Exhaust Emission Rates for Heavy-Duty Onroad Vehicles in MOVES_CTI_NPRM

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List of Acronyms

ABT	emissions averaging, banking and trading program
A/C	Air Conditioning
ACES	Advanced Collaborative Emission Study (CRC)
APU	auxiliary power units
ARCO	Atlantic Richfield Company
BC	black carbon
bhp	brake horsepower
BTU	British Thermal Unit
CARB	California Air Resources Board
CBD	Central Business District
CFR	Code of Federal Regulations
CH_4	methane
CNG	Compressed Natural Gas
CO	carbon monoxide
CO_2	carbon dioxide
CRC	Coordinating Research Council
DB	database
DOC	diesel oxidation catalysts
DOE	U.S. Department of Energy
DPF	diesel particulate filter/periodic trap oxidizer
EC	elemental carbon
ECOSTAR	gaseous and exhaust flow measurement system
ECU	Engine Control Unit
EFEE	Engine, Fuel and Emissions Engineering Inc.
EGR	exhaust-gas recirculation
EMFAC	CARB emissions factors model
EPA	U.S. Environmental Protection Agency

ESC	European Stationary Cycle
FEL	family emission limit
FHWA	Federal Highway Administration
FID	Flame Ionization Detection
FTP	Federal Test Procedure
g	Grams
GDI	Gasoline Direct injection engines
GHG	Greenhouse Gases
g/mi	Gram per mile
GPS	Global Positioning System
GVWR	Gross Vehicle Weight Rating
HC	Hydrocarbons
HD	Heavy-Duty
HDIU	Heavy-Duty Diesel In-Use
HDT	Heavy-Duty Truck
HFC	Hydrofluorocarbon
H-GAC	Houston-Galveston Area Council
HHD	Heavy-Heavy-Duty Class 8 Trucks (GVWR > 33,000 lbs)
HHDD	Heavy Heavy-Duty Diesel
HNO_2	nitrous acid (HONO)
HP	horsepower
hr	hour
HV	heating value
H_2O	water
I/M	Inspection and Maintenance program
IUVP	In-Use Verification Program
kJ	Kilojoules
kW	Kilowatt

LHD	Light-Heavy-Duty
LHD	Light-Heavy-Duty
LHD2b3	Light-Heavy-Duty Class 2b and 3 Truck (8,500 < GVWR ≤ 14,000 lbs
LHD45	Light Heavy-Duty Class 4 or 5 Truck (14,000 < GVWR ≤ 19,500 lbs)
LHDDT	Light Heavy-Duty Diesel Truck
LNT	Lean NO_x Trap aftertreatment
MDPV	Medium-Duty Passenger Vehicle
MECA	The Manufacturers of Emission Controls Association
MEMS	Mobile Emissions Measurement System
mg	milligram
MHD	Medium-Heavy-Duty Class 6 and 7 Trucks (19,500 < GVWR ≤ 33,000 lbs)
MOBILE6	Versioned Highway Vehicle Emission Factor Model post-2004
MOVES	Motor Vehicle Emission Simulator Model
MOVES201X	Motor Vehicle Emission Simulator Model version
MSOD	Mobile Source Observation Database
MY	model year
MYG	model year group
NCHRP	National Cooperative Highway Research Program
NCP	nonconformance penalty
NDIR	non-dispersive infrared
NFRAQS	Northern Front Range Air Quality Study
NH_3	ammonia
NMHC	Non-Methane Hydrocarbon
NMOG	non-methane organic gases
NonEC	non-elemental carbon
NonECnonSO4PM	non-elemental carbon non-sulfate particulate matter
NonECPM	non-elemental particulate matter carbon
NO	nitric oxide

