age Group	CH4/THC Ratio
1994-2001	0-3	0.917
2002-2006	0-3	0.950
2007-2012	0-3	0.950

To summarize, we scaled the newer model year rates r_p based off the measurements in the MY group 2002-2006 in proportion to the ratio of certification levels CL_p from MY group 2007-2012 to MY group 2002-2006. In this case,

$$r_{p,MY2007-2012} = r_{p,MY2002-2006} \cdot \frac{CL_{p,MY2007-2012}}{CL_{p,MY2002-2006}}$$ **Equation 4-2**

The estimated CO rate for MY group 2007-2012 is notably greater than the previous MY group, but this change was reflected in our certification level proxies, and has been observed in more recent testing with three-way catalyst, stoichiometric CNG buses.[89] Note that the increase in the CO rate from MY group 2002-2006 to MY 2007-2012 seems to be an outcome of transitioning from lean-burn CNG engines to stoichiometric-burn engines.[90]

Note that there was limited data on older vehicles in the literature, so the ratios from certification level to in-use rate that were developed using vehicles in the 0-3 age group have been applied to all other age groups. In addition, we are assuming that CNG buses exhibit deterioration rates in control equipment proportional to medium heavy-duty gasoline trucks (Sections 3.1.1.5 and 3.1.2.3).

Since there is no certification data on carbon dioxide (CO_2) or other greenhouse gases until 2011, we maintained the same total energy consumption rate from MY group 2002-2006 to MY 2007-2012.

4.3.3 Creating CNG Running Rates for Future Model Years

Table 4-5 shows CNG transit bus emissions on each drive cycle calculated using MOVES2010b rates for each MY group. These calculations are shown using a single model year within the group. The table also shows the emission rates estimated from our meta-analysis of the literature above. We converted MOVES default op mode rates (g/hr) to distance-based rates (g/mi) in order to compare them to the literature. When creating the new op mode rates, we simply multiplied the MOVES2010b rates by the ratio between the literature and the existing rates. These ratios were applied to the 1997, 2004 and 2009 MOVES2010b CNG bus rates in order to calculate the MOVES2014 rates by operating mode.

Table 4-5 Summary of MOVES2010b distance-dependent running emission rates for CNG transit buses and the ratios to be applied to the MOVES2010b STP-based operating mode rates to compute rates for MOVES2014.

	MOVES2010b CNG Rates (g/mile)								
MY	**Age Group**	**Cycle**	**NOx**	**CO**	**PM_Non EC**	**PM_EC**	**TOTAL ENERGY (BTU/mi)**	**THC**	**CH4**
1997	0-3	CBD	9.63	62.4	0.0024	0.0002	31137	1.84	0.049
2004 and 2009	0-3	WMATA	5.45	18.9	0.0035	0.0003	35489	1.43	0.032
	MOVES2014 CNG Rates (g/mile - measured/estimated from analysis)								
MY	**Age Group**	**Cycle**	**NOx**	**CO**	**PM_Non EC**	**PM_EC**	**TOTAL ENERGY (BTU/mi)**	**THC**	**CH4**
1994-2001	0-3	CBD	20.8	9.97	0.037	0.0038	42782	13.2	12.1
2002-2006	0-3	WMATA	9.08	2.17[1]	0.0039	0.0005	40900	11.2	10.6
2007-2013	0-3	WMATA	2.18	5.93	0.0016	0.0002	40900	4.33	4.12
	Ratios Applied to the STP-Based MOVES2014 Rates								
MY	**Age Group**	**Cycle ratioed**	**NOx**	**CO**	**PM_Non EC**	**PM_EC**	**TOTAL ENERGY**	**THC**	**CH4**
1994-2001	all	CBD	2.16	0.16	15.5	21.6	1.37	7.17	250
2002-2006	all	WMATA	1.67	0.11	1.09	1.87	1.15	7.79	330
2007-2013	all	WMATA	0.40	0.31	0.46	0.78	1.15	3.02	128

1. The raw measured CO rate was uncharacteristically low (0.14 g/mi), determined to be an outlier, and has been adjusted using sales-weighted certification data, as described in more detail in the text above.

For each model year group, a central model year was selected for scaling. We chose to use MY 1997 for MY group 1994-2001 due to it being a median year in the group. For MY group 2002-2006, we selected MY 2004 because that was the year all the measured vehicles in that group were manufactured. As for MY group 2007-2012, MY 2009 was chosen as one of the two model years near the median for the group.

For MY 2014 and later, the CNG energy consumption rates are reduced by the same percentage reduction as diesel urban buses (HHD vehicles), in response to the 2014 Medium and Heavy Duty Greenhouse Gas Rule as documented in Table 2-19.

4.4 Start Exhaust Emission Rates for CNG Buses

In the absence of any measured start exhaust emissions from CNG transit buses, their start rates are copied from the 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 buses are from running emissions, which are based on CNG test programs. We readily acknowledge that the diesel start rates may not accurately represent CNG start rates. This assumption will be revisited for future releases of MOVES if new data on CNG start rates becomes available.

4.5 Applications to Other Model Years and Age Groups

We applied the ratios in Table 4-5 to all ages of CNG bus emission running rates in MOVES2010b. In this way, the deterioration assumptions for criteria pollutants in the MOVES2010b running rates are preserved in the MOVES2014 CNG bus rates. For completeness, CNG buses prior to MY 1994 use the same emission rates as MY group 1994-2001. Rates for buses built after MY 2012 use the same emission rate as MY group 2007-2012. We hope revisit these rates in future MOVES releases as more data becomes available.

4.6 PM and HC Speciation for CNG Buses

MOVES estimates methane and nonmethane hydrocarbons (NMHC) through the use of CH_4 /THC ratios, as shown in Table 4-4. The MOVES2014 CH_4/THC ratios are binned by model year group and are constant across all age groups. For CNG buses, we set the start CH_4/THC ratios equal to the running ratios.

MOVES calculates emissions of total organic gases (TOG), nonmethane organic gases (NMOG) and volatile organic carbons (VOC) using information regarding the hydrocarbon speciation of emissions. Studies have shown that the speciation of hydrocarbon can be drastically different between uncontrolled CNG buses and CNG buses with oxidation catalysts. For example, formaldehyde emissions can be quite large from uncontrolled CNG buses[77, 91], but are significantly reduced with oxidation catalysts.[76] Large formaldehyde emissions have a large impact on the NMOG and VOC emissions estimated from THC emissions from CNG buses because THC-FID measurements have a small response to formaldehyde concentrations.[42,92]

We used hydrocarbon speciation data from the Ayala et al. (2003)[76] measurements of a 2000 MY transit bus with a Detroit Diesel Series 50G engine with and without an oxidation catalyst collected on the CBD cycle.[76] This data allows us to isolate the impact of the oxidation catalyst. We used the CBD test cycle to be consistent with our analysis of the criteria emission rates. The NMOG and VOC conversion factors are listed in Table 4-6. The NMOG values are calculated following EPA's regulation requirements using Equation 9 from the MOVES2014 Speciation Report[42].

The VOC emissions are calculated from subtracting the ethane from the NMOG values. The MOVES definition of VOC emissions from mobile-sources is NMOG minus ethane and acetone [bb]. The emissions of hazardous air pollutants, including formaldehyde and acetaldehyde, are also estimated from this study as documented in the MOVES2014 Toxics Emissions Report[93].

[bb] In the original analysis of the CNG emissions, acetone was not considered in the VOC calculation. Upon realization of the oversight, the emission values were not recalculated, due to the small fraction of acetone measured in the exhaust. The VOC results for CNG vehicles without control are negligible. VOC emissions for CNG buses with oxidation catalysts are impacted by less than 2.5%.

Table 4-6 Hydrocarbon speciation values for CNG transit emissions with no control and with oxidation catalyst from Ayala et al. (2003)[76]

Measured values (mg/mile)	**No Control**	**Oxidation Catalyst**
THC	8660	6150
Methane	7670	5900
Ethane	217	72.2
Acetone	4.67	5.51
Formaldehyde	860	38.4
Acetaldehyde	50.7	32.6
Calculated values (mg/mile)		
NMHC	990	250
NMOG	1881.0	309.0
VOC	1664.0	236.8
Ratios		
NMOG/NMHC	1.90	1.24
VOC/NMHC	1.68	0.95

As discussed in Section 4.3.1, the emission rates for the MY 2002-2006 CNG transit bus emission were based on vehicles that were all equipped with oxidation catalysts. The earlier emission rates (1996-2001 MY) emission rates were based on a mix of transit buses with and without oxidation catalysts. To be consistent with our emission rates, we used the NMOG and VOC for the 'No Control' emission factors for 2001 and earlier model years[cc]. We used the NMOG and VOC ratios for 'Oxidation Catalyst for the 2004 and later model years. We did not have information on 2007 and later CNG buses, so we also applied the oxidation catalyst from the lean-burn engine results to 2007 and later groups.

The composition of $PM_{2.5}$ emissions are estimated from CARB's measurements[94] on the 2000 MY Detroit Diesel Series 50G with and without the oxidation catalyst. The EC/$PM_{2.5}$ fractions are reported in Table 4-7 and are used to estimate the base PM components in MOVES: elemental carbon (EC) and non-elemental carbon (nonECPM) rates. By using the single bus, we again isolate the impact of the control, without confounding differences in different engine technologies. Similar for the HC speciation, we apply the uncontrolled EC/PM fraction to the 2001 and earlier MY CNG buses, and the oxidation catalyst equipped EC/PM profile for the 2002 and later MY buses.

Table 4-7 MOVES2014 EC/PM Fraction for CNG transit bus emissions by use of aftertreatment[94]

No Control	**Oxidation Catalyst**
9.25%	11.12%

[cc] Within the hcSpeciation table, MOVES combines 2001-2003 model years into a single model year group. So, the 2001-2003 model years all use the NMOG and VOC ratios from the 'No Control' case, and the 'Oxidation Catalyst' values do not begin until MY 2004.

The CARB measurements were also used to estimate the more detailed $PM_{2.5}$ composition, including organic carbon, elements, and sulfate as discussed in the TOG and $PM_{2.5}$ speciation report. Future work should be done to improve the emission rates and speciation profiles used in MOVES to represent emissions from recent technologies such as the stoichiometric-burn spark ignition CNG engines with three-way catalysts that have been introduced in 2007 and later CNG buses.

4.7 Ammonia and Nitrous Oxide emissions

No data were available on ammonia emissions rates from CNG buses. We used the ammonia emissions for heavy-duty gasoline vehicles, which are documented in a separate report[6].

We did not update the nitrous oxide emission rates for CNG in MOVES2014, and they remain unchanged from MOVES2009 and later versions. The rates are based on CNG-specific values as documented in a separate MOVES report[5].

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.[95]

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.[96] 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’.[95] 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 [97] [98] [99].

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.[100] Most manufacturers have adopted open crankcase filtration systems.[95] 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.[95] 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.[101]

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. NOx 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	NOx	PM
Hare and Baines, 1977[104]	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[97], Ireson et al. 2011[98]	2000, 2003	Conv. Diesel	2				13.5% - 41.4%
Clark et al. 2006[103], Clark et al. 2006[102]	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

MOVES2014 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 MOVES2014, the base exhaust rates for 2007 and later diesel engines are based on certification levels.

In response to the changes in certification testing, 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. A new crankcase calculator in MOVES2014 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. Unfortunately, due to budget and time constraints, only the $PM_{2.5}$ species are incorporated using the new crankcase calculator in MOVES2014. More details on the crankcase calculator is provided in the MOVES2014 Speciation Report.[42]

MOVES2014 continues to use the same calculator as MOVES2010 for the gaseous crankcase pollutants, THC, CO, and NOx. 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 MOVES2014 handles THC, CO, and NOx to avoid double-counting crankcase emissions. We anticipate that future versions of MOVES will include the updated crankcase calculator for all crankcase emission pollutants, including THC, CO, and NOx.

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 NOx, we selected the values measured on the MY2006 diesel engine reported by Clark et al. 2006[103]. These values compare well with the previous HC, CO, NOx values reported much earlier by Hare and Baines (1977), [104] 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 the same crankcase/tail-pipe ratio of 20% used in MOVES2010. The 20% ratio falls within the range of observations from the literature on diesel PM emissions. Zielinska et al. 2008[97] and Ireson et al. 2011[98] reported crankcase contributions to total $PM_{2.5}$ emissions as high as 40%. Jääskeläinen (2012)[95] reported that crankcase can contribute as much as 20% of the total emissions from a review of six diesel crankcase studies. Similarly, an industry report estimated that crankcase emissions contributed 20% of total particulate emissions from 1994-2006 diesel engines[105].

Table 5-2 MOVES2014 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
NOx	0.001	0.001
$PM_{2.5}$	0.200	0.167

As outlined in the MOVES 2014 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%, and the crankcase emissions EC/PM fraction reflects measurements from in-use crankcase emissions. Zielinska et al. 2008[97] reported that the EC/PM fraction of crankcase emissions from two conventional diesel buses is 1.57%. 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. [97,98]. The crankcase emission factors shown in Table 5-3 are derived such that the crankcase $PM_{2.5}$ emissions are 20% of the $PM_{2.5}$ exhaust measurements, and have an EC/PM split of 1.57%.

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 MOVES2014 TOG and PM Speciation Report.

Table 5-3. MOVES2014 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 NOx crankcase emissions are included in the exhaust emissions. However, with the current gaseous crankcaseemission calculator code, the crankcase contribution of THC, CO, and NOx to the base exhaust emission rates cannot be properly accounted. For MOVES2014, the crankcase to tailpipe emission ratios for THC, CO, and NOx are set to zero as shown in Table 5-4, and MOVES2014 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 MOVES2014 estimate of no crankcase emissions is reasonable for NOx, but not for THC and CO emissions. MOVES2014 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 MOVES2014 2007 and later diesel crankcase/tailpipe ratio for HC, CO, and NO_x.

Pollutant	MOVES2014 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%
NOx	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% 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% of the particulate matter emissions from 2007 and later diesel technologies[105].

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, MOVES2014 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 MOVES2014 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 MOVES2014 light-duty emission rates report.[8] We assume 4% 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 tatio 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 MOVES2014 exhaust and crankcase ratios 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.

Nitrogen oxides (NO_x) are defined as NO + NO_2.[106,107] NO_x is considered a subset of reactive nitrogen species (NO_y) with an nitrogen oxidation state of +2 or greater which contain other nitrogen containing species (NO_z), thus $NO_y = NO_x + NO_z$.[106] NO_z compounds are formed in the atmosphere as oxidation products of NO_x[107].

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.[108]

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.[6]

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%) of NO_x emissions from all vehicle types in MOVES, based on HONO and NO_x measurements made at a road tunnel in Europe.[109] 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.[110]

6.1 Heavy-duty Diesel

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. [6] 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[6] 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*	0.935	0.057	0.008
2007-2009	0.764	0.228	0.008
2010-2050	0.594	0.398	0.008

* 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,[6] 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[6] 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, and 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
1996-2050	2008-2050	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)[79] along with the 0.008 HONO fraction assumed for other source types, to estimate the NO_x fractions of NO, NO2, 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 transit buses.

Table 6-3 NO_x and HONO fractions CNG transit buses

Model Year	NO	NO_2	HONO
1960-2050	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

Accessor_ Load (kW): MDT

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

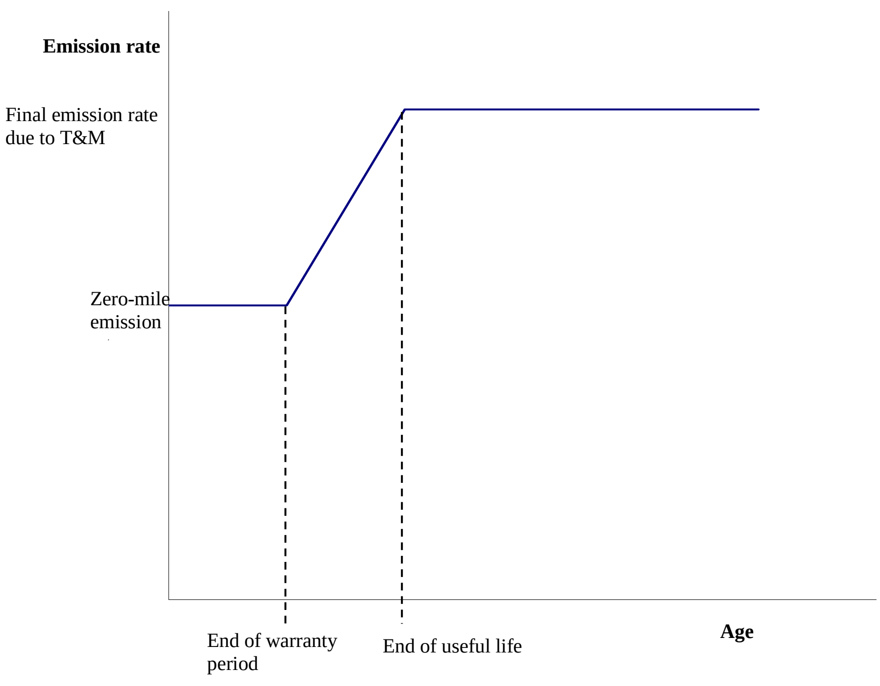
Appendix B Tampering and Mal-maintenance

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.

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[111] (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-1. Warranty and useful life requirements by regulatory class

Regulatory class	Warranty age (Requirement: 100,000 miles or 5 years)	Useful life mileage/age requirement	Useful life age
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

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-2. 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 the equation below. TM_{pol} represents the estimated emissions rate increase through the useful life for a given pollutant.