NOx	nitrogen oxide
NOy	combined NO_x and NOz compound
NOz	nitrous oxide
NO_2	nitrogen dioxide
NREL	National Renewal Energy Laboratory
NTE	Not-to-Exceed
NYSDEC	New York Department of Environmental Conservation
N_2O	nitrous oxide
OBD	On-Board Diagnostic
OC	oxidation catalyst
OEM	Original Equipment Manufacturer
OM	operating mode
OMNMHCE	organic material non-methane hydrocarbon equivalent
PCV	positive crankcase ventilation
PEMS	portable emissions measurement system
PERE	Physical Emission Rate Estimator
PHA	Port of Houston Authority
PM	Particulate Matter
$PM_{2.5}$	fine particles of particulate matter with aerodynamic diameters ≤ 2.5 µm
PM_{10}	particles of particulate matter with aerodynamic diameters ≤ 10 µm
ROVER	EPA dataset measurement collection system
RPM	revolutions per minute
SCAQMD	South Coast Air Quality Management District
SCR	selective catalytic reduction
SO_4	sulfate
STP	scaled-tractive power
STP	standard temperature and pressure
ST01	258-second driving cycle

T&M	Tampering and Maintenance
TC	total carbon
TCEQ	Texas Commission on Environmental Quality
TEOM	Tapered Element Oscillating Microbalance
THC	Total Hydrocarbon (FID detection)
TOG	Total Organic Gases
TTI	Texas Transportation Institute
TWC	three-way catalysts
UDDS	Urban Dynamometer Driving Schedule
UL	useful life
ULSD	Ultra Low Sulfur Diesel
VIN	Vehicle Identification Number
VIUS	Vehicle Inventory and Use Survey
VMT	Vehicle Miles Traveled
VOC	Volatile Organic Compounds
VSP	vehicle specific power
WMATA	Washington Metropolitan Area Transit Authority
WVU	West Virginia University
ZML	zero-mile emissions level

1 Principles of Modeling Heavy-duty Emissions in MOVES

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

From HC emissions, MOVES generates other estimates of organic gas emissions, including volatile organic compounds (VOCs) and total organic gases (TOG). MOVES then uses VOC emission rates to estimate individual toxic compounds such as formaldehyde and benzene. The derivation of the factors used to compute aggregate measures of organic gases and individual toxic emissions are available in the Speciation[1], Toxics[2] and Fuel Effects[3] MOVES Reports. MOVES reports PM emissions in terms of elemental carbon (EC) and the remaining non-elemental carbon PM (nonEC). This heavy-duty report covers the derivation of EC/PM fractions used to estimate elemental carbon (EC), and the remaining non-elemental carbon PM (nonEC). MOVES also estimates 18 PM subspecies beyond elemental carbon, such as organic carbon, sulfate and nitrate, through the use of speciation profiles as documented in the Speciation Report.[1]

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

In MOVES_CTI_NPRM, the following emission rates were updated from MOVES2014:

- Heavy-Duty Diesel Vehicles
    - HC, CO, NO_x, and $PM_{2.5}$ running exhaust emission rates for model year (MY) 2010+ (various sections under 2.1.1 through 2.1.3)
    - Energy rates for MY 2010+ vehicles, including the impact of the Heavy-Duty Greenhouse Gas Phase 2 rulemaking (sections 2.1.4.3 and 2.1.4.4)
    - Fraction of elemental carbon and non-elemental carbon fractions of $PM_{2.5}$ exhaust emissions from MY pre-2007 (section 2.1.2.2.8)
    - HC, CO, NO_x, and $PM_{2.5}$ start exhaust emission rates for MY 2010+ (Section 2.2)
    - Extended idle and auxiliary power unit (APU) exhaust HC, CO, NO_x, and $PM_{2.5}$ emission rates for all model years (section 2.3)
    - (New) Running, start, extended idle, and APU exhaust emissions from glider trucks (section 2.5)
- Heavy-Duty Gasoline Vehicles
    - HC, CO, NO_x, and $PM_{2.5}$ running exhaust emission rates for MY 2010+ (sections 3.1.1.6 and 3.1.2.2)
    - Energy rates for MY 2010+, including the impact of the Heavy-Duty Greenhouse Gas Phase 2 rulemaking (sections 3.1.3.3 through 3.1.3.5)
- Heavy-Duty Compressed Natural Gas (CNG) Vehicles

- HC, CO, NO_x, and $PM_{2.5}$ running exhaust emission rates for MY 2007+ (section 4.2.2.3)
- (New) CNG fuel-type is allowed for all heavy-duty source types (section 4)

This version of the report documents the heavy-duty emission factors used in the MOVES version developed to support an upcoming Notice of Proposed Rulemaking (NPRM) for the Cleaner Trucks Initiative (CTI). We refer to this version as MOVES_CTI_NPRM. MOVES_CTI_NPRM is updated from MOVES201X, a draft version which was peer-reviewed in 2017. MOVES201X (and hence MOVES_CTI_NPRM) was updated from both MOVES2014[85] and the MOVES version used to support the Heavy-duty Greenhouse Gas Phase 2 rulemaking (MOVES HDGHG2 FRM[4]). We anticipate MOVES_CTI_NPRM will serve as the foundation for a future MOVES public release.