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

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[112] (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

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 NOx Traps (LNT) for the NOx control in 2010 and beyond. On the other hand, we also assumed that Selective Catalyst Reduction (SCR) systems will be the primary NOx 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.

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 NOx 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.

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[113] so it cannot be ignored.

NOX Aftertreatment malfunction: EPA developed a NOx 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 NOx 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-3. NOx 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%**

NOx 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 NOx sensor. NOx 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 NOx 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 NOx 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.

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%

B.7 *NOx 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 NOx traps (LNT) in LHDD are 80 percent efficient and the selective catalyst reduction (SCR) systems in HHDD are 90 percent efficient at reducing NOx.

EPA developed the NOx emission factors of the NOx sensors based on SCR systems' ability to run in open-loop mode and still achieve NOx reductions. The Manufacturers of Emission Controls Association (MECA) has stated that a 75-90 percent NOx reduction should occur with open loop control and >95 percent reduction should occur with closed loop control.[114] Visteon reports a 60-80 percent NOxreduction with open loop control.[115]

In testing, the failure of the NOx aftertreatment system had a different impact on the NOx emissions depending on the type of aftertreatment. The HHDD vehicles with SCR systems would experience a 1000 percent increase in NOx 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 NOx 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 NOx emission effects with the frequency results in the initial Tampering & Mal-maintenance (T&M) effects shown in the

Table B-4 below. As noted in section 2.1.1.5, MOVES does not use the estimate NOx increase from T&M for 2009 and earlier model years, and assumes no NOx increase. This is incorporated into the 3rd column of Table B-4 labeled with (Remove 2009 and earlier)

Table B-4. Fleet-average Tampering & Mal-maintenance (TM) NOx emission increases (%) from zero-mile levels calculated over the useful life s. $TM_{NOx,nonOBD}$ are calculated using the NOx 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})

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

The LHD≤10K trucks have different T&M NOx increases than LHD≤14K trucks, due to the assumed penetration of lean NOx trap (LNT) aftertreatment which was assumed to penetrate 25% 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 2-10 to account for T&M of LNT aftertreatment, as shown in Equation B-2 :

$$\frac{2007-2009\ LNT\ NOx\ emissions\ (T\&M)}{2003-2006\ LHD \leq 10K\ NOx\ emissions} = (normal\ op.frequency) \times \left(\frac{LNT\ normal\ emissions}{baseline\ emissions}\right) \times (T\&M\ effect) + (DPF\ reg.frequency) \times \left(\frac{baseline\ emissions}{baseline\ emission}\right)$$ **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 NOx rates is calculated by adjusting Equation 2-11 to account for the T&M effects of LNT, as shown in Equation B-3.

$$\frac{2007-2009\ LHD \leq 10K\ NOx\ emissions\ (T\&M)}{2003-2006\ LHD \leq 10K\ NOx\ emissions} = (LNT\ market\ share)\left(\frac{2007-2009\ LNT\ NOx\ emissions\ (T\&M)}{2003-2006\ LHD \leq 10K\ NOx\ emissions}\right) + (non-LNT\ market\ share)\left(\frac{2007-2009\ emission\ standards}{2003-2006\ NOx\ emissions\ standards}\right)$$ **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 2-11.

$$\frac{2007-2009\ LHD \leq 10K\ NOx\ emissions\ (T\&M)}{2007-2009\ LHD \leq 10K\ NOx\ emissions\ (zero\ mile)} = \left(\frac{2007-2009\ LHD \leq 10K\ NOx\ (T\&M)}{2003-2006\ LHD \leq 10K\ NOx\ emissions}\right) \Big/ \left(\frac{2007-2009\ LHD \leq 10K\ NOx\ \ (zero\ mile)}{2003-2006\ LHD \leq 10K\ NOx\ emissions}\right)$$ **Equation B-4**

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

For 2010+, LHD≤14K, we assume that both LNT and SCR equipped vehicles will provide the same level of control with a 90% reduction from 2003-2006 levels (ignoring the PM regeneration NOx benefit for LNT aftertreatment). Thus, for calculating the T&M NOx 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% OBD penetration in 2010-2012, and full penetration for 2013+ model years. The NOx T&M effects by the MOVES regulatory classes and model year groups are shown in Table B-5.

Table B-5. NOx 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%

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 tPM Filter Tampering for the 2007-2009 and 2010+ model year groups. The PM filter leak was increased from 600% to 935% and the PM Filter Disabled emission effect was increased from 1000% to 2670%. This results in a fleet average PM Tampering & Mal-maintenance effect of 100% in 2007-2009 and 89% 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%
Nox Aftertreatment Sensor	0%	0%	0%	0%	0%
Replacement Nox Aftertreatment Sensor	0%	0%	0%	0%	0%
Nox Aftertreatment Malfunction	0%	0%	0%	0%	0%
PM Filter Leak	0%	0%	0%	935%	935%
PM Filter Disabled	0%	0%	0%	2670%	2670%
Oxidation Catalyst Malfunction/Remove	0%	0%	0%	0%	0%
Mis-fuel - EPA	30%	30%	30%	100%	100%

B.9 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%. This still represents a 70% 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%) 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 2-8 (NOx), Table 2-15 (PM), and Table 2-18 (HC and CO).

B.10 HD OBD impacts

With the finalization of the heavy-duty onboard diagnostics (HD OBD) rule, we made adjustments to 2010 and later model years to reflect the rule's implementation.

Specifically, we reduced the emissions increases for all pollutants due to 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.

$$TM_{pol} = TM_{pol,nonOBD}(1 - f_{OBD}) + 0.67 \cdot TM_{pol,nonOBD} f_{OBD}$$ **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 Extended Idle Data Summary

Idle HC Rates (gram/hour) Summary

Program	Condition	# Samples	Mean HC Emiss Rate
1991-2006 Low Speed Idle, A/C Off - HDT			
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 - HDT			
Broderick UC Davis	High Idle, AC On	1	86
Storey	High Idle, AC On	4	48
	Overall	**5**	**55.6**

1975-1990 MY Low Speed Idle, A/C Off - HDT			
Program	**Condition**	**Samples**	**Mean**
WVU - 1975-1990	Low Idle, AC Off	18	21
	Overall	**18**	**21.0**

1991-2006 MY Low Speed Idle, A/C Off - Bus			
Program	**Condition**	**Samples**	**Mean**
McCormick, High Altitude, Bus	Low Idle, AC Off	12	8.2
	Overall	**12**	**8.2**

Idle CO Rates (gram/hour) Summary

Program	Condition	# Samples	Mean CO Emiss Rate
1991-2006 Low Speed Idle, A/C Off - HDT			
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 - HDT			
Calcagno	High Idle, AC On	21	99
Broderick UC Davis	High Idle, AC On	1	190
Storey	High Idle, AC On	4	73
	Overall	**26**	**91.2**

1975-1990 MY Low Speed Idle, A/C Off - HDT			
Program	**Condition**	**Samples**	**Mean**
WVU - 1975-1990	Low Idle, AC Off	18	31
	Overall	**18**	**31.0**

1991-2006 MY Low Speed Idle, A/C Off - Bus			
Program	**Condition**	**Samples**	**Mean**
McCormick, High Altitude, Bus	Low Idle, AC Off	12	79.6
	Overall	**12**	**79.6**

Idle PM Rates (gram/hour) Summary

Program	Condition	# Samples	Mean PM Emiss Rate
1991-2006 Low Speed Idle, A/C Off - HDT			
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	1.3
	Overall	**91**	**1.8**

1991-2006 High Speed Idle, A/C On - HDT			
Calcagno	High Idle, AC On	21	4.11
Storey	High Idle, AC On	4	3.2
	Overall	**25**	**4.0**

1975-1990 MY Low Speed Idle, A/C Off - HDT			
Program	**Condition**	**Samples**	**Mean**
WVU - 1975-1990	Low Idle, AC Off	18	3.8
	Overall	**18**	**3.8**

1991-2006 MY Low Speed Idle, A/C Off - Bus			
Program	**Condition**	**Samples**	**Mean**
McCormick, High Altitude, Bus	Low Idle, AC Off	12	2.88
	Overall	**12**	**2.9**

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
Broderick UC Davis	Low RPM, AC Off	1	104
Storey	Low RPM, AC Off	4	126
	Overall	**188**	**94**

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
Broderick 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 MY Low Speed Idle, A/C Off			
Program	**Condition**	**Samples**	**Mean**
WVU - 1975-1990	Low RPM, AC Off	18	48
Lim, EPA CCD, 1985 MY	Low RPM, AC Off	1	20
	Overall	**19**	**47**

1991-2006 MY Low Speed Idle, A/C Off - Bus			
Program	**Condition**	**Samples**	**Mean**
McCormick, High Altitude, Bus	Low Idle, AC Off	12	121
	Overall	**12**	**121.0**

2007 Extended Idle Emissions calculation:

- Assumed 8 hour idle period where the emissions controls, such as EGR, oxidation catalyst, and NOx aftertreatment, are still active for the first hour.
- HC emissions standards:
  - Pre-2007: 0.50 g/bhp-hr
  - 2007: 0.14 g/bhp-hr
- NOx 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%
Idle NOx Rate Reduction = 1 - [(1/8 * 0.2 g/bhp-hr + 7/8 * 5.0 g/bhp-hr) / 5.0 g/bhp-hr] = 12%

Appendix D 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% confident level). The table below shows the regression statistics, and the equation shows the form of the resulting regression equation.

Table D-1. 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

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

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 1-4).

Appendix E Heavy-duty Diesel EC/PM Fraction Calculation

E.1 Introduction

This appendix describes the development and application of a simple emission model for estimating elemental and organic carbonaceous material (EC and OM) emission rates (or EC/OM ratios) for MOVES. The appendix describes the following steps involved in predicting EC/OM ratios. The appendix also briefly describes comparisons with independent emission data collected using the "Mobile Emission Laboratory," operated by the University of California Riverside.

The subsequent sections of the appendix describe the following topics:

- the extension of Physical Emission Rate Simulator (PERE) to estimate heavy-duty fleet-average emission factors for any specified driving cycle;
- the acquisition of data used in estimating EC/OC rates as a function of engine operating mode and the fitting of simple empirical models to them;
- the application of PERE to estimate EC and OC emission rates for different test cycles; and,
- the comparison of PERE-based EC and OC emission rates to those measured by independent researchers in HD trucks.

E.2 PERE for Heavy-duty Vehicles (PERE-HD) and Its Extensions

The Physical Emission Rate Estimator (PERE) is a model employed by EPA in early development of MOVES.[34] In particular, the MOVES team employed it in development of MOVES2004 to impute greenhouse gas emission rates for combinations of SourceBin and Operating Mode for which data was unavailable or of insufficient quality.

The underlying theory behind PERE and its comparison with measured fuel consumption data is described by Nam and Giannelli (2005).[34] Briefly, PERE estimates fuel consumption and emission rates on the basis of fundamental physical and mathematical relationships describing the road load that a vehicle meets when driving a particular speed trace. Accessory loads are handled by addition of an accessory power term. In the heavy-duty version of PERE (hereafter, "PERE-HD"), accessory loads were described by a single value.

For the current project, PERE was modified to incorporate several "extensions" that allowed it to estimate fleet-average emission rates, simulate a variety of accessory load conditions, and predict EC rates for any given driving cycle.

E.2.1 PERE-HD Fleet-wide Average Emission Rate Estimator

PERE-HD requires a number of user-specified inputs, including:

- vehicle-level descriptors (model year, running weight, track road-load coefficients (*A*,*B*,*C*), transmission type, class [MDT/HDT/bus]);
- engine parameters (fuel type, displacement); and
- driving cycle (expressed through a speed trace).

The specification of these inputs allows PERE to model the engine operation, fuel consumption, and GHG emissions for a HDV on a specified driving cycle.

However, the baseline PERE-HD provides output for only one combination of these parameters at once. To estimate fleet-wide average a large number of PERE-HD runs would be required. Furthermore, the specification of only fleet-wide average coefficients is likely to substantially underestimate variability in fuel consumption and emissions. Emissions data from a large number of laboratory and field studies suggest that a very large fraction of total emissions from all vehicles derives from a small fraction of the study fleet. Therefore, it is desirable to develop an approach that comes closer to spanning the range of likely combinations of inputs than using a small selection of "average" or "typical" values.

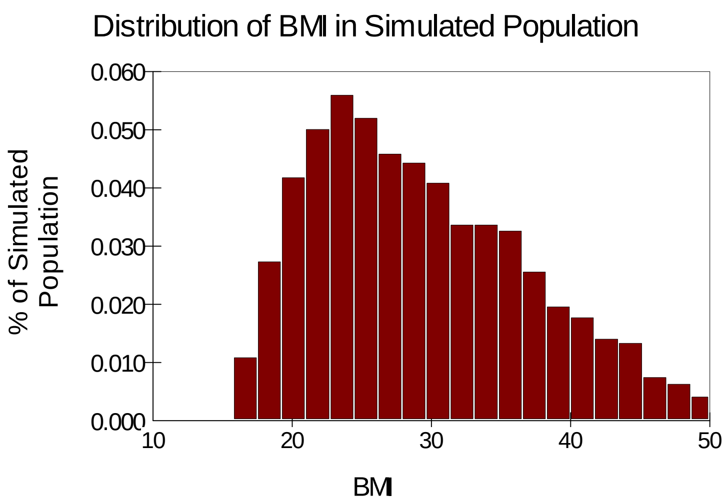
For the current application, PERE-HD (built within Microsoft Excel) was expanded to allow for a representative sample of [running weight] × [engine displacement] × [model year] combinations. A third-party add-on package to Excel, @Risk 4.5 (Palisade Corporation, 2004), allows users to supplement deterministic inputs within spreadsheet models with selected continuous probability distributions, sample input values from each input distribution, and re-run the spreadsheet model with sets of selected inputs over a specified number of iterations. This type of procedure is commonly referred to as "Monte Carlo" simulation.

E.2.2 Monte Carlo Simulation in PERE-HD

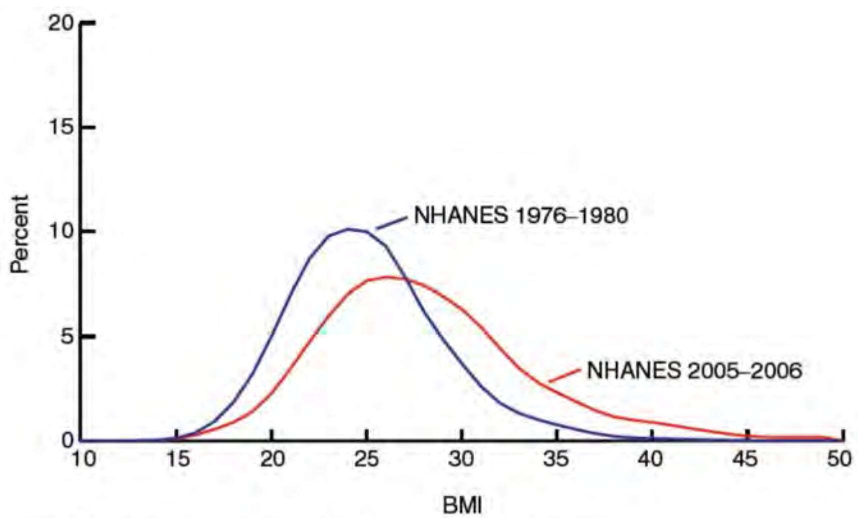
To illustrate how @Risk performs this process, we illustrate the application of a simple model, employing both deterministic calculations and stochastic Monte Carlo simulation:

$$BMI = \frac{M}{L^2}$$

This equation defines the body mass index for humans, a simple surrogate indicating overweight and underweight conditions. According to the Centers for Disease Control and Prevention (CDC), the average U.S. woman weighed 164.3 lb (74.5 kg) in 2002 and was 5'4" (1.6 m) tall. This result corresponds to a BMI of 28, suggesting that the average U.S. woman is overweight. While this is useful information from a public health perspective, it does not provide any indication as to which individuals are likely to experience the adverse effects of being overweight and obese. However, if we were to assume (arbitrarily) that the range of weight and height within the U.S. population was +/-50% of the mean, distributed uniformly, and perform a Monte Carlo simulation (5,000 iterations) using @Risk, we would predict a probability distribution of BMI in the population as follows:



In contrast, here is the BMI distribution in the entire U.S. population, according to the CDC's National Health and Nutrition Examination Survey (NHANES):



SOURCE: CDC/NCHS, National Health and Nutrition Examination Survey (NHANES).

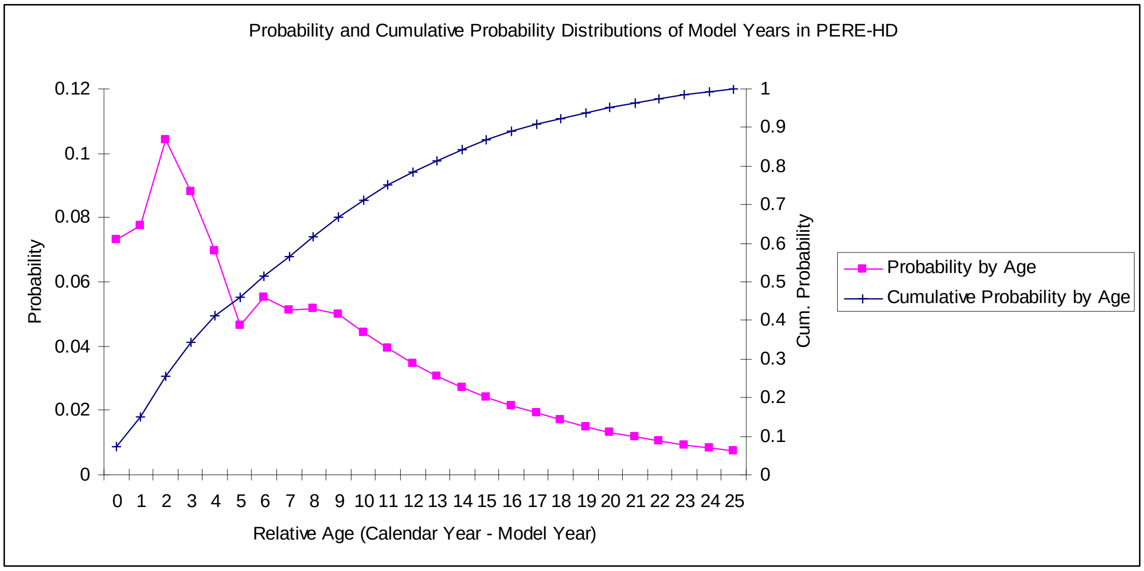
These graphs illustrate how Monte Carlo simulation can be used to provide meaningful information about the variability in a population. Although the model example is very simple, it illustrates the point that a model with "typical" inputs provides much less information than Monte Carlo simulation does with variable inputs.

For emission modeling purposes using PERE-HD, several key inputs were modeled as probability distributions.

E.2.3 Model Year

Model year is an important factor in PERE, as the frictional losses in the model, expressed as "friction mean effective pressure" (FMEP), vary by model year, improving with later model years. As such, model year was simulated as a probability distribution, based on data from the Census Bureau's 1997 Vehicle Inventory and Use Survey (VIUS)[116], which reports "vehicle miles traveled" (VMT) by model year. Accordingly these data were normalized to total VMT to develop a probability distribution. Model year distributions in 1997 were normalized to the current calendar year (2008).[dd] For instance, the fraction of 1996 vehicles reported in the 1997 VIUS is treated as the fraction of 2002 vehicles in the 2003 calendar year. Although a 2002 VIUS is available, previous analyses (unpublished) have shown the "relative" model year distribution of trucks to have changed little between 1997 and 2002, though this assumption is one limitation of this analysis.

The model year distribution for PERE-HD was represented as a discrete probability distribution, as shown below:

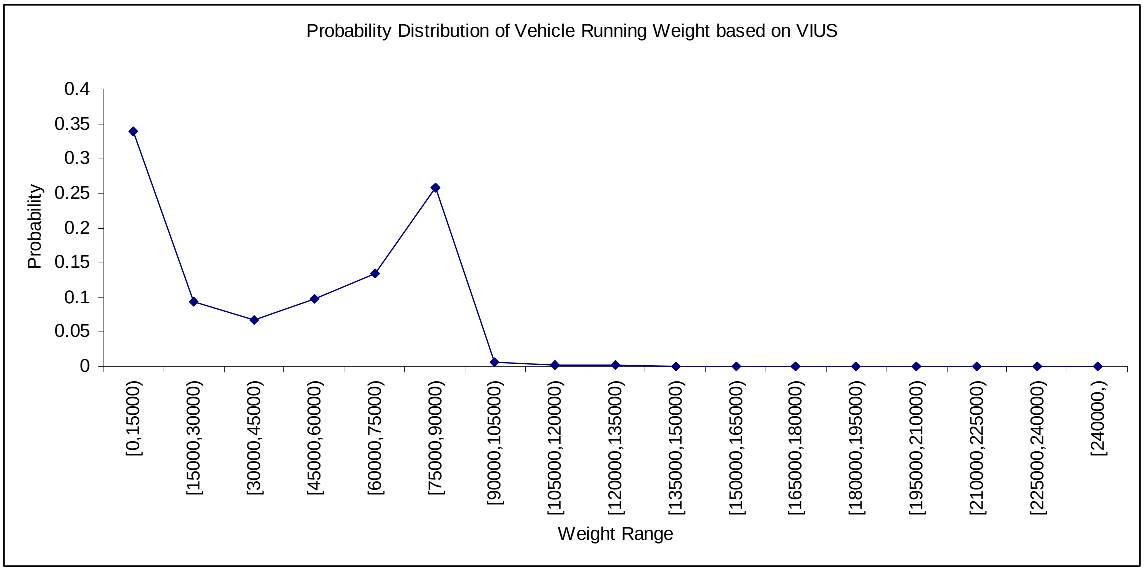


E.2.4 Vehicle Weight and Engine Displacement

Vehicle running weights and engine displacements were modeled as a two-way probability distribution with engine displacement depending on running weight. These data were derived from VIUS micro data obtained from the Census Bureau.[116] A two-way table was constructed to estimate VMT classified by combinations of [weight class] × [displacement class]. Analyses were restricted to diesel-powered trucks only.

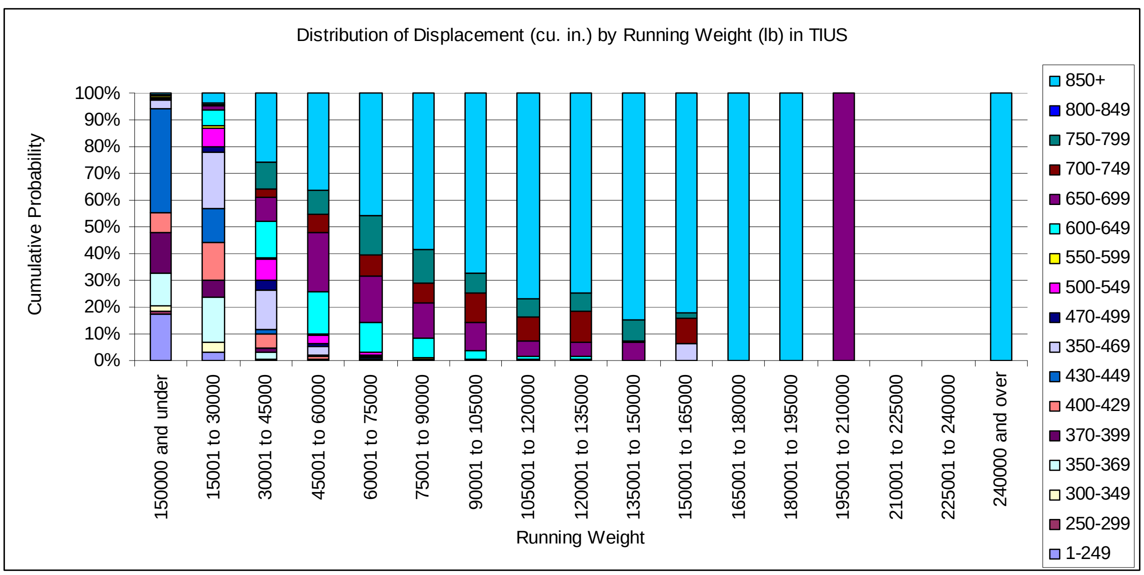
As a first step, @Risk selects a running weight from a probability distribution representing the fraction of truck VMT occurring at a given running weight:

[dd] VIUS reports model years 11 years old and greater as a single number. For the current analysis, the fraction of vehicles within each model year older than 10 years of age through 25 years was estimated using an exponential decay of the form $p(x) = A*\exp[-B*(x-10)]$. Coefficients representing the *A* and *B* parameters were estimated by minimizing least squares of the residuals. The sum of probabilities for model years older than 10 years was constrained the fraction of VMT driven by trucks older than 10 years in VIUS.



Because VIUS reports classes defined as ranges in running weight, any value of weight within each VIUS-specified class was considered equally likely and modeled as a uniform probability distribution within the class. For the upper and lower bounds of the distribution the minimum and maximum running weights were assumed to be 7,000 and 240,000 lb, respectively.

After @Risk selects a running weight, it selects an engine displacement based on a discrete distribution assigned to every weight class in VIUS, represented below:



Again, because VIUS describes ranges of values for displacement, all values within each range were given uniform weight and assigned a uniform distribution. For the extreme classes, the minimum and maximum engine displacements were assumed to be 100 in^3 and 915 in^3, respectively.

This procedure reflects the range in running weights present among HDV in operation, and constrains the combinations of weight and displacement to plausible pairs of values based on surveyed truck operator responses. These steps allow for plausible variability in weight-engine pairings, which translates into differences in engine parameters influencing EC and OC emissions.

For use in PERE-HD, all units were converted to SI units (kg and L).

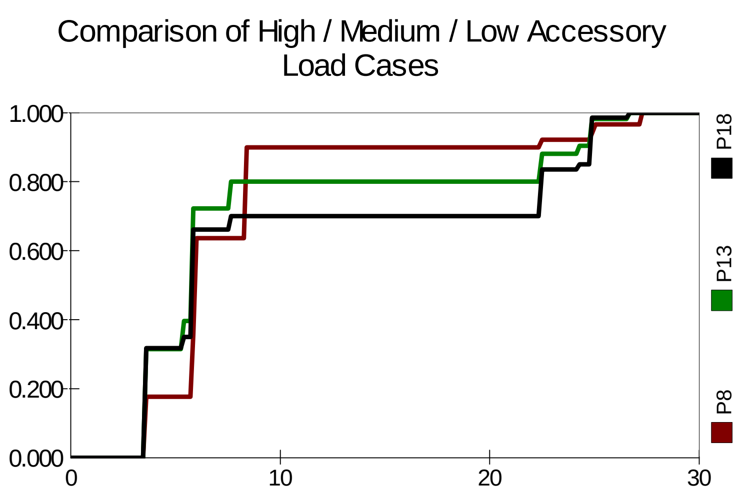
E.2.5 Accessory Load

The original PERE-HD treats accessory load as a fixed value, which may be varied by the user. It is set at 0.75, and used in calculating fuel rate and total power demand at each second of driving.

Following the development of PERE-HD, a more detailed set of accessory load estimates was developed based on several accessories' power demand while in use and the fraction of time each accessory is in use (see Table 2-4).[117] High, medium, and low accessory use categories were estimated for three vehicle classes: HDT, MDT, and buses. For the current version of the model, only the HDT accessory load estimates were employed, though a sensitivity analysis indicated that mean EC/OM ratios were most sensitive to accessory load during idle and creep driving cycles. In the "base case," a mean ratio of 0.54 was predicted, while in the sensitivity case, a mean ratio of 0.50 was predicted. This issue may be revisited at some point, although the limited sensitivity of total results limits the importance of the accessory terms within the current exercise.

Within @Risk, the variable in PERE-HD, P_{acc} for accessory use was substituted with a variable representing the distribution (in time) of accessory loads as estimated as the sum of a number of discrete probability distributions.

Depending on the assumption of high, medium or low use, the power demand for these accessories is distributed in time as follows:



E.2.6 Driving Cycle

For purposes of this exercise, the four phases of the California Air Resources Board's Heavy Heavy-Duty Diesel Truck (HHDDT) chassis dynamometer testing cycle were used to reflect variability in vehicle operations for PERE-HD.

E.2.7 Other Factors

Some elements of variability were not examined as part of this study. Hybrid-electric transmissions and fuel cell power plants were excluded from the analysis, due to their low prevalence within the current truck fleet.

One important source of variability that was not examined in this analysis is the variation in resistive forces among vehicles with identical running weights. This exclusion is important, given the potential role for aerodynamic improvements, low rolling resistance tires, and other technologies in saving fuel for long-distance trucking firms and drivers. Such considerations could be incorporated into PERE-HD in the future as a means of estimating the emission benefits of fuel-saving technologies.

E.3 Prediction of Elemental Carbon and Organic Mass based on PERE-HD

E.3.1 Definition of Elemental and Organic Carbon and Organic Mass

In motor vehicle exhaust, the terms "EC," "elemental carbon," and "black carbon" refer to the fraction of total carbonaceous mass within a particle sample that consists of light-absorbing carbon. Alternatively, they refer to the portion of carbonaceous mass that has a graphitic crystalline structure. Further, one can define EC as the portion of carbonaceous mass that has been altered by pyrolysis, that is, the chemical transformation that occurs in high temperature in the absence of oxygen.

EC forms in diesel engines as a result of the stratified combustion process within a cylinder. Fuel injectors spray aerosolized fuel into the cylinder during the compression stroke. The high-pressure and high temperature during the cylinder cause spontaneous ignition of the fuel vaporizing from the injected droplets. Because temperature can rise more quickly than oxygen can diffuse to the fuel at the center of each droplets, pyrolysis can occur as hydrogen and other atoms are removed from the carbonaceous fuel, resulting in extensive C-C bond interlinking. As a result, pyrolyzed carbon is produced in a crystalline form similar to graphite.

"Organic carbon" or "organic mass" (OC or OM) is used to denote the portion of carbonaceous material in exhaust that is not graphitic. Chemical analysis of this non-graphitic carbon mass indicates that it is composed of an extensive mixture of different organic molecules, including C15 to C44 alkanes, polycyclic aromatic hydrocarbons, lubricating oil constituents (hopanes, steranes, and carpanes), and a sizeable fraction of uncharacterized material. This component of exhaust can derive from numerous processes inside the engine involving both fuel and oil. Because of the complex chemical mixture that comprises this mass, its measurement is highly dependent on sampling conditions. The wide range of organics that compose it undergo evaporation and condensation at different temperatures, and the phase-partitioning behavior of each molecule is dependent on other factors, such as the sorption of vapor-phase organics to available surface area in a dilution tunnel or background aerosol.

E.3.2 EPA Carbon Analysis Techniques in Ambient Air

The definitions of EC and OM are critical, as different groups use different techniques for quantifying their concentrations within a given medium. For purposes of this document, it is assumed that EC, OC, and OM are *operationally defined* quantities, meaning that they are defined by the measurement technique used to quantify their concentrations on a filter or in air.

The different types of commonly used approaches for carbon include:

- Thermal/optical techniques, where the evaporation and oxidation of carbon are used in conjunction with a laser to measure optical properties of a particle sample. The major methods used for this type of analysis include:
  - *Thermal/optical reflectance (TOR).* EPA is adopting this technique for the $PM_{2.5}$ speciation monitoring network nationwide. It is also employed by the IMPROVE program (Interagency Monitoring of Protected Visual Environments) in national parks. This technique heats a punch from a quartz fiber filter according to a certain schedule. A Helium gas atmosphere is first employed within the oven, and the evolved carbon is measured with a FID as temperatures are increased in steps up to 580°C. All carbon evolved in this way is assumed to be volatilized organic material. Next, 2% oxygen gas is added to the atmosphere, and temperatures are stepped up a number of times to a maximum of 840°C. All carbon evolved after the introduction of oxygen is assumed to be elemental carbon. The reflection of light from a laser by the filter is employed to account for the pyrolysis of organic carbon that occurs during the warm-up process.
  - *Thermal/optical transmission (TOT).* The National Institute of Occupational Safety and Health (NIOSH) uses this technique for measuring EC concentrations in occupational environments. It is based on similar principles to TOR, but employs a different heating schedule and transmission of light as opposed to reflectance.
- Radiation absorption techniques
  - *Aethalometer®* – This instrument reports "black carbon" (BC) concentrations based the extent of light absorption by a "filter tape," that allows for a time series of BC concentrations to be estimated. It has a time resolution of several minutes.
  - *Photoacoustic Spectrometer* (PAS) – This instrument irradiates an air sample with a laser. The resulting heat that occurs from the absorption of the laser light by light-absorbing carbon in the air sample produces a pressure wave that is measured by the device. The signal from this pressure wave is proportional to the light-absorbing carbon content in exhaust.
- Thermogravimetric techniques, where the "volatile organic fraction" (VOF) is separated by heat from the non-volatile refractory component of a particle sample.
- Chemical extraction, where solvents are used to separate the soluble and insoluble components of exhaust.

A number of additional techniques are also described in the published literature, but the above techniques have been most commonly applied in emissions and routine ambient PM measurement.

Among the available techniques, it has been a point of controversy among academics as to which method provides the "correct" carbon signal. Rather than addressing these arguments in detail, this analysis adopts the technique employed by the EPA ambient speciation monitoring network, TOR. Needless to say, different researchers employ different sampling, measurement and analysis techniques. Desert Research Institute (DRI) employed TOR in analyzing the Kansas City gasoline PM emission study samples[118] , while other prominent academics employ TOT, notably the University of California Riverside College of Engineering Center for Environmental Research and Technology (CE-CERT) and the University of Wisconsin-Madison (UWM) State Hygiene Laboratory. As research results from these groups is employed throughout this analysis, an inter-comparison of the methods of TOT/TOR is necessary to "recalibrate" various datasets with respect to each other.

EPA defines measurement techniques for dynamometer-based sampling and analysis of particulate matter, in addition to techniques for sampling and analyzing particles in ambient air. Inventories estimated for EC and OM can be considered to reflect both broad categories of measurement techniques, depending on context.

The user community for MOVES is predominantly concerned with emissions that occur into ambient air. EPA regulations for demonstration of attainment of state implementation plans (SIPs) are based on monitored ambient particulate matter using Federal Reference Methods (FRM) for ambient air. FRM monitors for particle speciation in ambient air undergo analysis for EC and OC according to a defined standard operating procedure.[119] That standard operating procedure defines thermal/optical reflectance (TOR) as the desired method for analysis of ambient carbon PM.

E.3.3 TOR – TOR Calibration Curve

In the course of the Gasoline/Diesel PM Split Study funded by the Department of Energy (DOE), researchers from DRI analyzed filter samples using both TOR and TOT methods[120]. These data were obtained and analyzed in the SPSS 9.0 statistical package.

Briefly, the DOE study included emissions characterizations of 57 light-duty gasoline vehicles (LDGV) and 34 HD diesel vehicles (HDDV). The vehicles were operated on a number of different test cycles including cold-start and warm-start cycles. The data set employed in this study was generated by DRI and obtained from the DOE study web site.[121] Both EC and OC were analyzed using the same approach. All data from all vehicles were compiled.

First, EC and OC measured by TOR (denoted EC-TOR and OC-TOR) were regressed on EC-TOT and OC-TOT. Studentized residuals from these regressions were noted, and those with Studentized residuals >3 were excluded from further analysis.

Second, each test in the reduced data set was assigned a random number (RAND) on the range [0,1]. Those cases with RAND $\geq$ 0.95 were set aside as a cross-validation data set, and excluded from additional regression analyses.

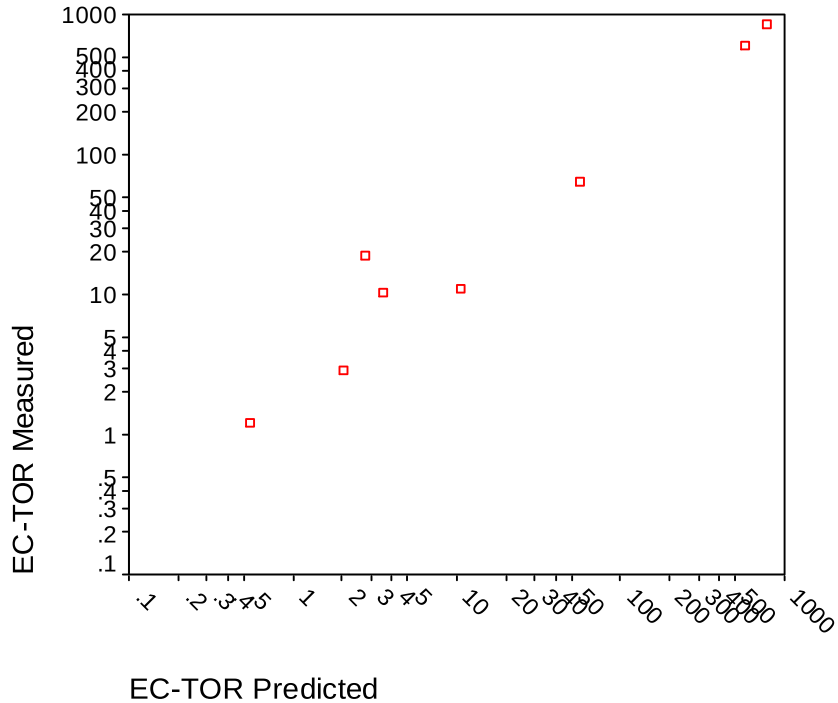
Third, those cases with RAND < 0.95 were regressed again, this time using an inverse uncertainty weighting procedure for each data point. When DRI analyzes a filter sample, it reports an analytical uncertainty associated with the primary estimate of EC and OC. Accordingly, the quality of each datum depends on the level of analytical uncertainty reported. The inverse of the DRI-reported uncertainty ($1/\sigma$) associated with the TOR-based measurement was used to weight each point in the weighted regression.

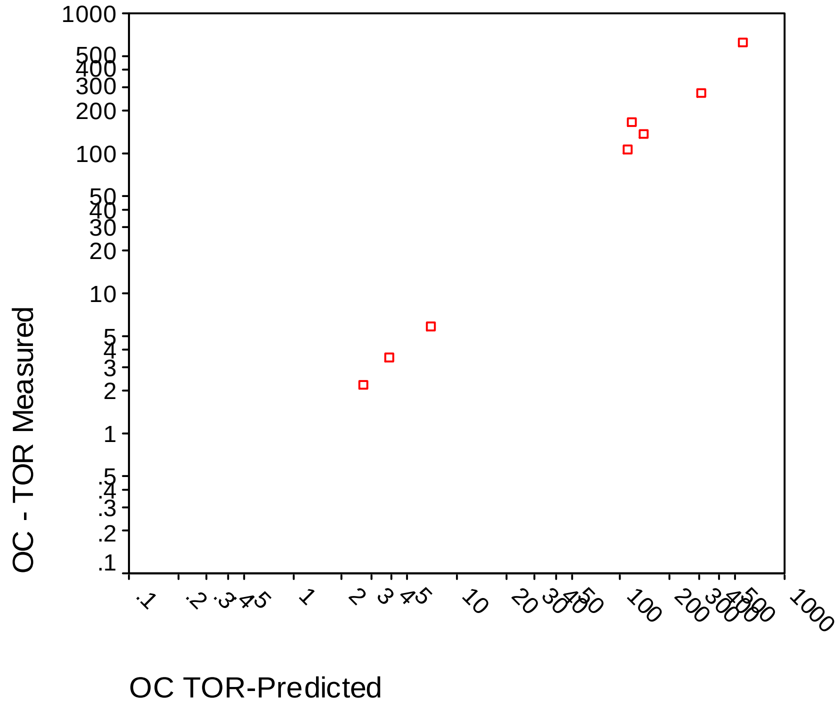
It should be noted that for each regression, the intercept term was set to zero. Models including intercepts did not have intercept terms that reached statistical significance. As such, R^2 values are not considered valid.

Coefficients from the weighted regression for EC and OC are reported below:

Slope	Beta	Std. Error	t-value	Sig.
EC-TOR	1.047	0.011	91.331	<0.0001
OC-TOR	1.014	0.007	153.923	<0.0001

To evaluate the quality of predictions resulting from these statistically-based adjustment factors, they were used to predict EC-TOR and OC-TOR values for the subset of data with RAND ≥ 0.95. Scatter plots of the statistical fits are illustrated below (note logarithmic scaling).





When measured values are regressed against predicted values, the following statistical estimates of fit are obtained:

Prediction	Slope	Std. Error	Intercept	Std. Error
EC	1.080	0.009	3.737	3.173
OC	1.092	0.069	-4.417	16.188

As shown, the prediction vs. observed comparison yields a slope near unity for both EC-TOR and OC-TOR, with nonsignificant intercepts. On this basis, the "calibration" factors for converting EC-TOT and OC-TOT into their respective TOR-based metrics appear reasonable.

It remains an unverified assumption that the "calibration" factors derived from the emissions data derived from DRI[120] as part of the DOE Gasoline / Diesel PM Split Study are general enough to apply to EC-TOT measurements obtained by other research groups.

E.3.4 EC and OC Emission Rates

Selection of Engine Parameters for Predictive Modeling

PERE-HD produces estimates of engine operating conditions and fuel consumption for a given driving cycle. Prediction of EC and OM emissions requires information on the composition of particulate matter as a function of some factor that may be related back to MOVES' activity basis, the time spent in a particular operating mode (opModeID).

It should be noted that continuous ("second-by-second, or "real time") measurement of EC and OM is an exceptionally complicated endeavor. While measurement techniques for EC have been developed that produce apparently good correlation with traditional filter-based methods,

While numerous publications report the EC and OM (or OC) exhaust emission rates across an entire driving cycle, it is not clear which parameter of a particular driving cycle, such as average speed (or power), might be applicable to the extrapolation of the observed rates to other vehicles or driving conditions. As a result, identifying one or more engine parameters that explain the observed variation in driving cycle-based emission rates for EC and OM is desirable. Such parameter(s) will assist in estimating emission associated with short-term variations in driving.

One good candidate for establishing an engine-based emission model is mean effective pressure (MEP). MEP is defined as:

$$MEP = \frac{Pn_R}{V_d N}$$

Here, P is the power (in kW or hp), n_R is the number of crank revolutions per power stroke per cylinder (2 for four-stroke engines, 1 for two-strokes), V_d is the engine displacement, and N is the engine speed. In other words, MEP is the engine torque normalized by volume.

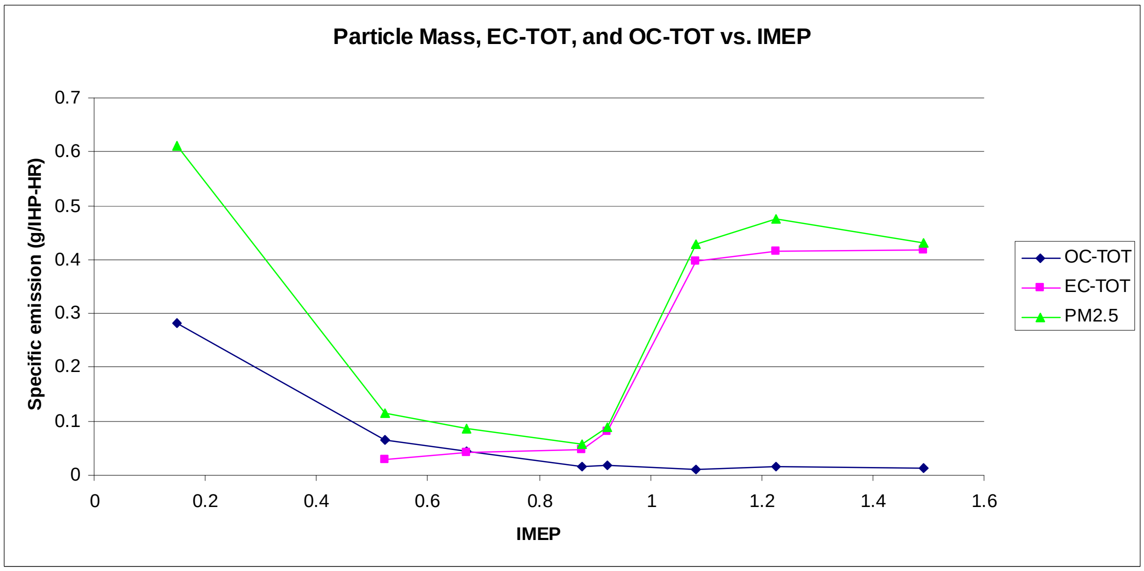
MEP can be broken into various components. "Indicated MEP" or IMEP refers to the sum of BMEP (brake MEP) and FMEP (friction MEP). Heywood (1988)[123] writes that maximum BMEP is an indicator of good engine design and "essentially constant over a wide range of engine sizes." Nam and Giannelli (2005)[34] note that it can be related to fuel MEP multiplied by the indicated or thermal efficiency of an engine, and have developed trend lines in FMEP by model year. As such, since maximum BMEP is comparable across well-designed engines and FMEP can be well-predicted by Nam and Giannelli's trends within PERE, IMEP should be an appropriate metric for building an engine emission model that can be applied across vehicles with different loads and engine displacements.

Emission Data

Kweon et al. (2002)[122] measured particle composition and mass emission rates from a single-cylinder research engine based on an in-line 2.333 liter turbo-charged direct-injection six cylinder Cummins N14-series engine, with a quiescent, shallow dish piston chamber and a quiescent combustion chamber. Emission data were obtained from all eight modes of the CARB 8-mode engine test cycle:

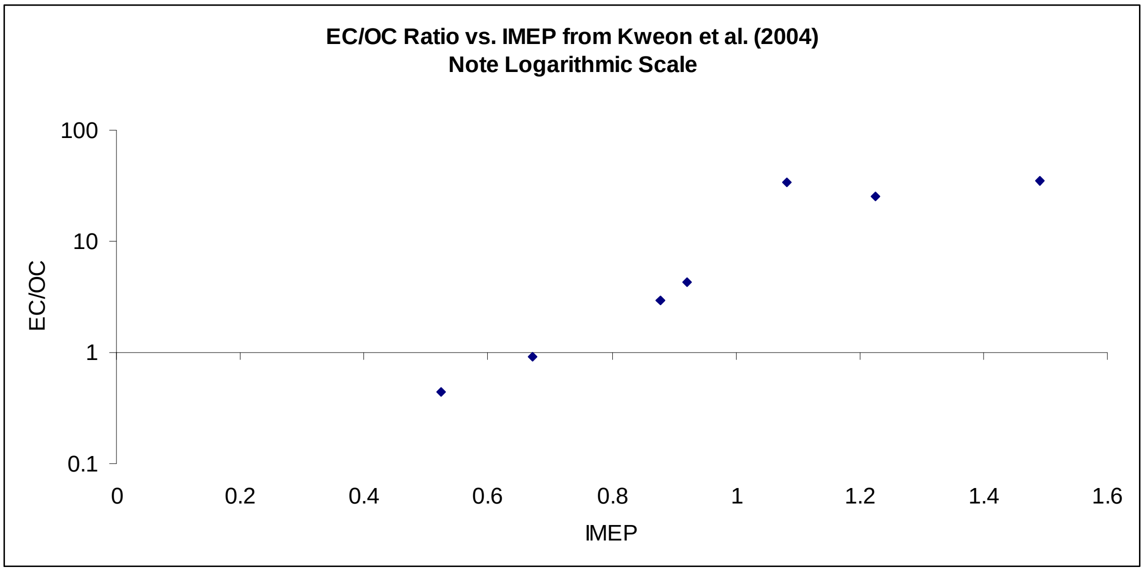
	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6	Mode 7	Mode 8
Speed	1800	1800	1800	1200	1200	1200	1200	700
Load%	100	75	50	25	100	75	50	10 (idle)
Equiv. Ratio (φ)	0.69	0.50	0.34	0.21	0.82	0.69	0.41	0.09
IMEP (MPa)	1.083	0.922	0.671	0.524	1.491	1.225	0.878	0.150

The study reports exhaust mass composition, including $PM_{2.5}$, EC, and organic mass (OM, estimated as 1.2 x OC) measured with TOT (denoted here as EC-TOT and OC-TOT). In the main study, the authors report that EC and OC are highly sensitive to the equivalence ratio. However, IMEP is highly correlated with the measured equivalence ratio ($R^2 = 0.96$). As such, it is reasonable to report the data as a function of IMEP, expecting it to have approximately equal explanatory power as has the equivalence ratio variable. The figure below plots the emission data from Kweon et al. (2002)[122] as a function of IMEP.



As shown in the figure, the EC-TOT work-specific emission rate is relatively insensitive to IMEP except between IMEP of approximately 0.85 and 1.1, where it undergoes a rapid increase. Overall, the EC-TOR/IMEP curve is S-shaped, similar to a logistic curve or growth curve. OC-TOT work-specific emissions are highest at low IMEP (i.e. idle) and are monotonically lower with higher IMEP. Total work-specific $PM_{2.5}$ is not monotonic, but appears to be described by a single global minimum around IMEP ~ 0.9 and two local maxima around IMEP of 0.2 and 1.2, respectively.

The oppositely signed slopes of the emission-IMEP curves for EC-TOT and OC-TOT suggest that there are different underlying physical processes. It is not the intent of this document to explicitly describe the particle-formation mechanisms in a diesel engine. However, the use of two separate functions to predict EC-TOT and OC-TOT separately is warranted. This implies that the EC/OC ratio will vary by engine operating mode. The following figure depicts the EC/OC ratio as a function of IMEP.



Estimation of IMEP-based Emissions of EC and OC

To produce a relationship that generalizes the implied relationship between EC-TOT and OC-TOT work-specific emissions and IMEP in the data presented by Kweon et al. (2002)[122], it is necessary to specify some functional form of a relationship between the two.

A priori, on the basis of visual inspection of the data, a flexible logistic-type curve was fit to the data by a least-squares minimization procedure using the Microsoft Excel "Solver" tool, which employs the GRG2 optimization approach.

The functional form of the logistic-type curves fit to both the EC-TOT and OC-TOT data from Kweon et al. (2002)[122] is as follows:

$$Y = \frac{A}{e^{-Bx} + C}$$

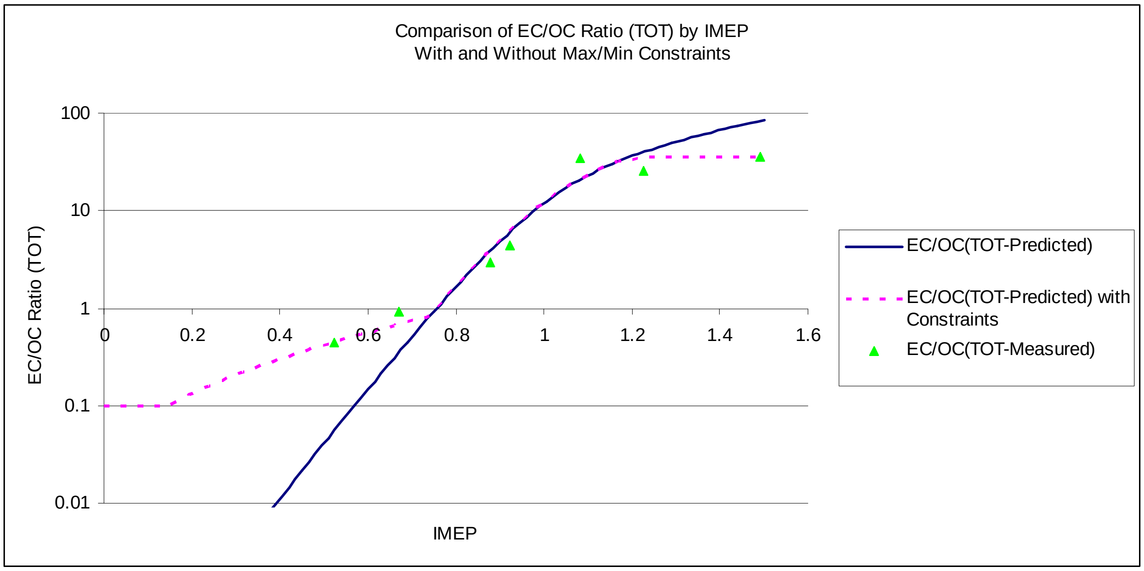
A least-squared error approach was implemented within Microsoft Excel to derive the coefficients for the logistic curves for EC-TOT and OC-TOT. The solutions to the fits are as follows:

Y	*A*	*B*	*C*
EC-TOT	2.12×10^{-5}	-9.79	4.67×10^{-5}
OC-TOT	0.155	-2.275	-0.859

Graphically, in comparison to observed values of EC-TOT and OC-TOT, the fitted curves result in predictions reasonably close to the observed values. Furthermore, when compared to the observed $PM_{2.5}$ values, the sum of predicted EC-TOT and OC-TOT values predict the lack of monotonicity and patterns of maxima and minimum seen in the $PM_{2.5}$ data.

However, as a result of the values predicted by these sigmoid-type curves at high and low IMEP values, extreme patterns in the EC-TOT/OC-TOT ratios predicted occur. These extreme values are artifacts that result solely from the behavior of simplistic logistic curves at the bounds of IMEP in the observed data sets. As a result, for predictive purposes, the maximum and minimum observed EC-TOT and OC-TOT values observed in the data set were set as the artificial limits of predicted EC-TOT and OC-TOT, respectively. While this approach is arbitrary, it does ensure that extreme predictions resulting from the selection of the logistic functional form do not occur.

The following graph (log-scale) depicts the behavior of the TOT-based EC/OC ratio as a function of IMEP. As demonstrated on the graph, without the max/min constraints on predicted EC-TOT and OC-TOT, the predicted ratio assumes values with a much broader range than found in the data.



The approach of constraining predictions to the maximum and minimum values observed in the measured data set is not grounded in any theoretical basis, but is a "brute force" approach. Future revisions to this analysis may consider alternative approaches more grounded in accepted theoretical or statistical methodology.

The logistic curves described above receive IMEP predictions from PERE to predict EC-TOT and OC-TOT emission rates (g/bhp-hr) for every second of a driving cycle. Combined with real-time work estimates from PERE, emissions are expressed in g/s, the same units required for MOVES.

EC-TOT and OC-TOT emission rates are converted to TOR-equivalent rates for use in MOVES, using the TOT-TOR "calibration" relationships described above. Alternatively, TOT-equivalent rates can be used to compare with data from studies employing TOT for carbon analysis.

It should be noted that these emission estimates are based on a single engine. Therefore, predictions of EC and OC emission rates based on these relationships are insensitive to model year, although PERE-HD does vary frictional MEP as a function of model year.

Organic Carbon to Organic Mass Conversion

Carbon is only one component of the organic material found in PM emission samples. Hydrogen, oxygen, and nitrogen are also components of organic molecules found in exhaust PM. For this study, a simple set of OC/OM conversion ratios were employed.

Heywood (1988)[123] presents data on the chemical composition of diesel exhaust PM, presenting characterization of both the "extractable composition" and "dry soot" components of PM measured at idle and at 48 km/h.[123] The composition data is as follows:

	Idle	48 km/h
Atomic formula	$C_{23}H_{29}O_{4.7}N_{0.21}$	$C_{24}H_{30}O_{2.6}N_{0.18}$
OM/OC Ratio	1.39	1.26

The data for the "extractable composition" is assumed to represent the organic mass of particles. The total molar weight to carbon molar weight ratio was used to convert OC to OM. The idle data from Heywood et al. (1988) were used when engine IMEP was 0.15 or under, corresponding to the idle mode of the cycle employed by Kweon et al. (2002)[122]. All other engine conditions employed the ratio based on the 48 km/h sample in Heywood et al. (1998).

E.4 Comparison of Predicted Emissions with Independent Measurements

To ensure that predicted EC and OC emission rates from this approach are reasonable prior to any application for MOVES, PERE-HD based EC and OC emission factors were compared with measured emission factors from an independent study. Shah et al. (2004)[124] report EC and OC emission factor and rates for a series of heavy heavy-duty diesel trucks (HHDT) in California. Shah et al. (2004) report the results of emission testing using the CE-CERT Mobile Emissions Laboratory (MEL), a 53-foot combination truck trailer containing a full-scale dilution tunnel designed to meet Code of Federal Register (CFR) requirements. The primary dilution tunnel is a full-flow constant volume sampler, with a double-wall insulated stainless steel snorkel that connects the MEL directly to the exhaust system of a diesel truck. PM collection systems were designed to meet 2007 CFR specification, including a secondary dilution system (SDS).

The 11 trucks sampled in this study were all large HHDDTs with engine model years 1996-2000, odometers between approximately 9,000 and 547,000 miles, and rated powers from 360-475 hp. It should be noted that these trucks, on average, have larger engines and higher rated power than "typical" trucks on the road. Furthermore, they were loaded with only the MEL, which weighs 20,400 kg. As a result, the emissions from these trucks do not reflect the expected variability in truck running weight described above and used in the PERE-HD runs for this study.

Shah et al. (2004)[124] report emission data for each of the four modes of the CARB HHDDT cycle, including cold start/idle, creep, transient, and cruise. The test cycle represents a wide range of driving patterns, as suggested in the table below. Note that these test cycles are trip-based, so each begins and ends with the vehicle at stop.

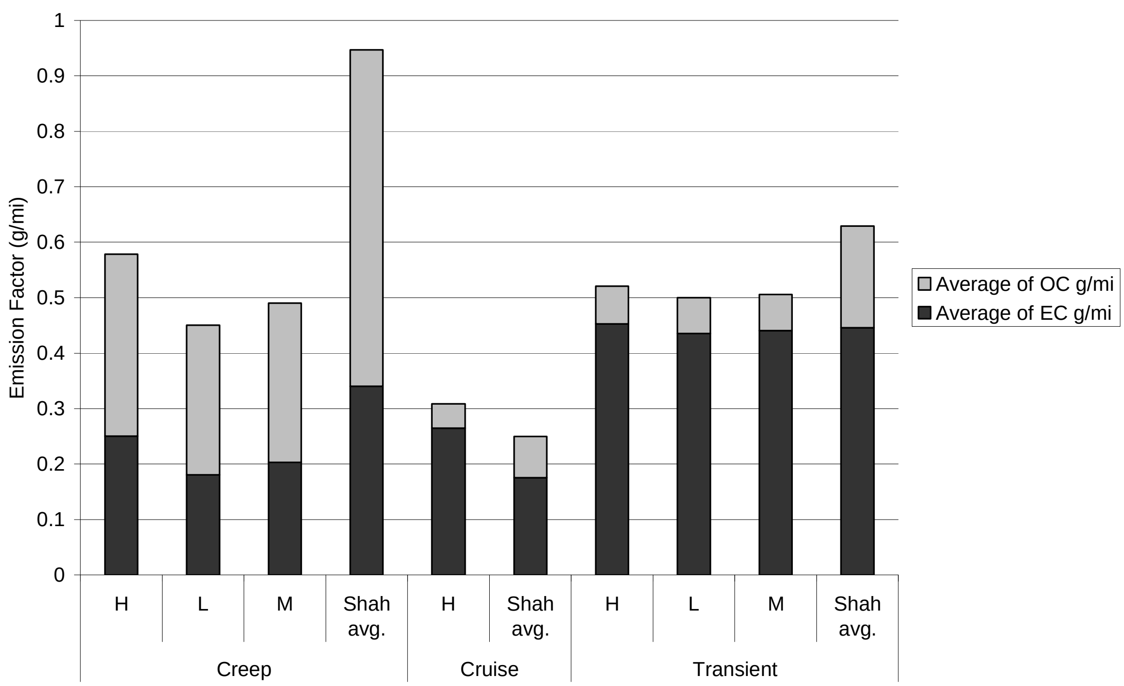
Cycle	Distance (mi)	Duration (s)	Average Speed (mph)	Maximum Speed (mph)	Maximum Acceleration (mph/s)
Cold start/idle	0	600	0	0	0
Creep	0.124	253	1.77	8.24	2.3
Transient	2.85	668	15.4	47.5	3.0
Cruise	23.1	2083	39.9	59.3	2.3

The following table presents the EC-TOT and OC-TOT emission rates reported in Table 6 of the study:

Rate	Idle	Creep	Transient	Cruise
EC (mg/mi)		340±140	446±115	175±172
OC (mg/mi)		607±329	182.9±51.2	74.7±56.3
EC (mg/min)	4.10±2.38	10.4±4.8	110.7±27.0	93.0±68.3
OC (mg/min)	20.9±11.6	17.0±6.4	45.5±13.2	42.3±26.8

The following graph illustrates the comparison between predicted EC-TOT and OC-TOT emission factors predicted by PERE-HD and those reported by Shah et al. (2004)[124]. The letters “H,” “M,” and “L” refer to high, medium, and low accessory loads employed in the PERE-HD runs with IMEP-based emission rates. As shown in the graph, it appears that for transient and cruise conditions, PERE-HD predicts the general between-cycle trends in EC-TOT and OC-TOT emission factors. It appears that for the low-speed “creep cycle,” PERE-HD or the IMEP-based emission rates underpredict total carbon (EC+OC) emission factors, but that the general trend in the EC/OC ratio is directionally correct.

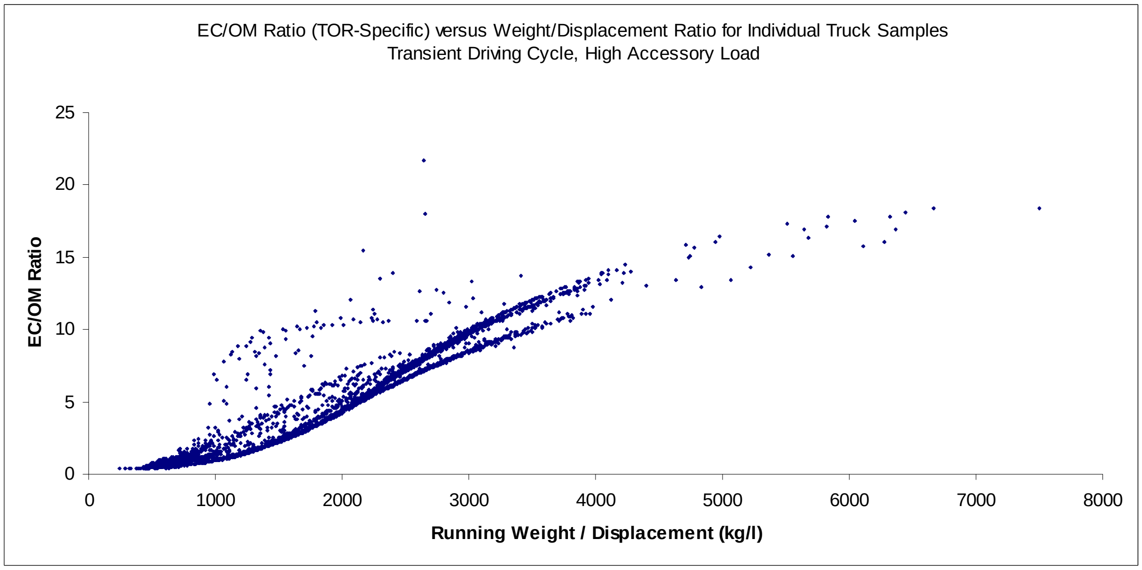
Predicted EC and OC Emission Factors(g/mi) vs. Measured Values in Shah et al. (2004)



E.5 Variability in Predicted EC and OC Emission Rates

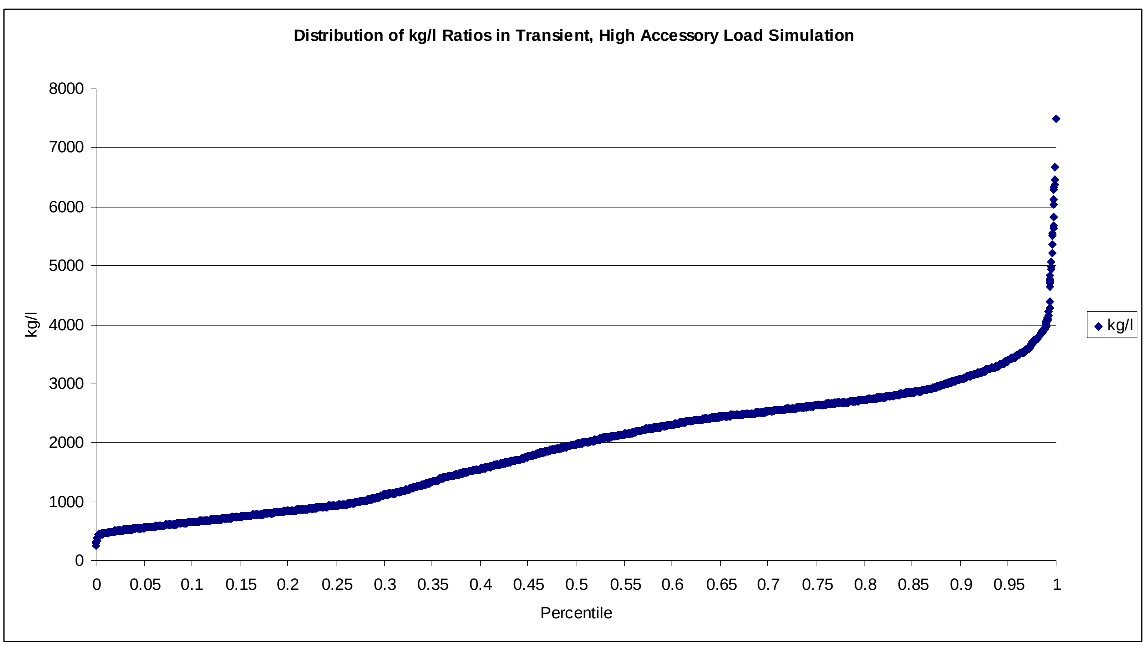
Through the modeling approach used here the influence of variability in vehicle weight and engine displacement on heavy-duty EC and OC emission rates can be assessed. It should be noted that these relationships are contingent on the particular algorithms employed in PERE-HD for estimating power and IMEP, as well as on the functional form of the IMEP-based emission relationship described above. As such, the analysis of variability in EC and OC emission rates is constrained within the functional forms of all models employed.

The graph below depicts the TOR-specific ratios of the total amount of EC and OM emitted across the transient driving cycle. As is apparent, increasing running weight per unit of engine displacement is associated with an increased EC/OC ratio. The highest EC/OM ratios, located in the upper right-hand-quadrant of the graph, correspond to vehicles loaded with extreme weight relative to the total available engine displacement.

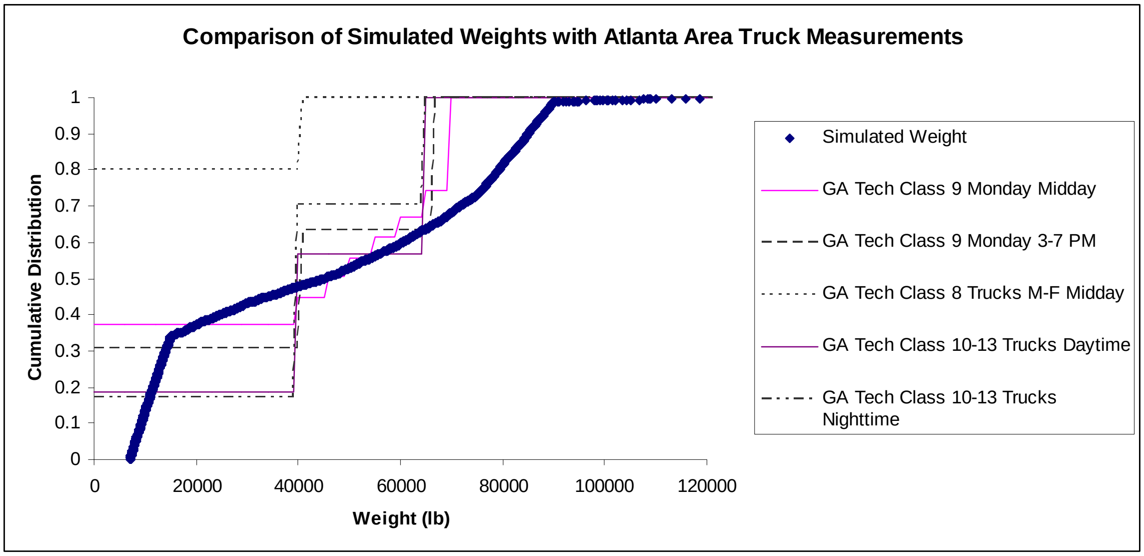


In general, these results reflect the role that running weight has on IMEP in a truck. Since IMEP correlates highly with the air/fuel ratio (or equivalence ratio φ), the data suggest that EC/OC partitioning is driven by the pyrolysis that occurs in engines under load.

Very few weight/displacement pairings are greater than 3,300 kg/L. The following graph depicts the cumulative frequency distribution (CFD) of simulated weight/displacement ratios in PERE-HD.



For a 12 L engine, 3,000 kg/L would correspond to a running weight of 39600 kg (87,302 lb). Such vehicle loadings are infrequent, as they exceed Federal and state limits for vehicle weights on highways. The graph below presents the cumulative distribution of simulated weights, based on the VIUS microdata. Furthermore, the graph presents cumulative frequency distributions for several broad weight categories reported by Ahanotu (1999)[125] for trucks in the Atlanta metropolitan area. Note that in the graph, the highest weight category reported by Ahanotu (1999) is represented as 100%, although the actual maxima of observed trucks are unknown.



In general, the sensitivity of EC/OM ratios to the weight/displacement ratio suggest that properly capturing the variability in both inputs is key to developing representative inputs for MOVES.

E.6 Calculating EC/OC fraction by Operating Mode

The modeling described in the previous sections has been employed to create second-by-second estimates of EC-TOR and OC-TOR emission factors for use in the MOVES emissionRateByAge table. The next step of consists of appropriately binning the outputs to fit the MOVES operating-mode structure. EC and nonECPM emission rates, , are the inputs to the MOVES model for PM inventory calculations. To convert the total PM rates calculated from heavy-duty emissions analysis into EC and nonECPM rates, we must calculate EC and nonECPM fractions by operating modes. Then, the total PM rate can be multiplied by the EC and nonECPM fractions to obtain EC and NonECPM input emission rates.

PM emissions contain additional inorganic species. However, the total carbon (TC =EC + OC) composes almost all the $PM_{2.5}$ emissions from conventional diesel emissions. As such, we use the EC/TC as a surrogate for the EC/PM emissions in MOVES.

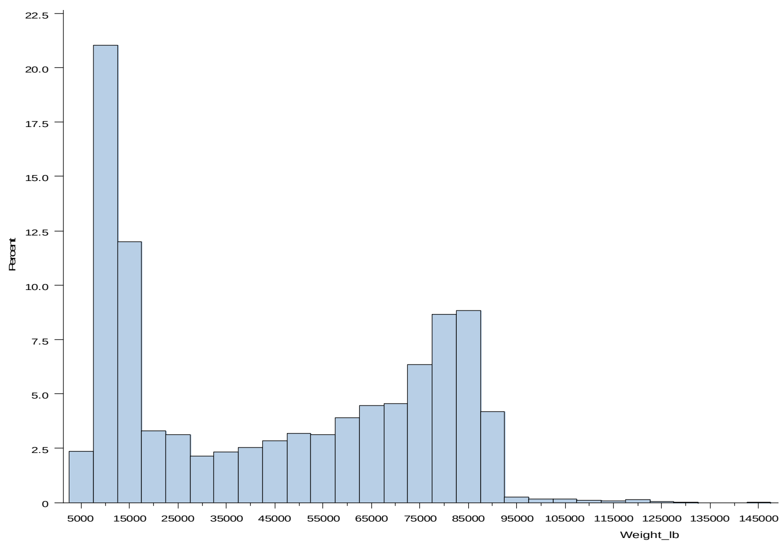
One of PERE's outputs for heavy-duty vehicles is the track road-load coefficients. For each individual weight in the distribution, PERE outputs a set of *A*/*B*/*C* coefficients similar to the ones used to calculate VSP in the HC, CO, and PM emission rate analysis. We used these coefficients and weights to calculate VSP for each second using the equation below.

$$VSP_t = \frac{Av_t + Bv_t^2 + Cv_t^3 + mv_t a_t}{m}$$

This equation is implemented slightly differently than the one used for analysis of the chassis dynamometer testing for PM, HC, and CO since the road load coefficients (*A*, *B*, and *C*) and weight (or mass) *m* were specific to each individual vehicle, not general to the regulatory class. In the PM, HC, and CO equation, the road load coefficients and denominator mass were not specific to the vehicle and the numerator mass was specific to the vehicle. We felt confident in using vehicle-specific numbers because we performed the analysis using a full representative distribution of weights and displacements. Also, since we are interested in the EC and nonECPM fractions rather than the actual rates themselves, normalizing by the actual weight provides a more accurate picture. For example, a large engine operating at 90% of rated power (high VSP) would have a similar EC fraction as a smaller engine operating at 90% of rated power, even though the large engine would likely be hauling a proportionally greater amount of weight. This is also supported by the previous research and analysis that relates EC fraction to IMEP and not power itself. The large engine would, however, emit a larger EC rate than the smaller engine, but this difference in rates is captured by our PM emission rate analysis.

We separated vehicles into two different regulatory classes based on running weight (we did not have GVWR information). The weight distribution used in the analysis is shown below.

Representative distribution of weights used in the EC/OC analysis.



Based on this weight distribution, we considered all vehicles weighing more than 40,000 lb to be HHD vehicles and all vehicles less than 40,000 to be MHD vehicles. This was a very simple approach to stratifying by regulatory class.

As EC and nonECPM rates were also computed for each second during each cycle, we were able to average the EC and nonECPM rates by operating mode. Then, we calculated the fractions of EC and nonECPM for each operating mode. For the LHD classes, we used the MHD fractions, and for buses, we used the HHD fractions.

$$f_{EC} = \frac{\sum \bar{r}_{EC}}{\sum \bar{r}_{EC} + \sum \bar{r}_{OC}}, \quad f_{NonEC} = 1 - f_{EC}$$

The resulting EC fractions by operating mode are shown in Figure 2-20 in the main body of this report.

Appendix F Heavy-duty Gasoline Start Emissions Analysis Figures

Figure F-1. Cold-Start Emissions (FTP, g) for Heavy-Duty Gasoline Vehicles, averaged by Model-year and Age Groups

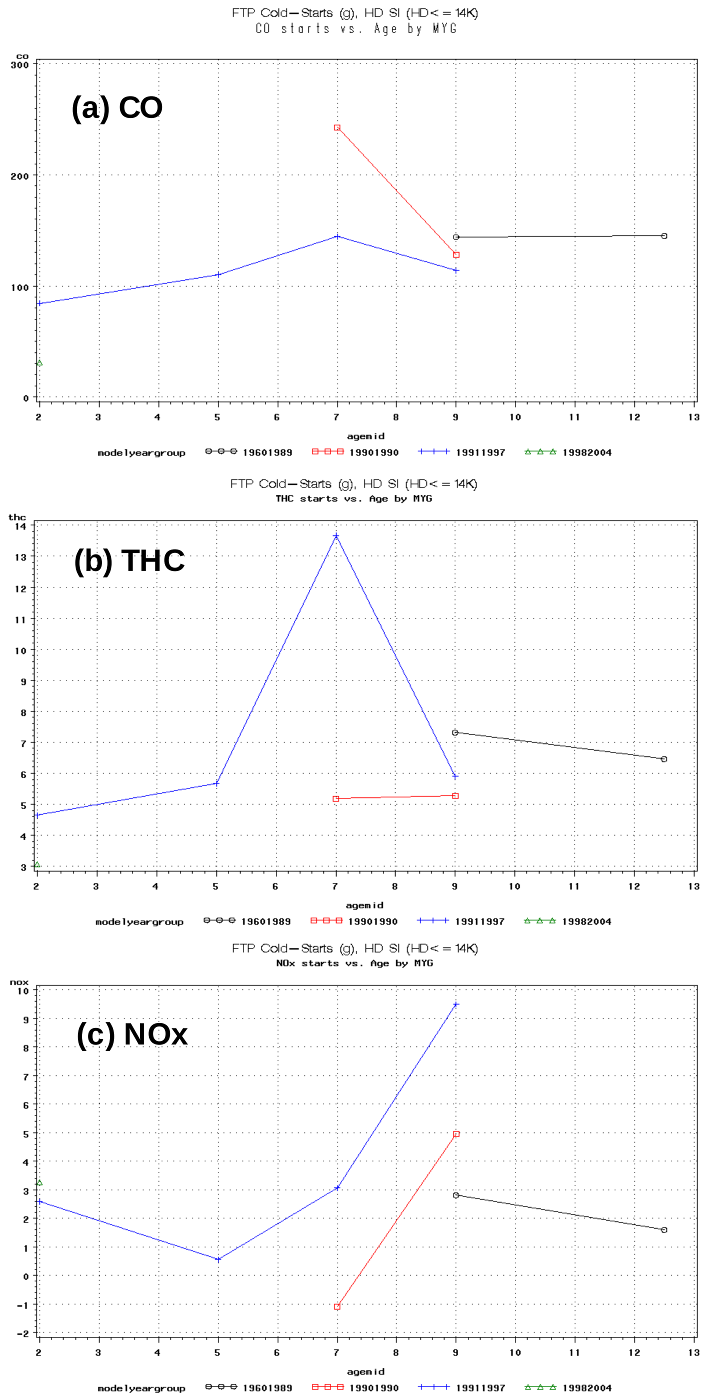


Figure F-2. Cold-Start FTP Emissions for Heavy-Duty Gasoline Vehicles, GEOMETRIC MEANS by Model-year and Age Groups

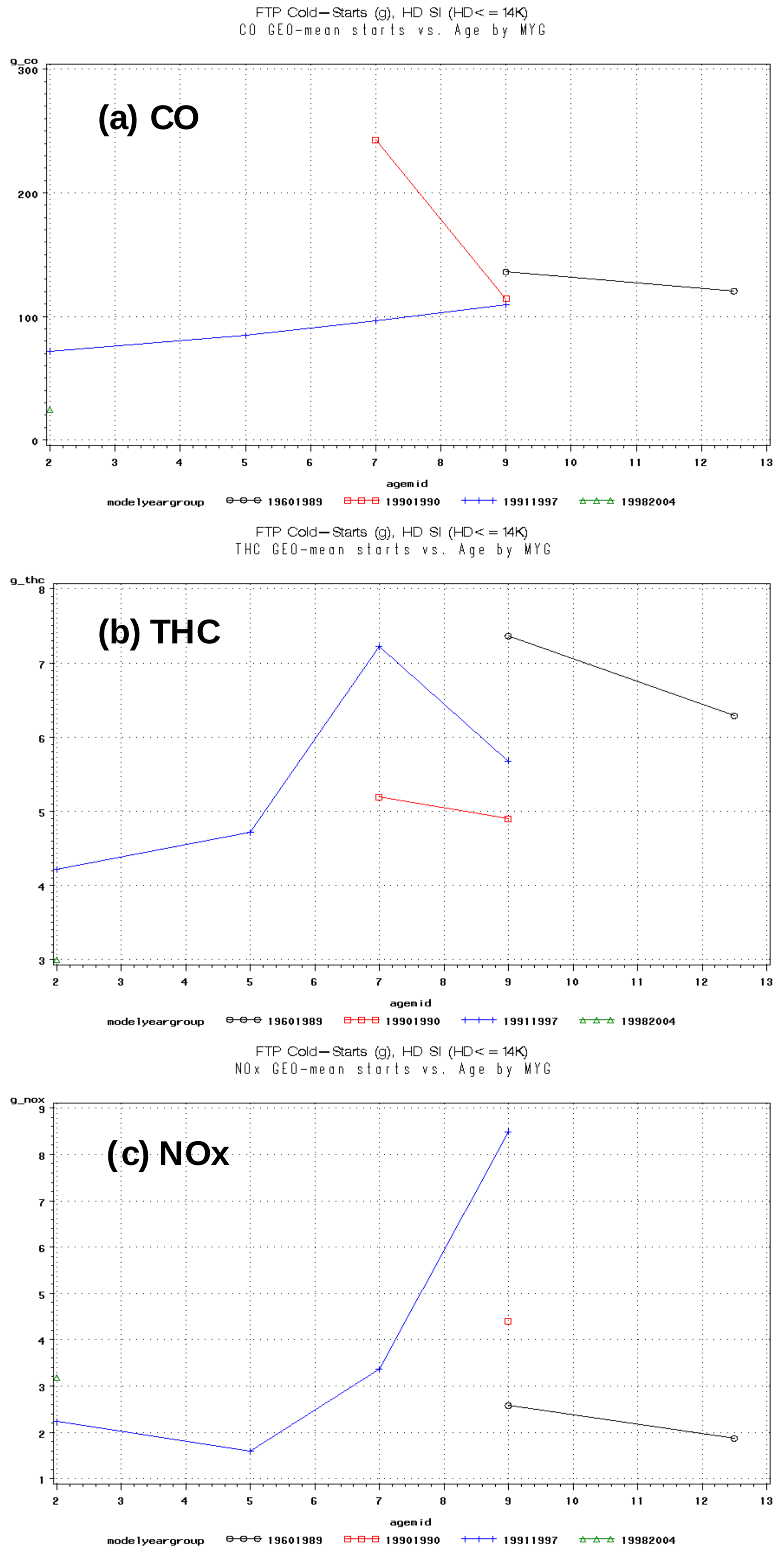


Figure F-3. Cold-start FTP Emissions for Heavy-Duty Gasoline Trucks: LOGARITHMIC STANDARD DEVIATION by Model-year and Age Groups.

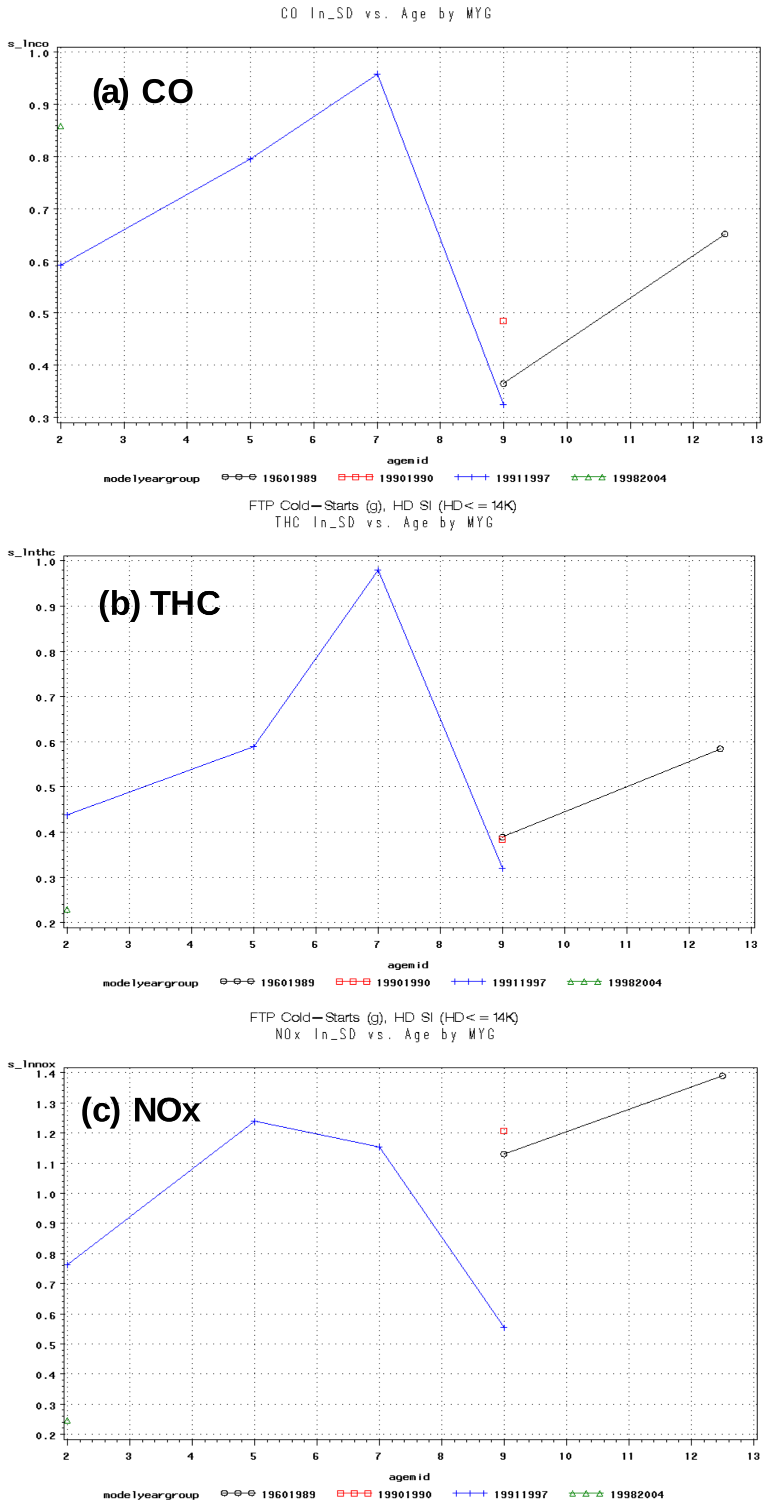


Figure F-4. Cold-Start Emissions for Heavy-Duty Gasoline Trucks: RECALCULATED ARITHMETIC MEANS by Model-year and Age Groups.

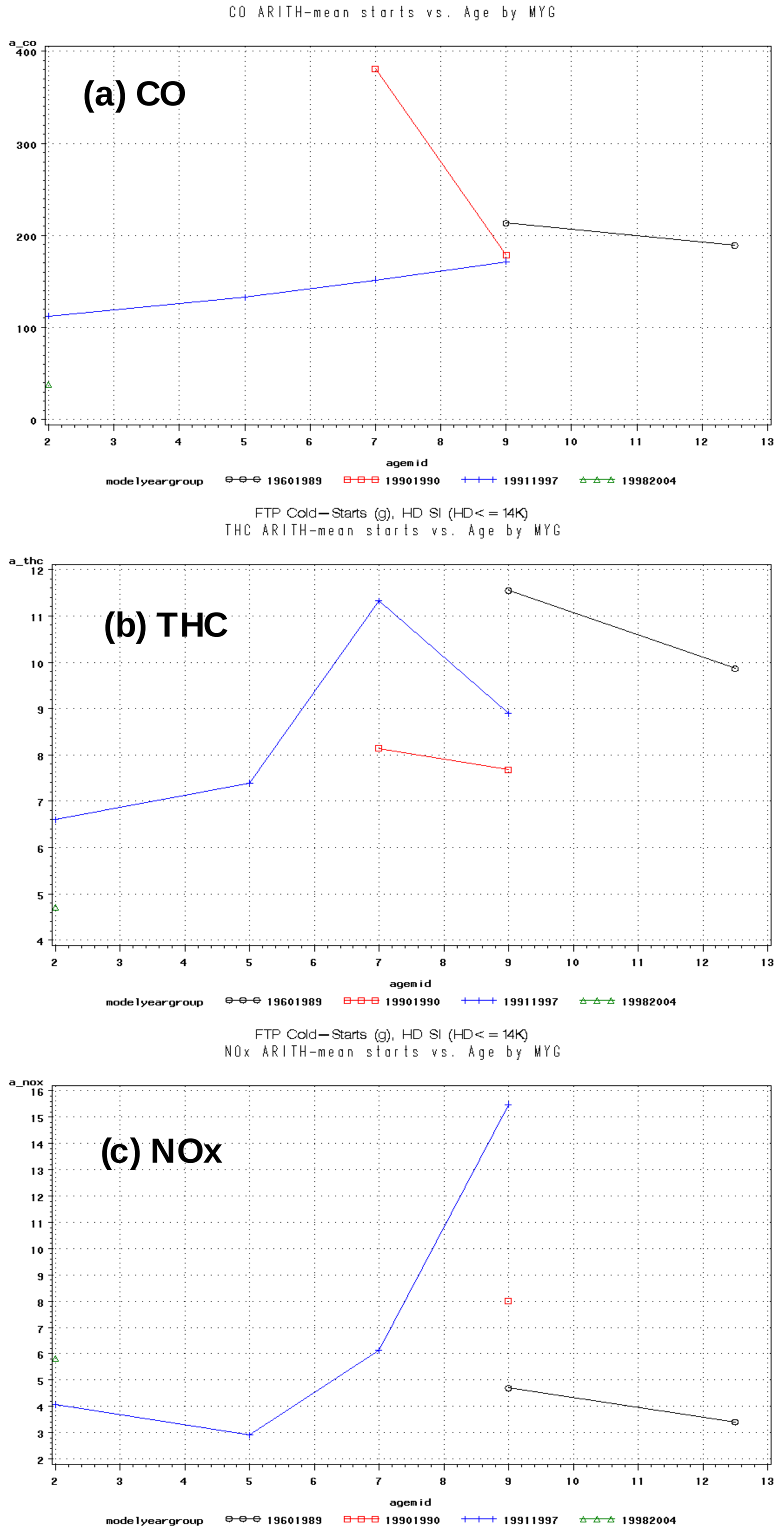


Table F-1. Emission Standards for Heavy-Duty Spark-Ignition On-road Engines

Regulatory Class	Model Year	Emissions Standards (g/hp-hr)				
		CO	THC	NMHC	NOx	NMHC + NOx
LHD2b3	1990	14.4	1.1		6.0	
	1991-1997	14.4	1.1		5.0	
	1998-2004	14.4	1.1		4.0	
	2005-2007	14.4				1.0
	2008+	14.4		0.14	0.20	
LHD45, MHD	1990	37.1	1.9		6.0	
	1991-1997	37.1	1.9		5.0	
	1998-2004	37.1	1.9		4.0	
	2005-2007	37.1				1.0
	2008+	14.4		0.14	0.20	

Appendix G Responses to Peer-Review Comments

This section provides the list of peer reviewer comments submitted in response to the updates made to the draft MOVES2014 Heavy-Duty Emission Rates Report received February 5, 2014.

The peer-reviewers were charged with reviewing the following sections of the report.

- Updates to Chapter 2.1.1: Heavy Duty Diesel, Running NOx Emissions
- Section 2.1.2.3.5 Computation of Elemental Carbon and Non-Elemental Carbon Emissions
- Section 3.3 "Updates to Emission Rates in MOVES2014" [material in Sections 3.1.1.3 and 3.1.1.4 in the current report]
- Chapter 4 Heavy-Duty Compressed Natural Gas Transit Bus Emissions
- Chapter 5 Heavy-Duty Crankcase Emissions

After the peer-review, additional changes were made to the report in response to the peer-review comments, internal EPA review, and updates made to the MOVES2014 heavy-duty emission rates that occurred after the peer-review (Such as the addition of regulatory class LHD≤10K and LHD≤14K, and the redefinition of regulatory class LHD45 described in Section 1.1). The edits have results in section changes and page number changes. In the responses to comments, we have updated section number, table, figure, equation, and page number references [in brackets] to be current with the released report.

G.1 Adequacy of Selected Data Sources

Does the presentation give a description of selected data sources sufficient to allow the reader to form a general view of the quantity, quality and representativeness of data used in the development of emission rates? Are you able to recommend alternate data sources which might better allow the model to estimate national or regional default values?

G.1.1 Dr. Mohamadreza Farzaneh

In general, the authors adequately described the data sources, data gaps and limitations, and assumptions and methodologies they used to address these limitations. The list below shows a few instances that they can improve the presentation by providing more details on their assumptions:

Page 14 [Section 2.1.1.4.4, Page 23] , last line – A temperature threshold of 300C is assumed for PM regeneration. No reference is provided to support this assumption.

> *RESPONSE: Temperature, along with air-fuel ratio, and ECU signals, was used to estimate the state of the engine/emission control system (in PM regeneration, or normal operation). We have clarified the text that additional variables were used then temperature alone.*

Page 15 [Section 2.1.1.4.4, Page 23] line 2 – it is assumed that 10% of VMT for PM regeneration frequency. No reference listed for to the data used for this assumption.

RESPONSE: The approximate 10% frequency of PM regeneration was observed from the EPA data set on the LNT/DPF equipped vehicle. We have clarified that the 10% assumption is obtained from the LNT data set.

Page 37,[Page 49] section 2.1.2.3.2 – the values "0.46" and "0.60" are taken from MOBILE6.2; is there any data to confirm they are still valid?

RESPONSE: The "0.60" value is removed from the report, since the updated LHD≤14K and LHD45 emission rates for MOVES2014 s use the same STP-based PM emission rates as MHD vehicles. We added a footnote in Section 2.1.2.3.2 that discusses this change between MOVES2010 and MOVES2014. Presently we do not have second-by-second PM emissions from regulatory class LHD≤10K diesel vehicles to evaluate whether the "0.46" value is still a reasonable value.

Page 37. [Page 50] Section 2.1.2.3.2 – Where [are] the coefficient values "0.40, 0.70, and .50" coming from?

RESPONSE: We added Table 2-13 which displays the heavy-duty CI and Urban Bus PM emission standards for model year groups 1991-1993, 1994-1995, and 1996-2006. The ratio in standards shows the derivation of 0.40, 0.70, and 0.50.

Page 104 [Page 160]-– NO2/NOx fractions are based on a single 2003 study (three CNG transit buses and the same engine make/model). A 12.7% seems to be too low (based on a limited data for CNG refuse trucks collected by TTI). Although, I should admit that this fraction for CNG engines is sensitive to the drive cycle and can vary significantly for different vehicle types. Further data is definitely needed and TTI will be happy to share the mentioned CNG refuse trucks data with EPA.

RESPONSE: We added Chapter 6: Nitrogen Oxide Composition, which presents the NOx fractions for all vehicle types, including diesel and gasoline, which were previously not located in this report. We agree that further data is needed to evaluate all the NOx fractions, including from CNG transit buses. By clearly stating the fractions, we intend that the MOVES rates can be more easily evaluated by making comparisons to NO and NO_2 emission measurements.

TTI's Air Quality Program has performed quite a few studies using mostly PEMS equipment that could enhance the database used for this analysis. We will be happy to share any information gathered during these studies. Specifically, TTI collected second by second data from class 8b HHDVs driving at speeds as high as 85 mph which can be used to improve the rates for the high power/high speed bins.

Expanding MOBILE6 Rates to Accommodate High Speeds

Sponsor: Houston Advanced Research Center and Center for International Intelligent Transportation Research

Budget: $150,000

Description: PEMS testing of 3 long haul HHD trucks under different acceleration and speed conditions including speeds up to 85mph.

Location: Study performed at TTI's High Speed Test Track in Pecos, Texas

RESPONSE: We intend to use this study and others to evaluate MOVES and improve MOVES data in future versions.

G.1.2 Dr. Janet Yanowitz

p. 7 [Page 1] – "From each data set, we used only tests we determined to be valid." Specify what proportion of each data set was discarded for time alignment and other issues.

RESPONSE: We added a sentence specifying that approximately 7% of the ROVER and HDIU data were removed due to the correlation checks. No data was removed from the WVU MEMS data, as is stated in the paragraph. All the data from Houston Drayage met the criteria for correlation between CO2 and engine power. Table 2-2 specifies the number of vehicles that were included in the final data set.

p. 19, Figure 1 [Page 32, Figure 2-3]- it would be useful to include the number of data points available for each operating mode, as perhaps that explains why the error bars are so large for certain operating modes. If not, perhaps the authors could suggest another reason for the large error bars (does your hole-filling technique result in these large error bars? Why?).

RESPONSE: As discussed in Section G.2.2. (4th Comment), the error bars represent 95% confidence intervals of the mean, which increase with smaller number of sample points and with the standard deviation. Also, as stated in Section G.2.2, and Section 2.1.1.8 of the report, if no data were available, the relative standard error, was applied to the forecasted to estimate confidence intervals for the operating modes, age groups, or regulatory class with missing data.

G.2 Clarity of Analytical Methods and Procedures

Is the description of analytic methods and procedures clear and detailed enough to allow the reader to develop an adequate understanding of the steps taken and assumptions made by EPA to develop the model inputs? Are examples selected for tables and figures well-chosen and designed to assist the reader in understanding approaches and methods?

G.2.1 Dr. Mohamadreza Farzaneh

The descriptions are clear and I was able to develop an adequate understanding of the steps taken and assumptions made. The following are a few questions I had on the procedures:

Page 36, eq. 14 [Page 48, Equation 2-16] – Is there any study on the validity of this normalization approach? The main concern is that in the current form, it assumes that all the changes are essentially linear; which might not be necessarily true. An empirical comparison will show how this assumption is representative of the actual behavior of the data.

RESPONSE: We added a reference Kinsey et al. (2006) that showed that time-integrated TEOM measurements have good correlation with gravimetric filter measurements.

Page 37 [Page 50], first paragraph under 2.1.2.2.3, line 4 – what is the criteria/definition for "sufficient"?

RESPONSE: The material in this section was peer-reviewed for MOVES2010, and was outside the scope of the review for MOVES2014. The details on the original analysis are no *longer available, but the original author believes that 'sufficient' meant that there were less than ~ 25 points within each operating mode bin.*

The examples for tables and figures provide adequate information are on the methodologies used. The presentation of figures and tables can be improved as follows:

Some of the tables and figures that use colors are not easy to follow in black and white print. For example, in figures 47 [Figure 4-6] to 52 [Figure 4-11], the same symbol is used for 0-3 and 4-5 age groups while their colors are not different in BW print. The same is true for figure 42 [45]. In general, when using colors in tables and charts, they should be selected in a way so they could be differentiated in BW print.

RESPONSE: The two age groups of measurements are now represented by different symbols, blue diamonds correspond to the 0-3 age group and purple triangles correspond to the 4-5 age group.

I suggest including the pollutant name on all graphs dealing with the rates; e.g. figures 47-58. [Now Figure 4-6 through Figure 4-11].

Tables 51 to 55 [Table 5-2 to Table 5-7]. Table captions need to mention what pollutant they cover.

RESPONSE: These pollutant names have been added to the y-axis labels for Figure 4-6 through Figure 4-11, and the pollutant names have been added to Table 5-2 through Table 5-7.

G.2.2 Dr. Janet Yanowitz

Add a list of acronyms, with their meanings spelled out.

RESPONSE: We have revised the report to define the acronym when it is first used in a new section, and to be consistent with their use (for example using the regulatory class name consistently,, e.g. LHD≤10K, rather than intermixing references to the regClassID, e.g. 40.

p. 1 [Page 1]– first paragraph, "exhaust rate inputs" is a confusing way to refer to "emission factors" based on various inputs such as model year, engine type, etc. Emission factors were also developed for organic species (including formaldehyde and acetaldehyde) and PM components.

RESPONSE: We removed the terminology "exhaust rate inputs", and replaced it with emission rates, which is the terminology we use to express emissions/distance or emissions/time in the report. We also added several sentences to the introductory paragraphs of the report that reference the Toxics and Speciation report to the places where aggregate measures of organic gases (e.g. VOC, NMOG, TOG) and individual compounds (e.g. formaldehyde and acetaldehyde) are located.

p.15 – Table 10 [Page 25, Table 2-6] is a very useful table, but it could be made better by ensuring that each box representing an estimate detailed the base case upon which the estimate was made and the whether it was done by proportioning by emissions standards or certification data (e.g. "proportioned to 1990 LHD by certification levels", or "proportioned to 1991-1997 HHD by emissions standards" instead of just "proportioned to certification levels" or "proportioned to HHD").

RESPONSE: We have updated the table so that the source the data used as the 'base data', and what data is being used to ratio the 'base' data is clear from the table. We also added

Equation 2-8, Equation 2-9, Equation 2-10, and Equation 2-11 were added to clarify the adjustments made with limited data.

p. 19 through p. 31, Figures 1-3, 6-17 [Pages 32-43, Figure 2-3-Figure 2-19] It would be beneficial to show which graph points were developed from "hole-filling" estimation techniques for individual mode and which reflect actual data, so that the reader could better judge how well the estimation techniques work. This could be accomplished by showing all the estimated data using a different symbol than the measured data. How were the error bars for operating modes in which there was no data calculated?

RESPONSE: Where data existed, error bars were estimated using a 95 percent confidence interval of the mean emission rate. The standard error was the statistic used for this. Where holes were filled, the relative standard error of the emission rate (i.e. standard error normalized by the mean) was kept constant with that of the data from which any missing rates were proportioned. We have added text in the Figure with error bars: "Error bars represent the 95% confidence interval of the mean."

We agree that labeling the 'hole-filled' data differently from the actual data on the emission rate figures would be beneficial to judge the quality of the 'hole-filled' data. We will consider doing this for future updates to the emission rates.

p. 112, Table 54 [Page 156 Table 5-6]– If I understand the text correctly, the emission factors for CNG and gasoline (1969 and later) are the same. If so the title of the table and the top of the second column should state that Table 54 applies also to CNG. If not please explain how the CNG criteria emissions from the crankcase are estimated

RESPONSE: We added CNG to the Table heading for Table 5-6.

G.3 Appropriateness of Technical Approach

Are the methods and procedures employed technically appropriate and reasonable, with respect to the relevant disciplines, including physics, chemistry, engineering, mathematics and statistics? Are you able to suggest or recommend alternate approaches that might better achieve the goal of developing accurate and representative model inputs? In making recommendations please distinguish between cases involving reasonable disagreement in adoption of methods as opposed to cases where you conclude that current methods involve specific technical errors.

G.3.1 Dr. Mohamadreza Farzaneh

Yes, I found the methodologies sound and reasonable given the data available. Below are a few questions and comments on the analyses.

Page 8, first paragraph [Page 9]– it is implied that using ECU data will be more accurate than using speed and acceleration. Is this a fact supported by data (any references)? The methodology based on the ECU data uses a few simplifying assumptions that can introduce significant uncertainty into the process. A quantitative comparison would validate the implied assumption for this section.

RESPONSE: We added discussion in Section 1.3 why we regard ECU data as more accurate for on-road tests, than using generic road-load coefficients. However, we are not aware of studies that have compared power estimates from ECU to estimates from speed/acceleration data from road load coefficients.

Figures 9 through 11 [Figure 2-10 through Figure 2-12] - opMode 33 seems to have a high discrepancy between MOVES and data. Is there any explanation for this trend.

RESPONSE: Considering the small number of vehicles in the Houston Drayage data and the fleet characteristics, such as driving pattern and the level of maintenance, of the drayage fleet, we believe that much higher NOx rates from Houston Drayage seen for opMode 33 may not be representative of the general heavy-heavy duty fleet. However, we agree that it is an interesting observation and we plan to look into this issue when we validate the MOVES rates compared to other independent data.

G.3.2 Dr. Janet Yanowitz

p. 12 Eq. 4 [Equation 2-3]- rather than k=1 underneath the leftmost sigma it should be j=1

p. 12 Eq. 5 [Equation 2-4] - s2veh should be s2j, n should be nj in description s2veh should be s2j = the variance in data for vehicle j

p. 13 Eqs. 7 and 8 and in text above [Equation 2-6 and Equation 2-7]–all subscripts pol should be p to be consistent with Equations 4 and 6 [Equation 2-3 and Equation 2-5]

Response: We have incorporated these corrections to assure that the notation is consistent across these equations and within the text.

G.4 Appropriateness of Assumptions

In areas where EPA has concluded that applicable data is meager or unavailable, and consequently has made assumptions to frame approaches and arrive at solutions, do you agree that the assumptions made are appropriate and reasonable? If not, and you are so able, please suggest alternative sets of assumptions that might lead to more reasonable or accurate model inputs while allowing a reasonable margin of environmental protection.

G.4.1 Dr. Mohamadreza Farzaneh

Overall, I found the assumptions reasonable and valid; however, some of the assumptions lack any supporting information/reference. Citing an appropriate reference would increase the validity of these assumptions.

RESPONSE: In the revised report, we have made an effort to be more transparent about our assumptions we have used. For example, we have added Equation 2-10 and Equation 2-11 in Section 2.1.1.4.4 to clearly state how our assumptions on the LNT penetration and LNT emission impacts are used to estimate the 2007-2009 LHD≤10K emissions.

G.4.2 Dr. Janet Yanowitz

p. 7 [Section 2.1.1.8, Page 36]- “Updating MOVES emission rates …was considered when….MOVES 2010 rates …were not based on actual data….and the comparisons between MOVES 2010 and independent data show a clear indication of disagreement” . I would suggest that you develop criteria for what is a “clear indication of disagreement” such that it can be consistently applied for all comparisons between existing rates and new data.

RESPONSE: We clarified criteria used when comparing the emission rates in MOVES2010 to the independent data, in the text, stating: “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."*

This reviewer recommends that you replace older values not based on actual data, whenever actual data becomes available, rather than set some arbitrary level of acceptable disagreement. Actual data should take precedence over estimated values in virtually all circumstances except when there is reason to believe the actual data is not representative.

RESPONSE: Although we agree that it is preferable to have all emission rates based on real-data when possible, due to limited resources, we only updated emission rates that met both of these criteria. We will consider this in our planning for updating MOVES in the future.

p. 13 [Page 22, Section 2.1.1.4.3]– please clarify why you use[d] MY 2003-2006 data to estimate the rates for model year 2010 instead of the 2007-2009 data.

RESPONSE: Due to limited resources, we determined to only update emission rates for which we had additional data. We plan to update the emission rates for model year 2010 and later heavy-heavy trucks based on actual measurements as they become available in the near future.

p. 14 [Page 21, Section 2.1.1.4.2] – paragraph beginning "For certain model years…" clarify why you used a ratio of emission standards for missing regulatory classes instead of a ratio of certification data. Generally it appears that you used certification data to predict missing values (for example for all the 1990 and earlier data), as opposed to emission standards. To this reviewer this appears to be the better approach as it is based on actual emissions measurements as opposed to standards which are frequently exceeded by a significant safety factor. For the years 2007-2009 you have data to test which approach works best, certification data or emissions standards for different regulatory classes – consider running a test, although in the absence of further information you should use a ratio of certification data in place of a ratio of emissions standards where possible.

RESPONSE: We have revised this paragraph so that it better communicates that we used the ratio in emissions data rather than ratio of emission standards. Also, we agree that it is preferable to use ratios of certification data, rather than ratios in emission standards. We have used ratios in certification data rather than emission standards in all places where we had available data, or a citable reference. For example, for future model years, the emission standards were used to predict emissions because certification did not exist yet. These rates could be updated as those model years enter the fleet and enter into test programs.

G.5 Consistency with Existing Body of Data and Literature

Are the resulting model inputs appropriate, and to the best of your knowledge and experience, reasonably consistent with physical and chemical processes involved in exhaust emissions formation and control? Are the resulting model inputs empirically consistent with the body of data and literature that has come to your attention?

G.5.1 Dr. Mohamadreza Farzaneh

Yes, the model inputs are appropriate are consistent with physical and chemical processes involved in exhaust emissions formation and control. The rates can benefit significantly from more data collection and assembly.

I found the resulting inputs empirically consistent with the body of data and literature that I have worked with. In my response to Question 1, I listed a study by TTI that produced emissions testing data of heavy duty vehicles at high speeds which could be of use to expand the existing database. The following are a few examples of areas where additional data will greatly enhance the emission rates developed for heavy duty vehicles:

- NOx emissions increase due to disabling SCR after the end of warranty period
- More data on crankcase emissions for 2007+ to better characterize the effect of aging
- Emissions of 2010+ heavy duty diesel vehicles
- I suggest using "×" symbol instead on "*" in equations on page 37 [Page 50, Equation 2-17].

RESPONSE: We agree that additional data on 2007+ diesel vehicles are needed, particularly real-world data on vehicles equipped with SCR technology. We will consider these suggestions as we set our priorities for future MOVES updates. We have made change to using "×" symbol for multiplication in Equation 2-17 .

G.5.2 Dr. Janet Yanowitz

Yes.

G.6 CNG Transit Bus Running and Start Exhaust Emission Rate Methodology

Is the methodology for creating new MOVES2014 running and start exhaust emission rates for compressed natural gas transit buses sufficiently explained? Can you follow the procedure that was used to calculate ratios from the MOVES2010b rates to the MOVES2014 rates and how those ratios were applied? Do you have any suggestions for improving this methodology for CNG emission development or the documentation itself?

G.6.1 Dr. Mohamadreza Farzaneh

Yes, the methodology and data were adequately explained and I was able to follow the procedures.

G.6.2 Dr. Janet Yanowitz

All references to MOVES2013 should be replaced with MOVES2014.

RESPONSE: All references refer to the released model (MOVES2014).

p. 85 - Figure 42 [Page 134, Figure 4-1] does not show what is discussed in the text referencing this table. A table which showed the number of natural gas buses relative to the total number of buses would have been useful.

RESPONSE: We have replaced the original plot with Figure 4-1 showing the growth of natural gas transit buses out of the total transit buses and amended the text appropriately.

p. 88 - Equation 28 [Page 137, Equation 4-1] use consistent subscript – either p or pol for pollutant

RESPONSE: Equation 4-1 has been updated to use the subscript p throughout.

p. 90 – [Page 139] text says that in some cases the same vehicle may have been driven over more than one driving cycle, although the table says that each study included only one driving cycle; it is possible that one of the NREL vehicles was used in one of the other tests but that seemed unlikely.

RESPONSE: We added text in the paragraph proceeding Table 4-1 specifying which measurements were made on the same vehicle/aftertreatment configuration. Beside the exception given in the text, each program tested a unique set of vehicles, and each measurement represents a unique vehicle.

The studies chosen tested the same vehicles over various driving cycles, but we only evaluated each vehicle over one driving cycle, as indicated in Table 4-1. The seven CNG buses in the NREL study (Melendez 2005), three had Cummins-Westport engines and four had John Deere engines, were only tested on the WMATA cycle. Ideally these vehicles from the NREL study would have been tested on the CBD cycle, but they were not. Therefore, we decided to juxtapose data from these two cycles in order to create emission rates for more recent model years.

p. 101, Table 42 [Page 148, Table 4-5]- This table could use some clarification – for example the title and the caption should indicate that the table also includes calculated data not just measured and certification data, and the caption could explain that the last line is the calculated values. The caption could also include a brief description of how the calculation was made, i.e. Equation 29 [Equation 4-2]. It is unclear what the footnote refers to – I would think it would be better placed under the column for THC on the two certification lines with an explanation. A footnote to explain where the red value for CO comes from would also be useful.

RESPONSE: We have edited the title, caption, and footnote in Table 4-5 to better explain how the calculated emission rates were derived and how we adjusted the MY 2002-2006 CO rate.

p. 102 and p. 99 seem to conflict [Section 4.3.1 and 4.3.2, Starting Page 144] On p. 102 compare the sentence which begins: "We replaced it with a value equal…." To what is written at the bottom of p. 99 " We did, however, throw out the CO rate (0.14 g/mi) for these WMATA vehicles………" p.. 99 appears to say that the anomalous CO data point was discarded, and that there was more than one vehicle involved in the calculation of the anomalous CO data point, where p. 102 refers to only a single vehicle with an anomalous CO rate, and appears to say (it is not really clear) that the new value somehow includes the certification level.

RESPONSE: The measured CO rate for MY 2002-2006 was adjusted rather than discarded, omitted, or removed. We multiplied it by the ratio between the MY 2004 sales-weighted CO certification level and the CO certification level for that particular John Deere vehicle. This way the CO rate should align better to the other 2004 models. The description of this adjustment has been clarified in the text in Section 4.3.1 and 4.3.2.

p. 102 – typo – developing for developed

RESPONSE: The verb tense has been changed in that sentence.

p. 102 Table 43- [Table 4-2, Page 145] This table can provide a useful summary, with a little additional explanation in the caption and explanatory subtitles.

RESPONSE: The caption and subtitles in the revised Table 4-2- have been updated to be more descriptive of the procedure followed to generate the new MOVES2014 emission rates. Additionally, the cycle average emission rates from the analysis have been removed since they are already presented in Table 4-5.

p. 104 and p. 107 [Page 149, Section 4.6 and Section 4.5]– it is not at all clear how you propose changing the CH4/THC ratio with age of bus. If you are changing the ratio with age, please provide those values. You say (p. 104) that the CH4/THC ratio changes with deterioration of the after-treatment equipment, but then later state that you keep the CH4/THC ratio constant at all ages ("we assume that the change in the THC emission rate is proportional to the changes in the methane emission rate, and keep this ratio constant at all ages." Then on p. 107 you say something different again: deterioration assumptions used in the MOVES 2010b rates are incorporated into the new model

RESPONSE: We clarified the text in Section 4.6 that the CH4/THC ratios used in MOVES do not to vary by age. Deterioration assumptions from MOVES2010b CNG emission rates are applied to criteria pollutants: THC, CO, NOx, and PM as discussed in the revised Section 4.5.

p. 104 [Page 149, Section 4.6]- It is not clear why keeping "the THC emission rate …proportional to the changes in the methane emission rate…. is consistent with a decrease in combustion efficiency." Please explain.

RESPONSE: Section 4.3.2 discusses that the THC emission rates for 2007-2012 were estimated from the 2003-2006 THC emission rates and the ratio of the THC certification results

We revised the text in Section 4.6 to clarify that the methane emissions are calculated as a ratio of THC in MOVES. The CH4/THC ratio is unchanged between 2003-2006 and 2007-2012 model years. We have removed the text referring to the 'proportional changes in the methane emission rate' and 'decrease in combustion efficiency'.

p. 104 Table 44 [Page 146, Table 4-4]-– this table is not a comparison of different ratios as stated in the title, as no information is given for the MOVES 2010B CNG bus rates. The values for 2002-2006 and 2007-1012 should actually be exactly the same as that is how the ratio for 2007-2012 was derived (see p. 101) - seems like you are including too many significant digits.

RESPONSE: We have revised the heading in Table 4-4 to only refer to the CH4/THC values for MOVES2014. Also, we have corrected the table to show the same CH4/THC ratio that MOVES uses (0.950) for the 2002-206 and 2007-2012 model year groups. We have also decreased the significant digits to 3.

p. 104 [Section 4.6, Page149]- The sentence which begins "Studies have shown…." refers to three categories of buses: "uncontrolled CNG buses, CNG buses with oxidation catalysts and CNG buses." Looks like a typo or it needs a better explanation.

RESPONSE: Yes, we have updated the text to only refer to the two categories of CNG buses we analyzed only analyzed: uncontrolled and those with oxidation catalysts.

p. 104 [Section 4.6, Page149]- - "Formaldehyde has … a large impact on the NMOG/NMHC ratio because formaldehyde has a small response to the THC-FID measurements." This is not clear - please explain further or revise

RESPONSE: We revised this sentence. The sentence also now references the speciation report, where the THC-FID response for formaldehyde is presented in Table A-1.

p. 104 [Section 4.6, Page149]- last partial paragraph references tests made by Ayala et al. on an engine and then speciated measurements made on a vehicle. If this is not a typo, please clarify where data for the vehicle test came from.

RESPONSE: We clarified that the measurements were made on a transit bus (chassis dynamometer), while also providing the engine information of the vehicle.

p. 106 – Please explain how you calculated MOVES2010b emission rates for diesel transit buses by model year if the rates are applied by engine family. Did you do sales weighting of the various engine families?

RESPONSE: This section is removed. Presenting MOVES2010b emission rates is not relevant in the MOVES2014 report.

G.7 Changes in Control Technology and Emission Standards for CNG Buses

Does this EPA analysis of CNG buses accurately reflect the changes in control technology and emission standards? If not, how would you recommend to make the CNG emission rates more reflective of bus emission reduction trends over the past two decades?

G.7.1 Dr. Mohamadreza Farzaneh

To the best of my knowledge and based on the available data used for this purpose by the EPA, the described methodology accurately reflects the changes in the control strategies and emissions standards.

G.7.2 Dr. Janet Yanowitz

The inclusion of emission factors out to four or more significant digits give the appearance of far more certainty in these emissions factors than is reasonable based on the available data.

RESPONSE: We have reduced the significant digits from the summary tables (Table 4-5, Table 4-4) where our analysis had less certainty than the significant digits previously implied.

Given the limited data which was available to the authors of this report, the approach used was defensible, and will show, as is warranted, reduced emissions from more modern CNG buses. It is an improvement on the emission factors used in MOVES2010b. However, as the authors themselves point out a number of papers discuss newer CNG vehicles. It is hard to believe that studies from 2007 (cited on p. 99 [Page 1 z]) or 2011 (see first paper cited below) cannot be included in the 2014 version of the MOVES model, because they were not available in time.

Although a review of additional data available was beyond the scope of this reviewer's charge, the authors of the MOVES2014 should consider additional data available in the following documents, even if they are only able to do so briefly to roughly evaluate the accuracy of their proposed model:

Gautam, M., Thiruvengadam, A., Carder, D., Besch, M., Shade, B., Thompson, G. & Clark, N. Testing of volatile and nonvolatile emissions from advanced technology natural gas vehicles. West Virginia University. 2011; available at http://www.arb.ca.gov/research/apr/past/07-340.pdf

Seungju Yoon, John Collins, Arvind Thiruvengadam, Mridul Gautam, Jorn Herner, Alberto Ayala. Criteria pollutant and greenhouse gas emissions from CNG transit buses equipped with three-way catalysts compared to lean-burn engines and oxidation catalyst technologies Journal of the Air & Waste Management Association Vol. 63, Iss. 8, 2013.

RESPONSE: Thank you for pointing us to these recent studies. Unfortunately, we did not have enough time or resources to analyze any data from Stoichiometric-burn CNG buses with three-way catalysts for MOVES2014; however, we would like to incorporate measurements of vehicles equipped with these technologies in future releases of MOVES.

G.8 General/Catch-All Reviewer Comments

G.8.1 Dr. Mohamadreza Farzaneh

The report is well written, and methodologies and assumptions adequately described. The authors applied creative methodologies to address the data gaps specifically for the newer vehicles. I did not notice any major flaws in the methodologies and assumptions used.

The MOVES model has come a long way since its first release. It is clear that it still requires more data to strengthen the overall emission rates as well as to address current data limitation such as newer model years.

A recent remote sensing data by TTI showed that some of the newer trucks have high NOx levels. When the researchers checked with the owners, they mentioned that SCR causes problem and requires repairs, therefore they sometime disable the SCR unit after the warranty period.

RESPONSE: We will consider this information, as we plan future work on MOVES emission rates for SCR equipped vehicles.

Section 2.1.1.3.4 – As stated above, some truck owners disable the SCR unit entirely. These are not captured under this section.

RESPONSE: The Tampering and Mal-maintenance effects on NOx were not updated in MOVES2014. We will consider providing additional rationale for new tampering and mal-maintenance effects when we update the values. However, in this section we do mention that we continue to believe that there is deliberate tampering of emission control components with trucks that comply with to 2007/2010 standards.

Table 42 [Table 4-2]– since certification testing is an engine dynamometer testing, "duty cycle" would be a better term for vehicle activity than "drive cycle."

RESPONSE: We have removed the term 'drive cycles from Table 4-2 because it no longer reports emission results from different drive cycles. However, we refers to second-by-

second speed traces that can be run on a chassis-dynamometer as drive cycles (2.1.3.1) or driving schedules[4] and have retained the terminology 'drive cycle' in Chapter 4.

There are references to MOVES2013 in the text which I believe should be updated to MOVES2014; especially in section 4.

RESPONSE: These have been changed.

Table 35 [Table 3-6] – The table uses "VSP bin" and "TSP bin", my understanding is that the correct term for them is "operating mode bins"

RESPONSE: We clarified the heading of Table 3-6, to clarify that the operating mode is calculated for a light-commercial truck on the Federal Test Procedure. We used the term Operating Mode Bin in the heading, and use the short hand term, OpModeID, to label the operating mode bin IDs in the table.

Section 4 - A statement on the use of these rates for LNG buses, whether it is acceptable or not, would be helpful for users.

RESPONSE: EPA does not encourage or discourage users from utilizing CNG transit bus emission rates as surrogates for LNG bus rates. Any use of surrogate emission rates is done at the users' discretion.

G.8.2 Dr. Janet Yanowitz

No further comments

G.9 General/Catch-All Reviewer Comments: EC emission rates

Comments on 2.1.2.3.5 Computation of Elemental Carbon and Non-Elemental Carbon Emission Factors from the Report: Exhaust Emission Rates for Heavy-Duty On-road Vehicles in MOVES2014. Conducted by Tom Durbin and Allen Robinson as part of the review of the TOG and PM Speciation Report. Related comments to $PM_{2.5}$ speciation profiles used for heavy-duty are located in the PM Speciation Report appendix.

G.9.1 Dr. Tom Durbin

It would be interesting to see how the EC fractions developed based on Kweon et al. compare to those of other should, which could be evaluated by looking at cycles such as cruise cycles, or idle, vs. transient cycles. Comparisons could be made against E-55/59 or studies by CARB.

Response: We have added a sentence in Section 2.1.2.3.5 that references the TOG and PM Speciation Appendix C.2 which compares the EC/PM fractions developed for MOVES on Kweon et al. (2002) with fractions measured on the E55/59, DOE Gasoline/Diesel PM Split Study, and the Northern Front Range Air Quality Study. It also compares the extended idle and running driving cycles from the E55/59 study.

Last paragraph on 1st page – 1st sentence add comma after i.e., ; and also the reference for Kweon is given in the author/year format, whereas the references in the back are listed by number.

Response: We added numeric references to the citations listed in Appendix E, and added the full references to the numeric reference list at the end of the report.

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