This report first introduces the principles used to model heavy-duty vehicles in MOVES. Then, Sections 2 through 4 document the emission rates for heavy-duty diesel, heavy-duty gasoline, and heavy-duty CNG vehicles. Section 5 documents the crankcase emission rates used for each fuel type of heavy-duty vehicles. Section 6 documents the methods used to estimate nitric oxide (NO), nitrogen dioxide (NO_2), and nitrous acid (HNO_2 or HONO) emissions from NO_x emissions using ratios.

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

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

Energy emission rates are stored in the "EmissionRate" table, which is similar to the "EmissionRateByAge" table, except emission rates are not differentiated by vehicle age. The MOVES framework and additional details regarding the "EmissionRateByAge" and "EmissionRate table are discussed in the report documenting the rates for light-duty vehicles.[10]

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

1.1 Heavy-Duty Regulatory Classes

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

There are additional criteria that define two of the heavy-duty regulatory classes in MOVES. Urban Bus (regClassID 48) engines are distinguished from other heavy heavy-duty vehicles (GVWR >33,000 lbs.) because they have tighter PM emission standards for the 1994 through 2006 model years.[5] 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[6]").

In MOVES, gliders (regClassID 49) are defined as heavy heavy-duty trucks with an old powertrain, combined with a new chassis and cab assembly. Currently in MOVES, gliders are limited to the long-haul and combination short-haul sourcetypes. As discussed in Section 2.5, the emissions are equivalent to MY 2000 Class 8 heavy heavy-duty vehicles (regClassID 47).

Table 1-1 Regulatory Classes for Heavy-Duty Vehicles

Regulatory Class Description	regClassName	regClassID	Gross Vehicle Weight Rating (GVWR) [lb.]	Source Types (sourceTypeID)
Light Heavy-Duty Class 2b and 3 trucks	LHD2b3[1]	41	8,501 – 14,000	Passenger Trucks (31), and Light-Commercial Trucks (32), Buses (41, 43), and Single Unit Trucks (51, 52, 53, 54)
Light Heavy-Duty Class 4 and 5 Trucks	LHD45	42	14,001 – 19,500	Buses (41, 42, 43) and Single Unit Trucks (51, 52, 53, 54)
Medium Heavy-Duty (Class 6 and 7 Trucks)	MHD	46	19,501 – 33,000	Buses (41,42,43), Single Unit Trucks (51, 52, 53, 54), and Combination Trucks (61, 62)
Heavy Heavy-Duty (Class 8 Trucks)	HHD	47	> 33,000	Buses (41, 42, 43), Single Unit Trucks (51, 52, 53, 54), and Combination Trucks (61, 62)
Urban Bus	Urban Bus[2]	48	> 33,000	Transit Bus (42)
Gliders (Class 8 Trucks)	Glider Vehicles	49	> 33,000	Combination Trucks (61, 62)

Notes:
[1] In MOVES_CTI_NPRM, we consolidated regClassID 40 and 41 into regClass 41. RegClassID 40 was used in MOVES2014 to model Class 2b trucks classified in the light-duty source types (31,32). RegClassID 41 was used to model Class 2b and 3 trucks classified in the heavy-duty source types (41,42 ,43, 51 ,52 ,53, 54). In MOVES2014, the emission rates in regclassID 40 and 41 were intended to be the same. However, separate regClassIDs were needed to have the emission rates calculated with different f-scales. This was needed because MOVES2014 required the f-scale values (stored in the sourceUseTypePhysics table) to be different between 2b trucks in the light-duty sourcetypes (passenger and light-commercial trucks) and the 2b3 trucks in the heavy-duty sourcetypes (single unit trucks, refuse, motorhomes and buses). Because they had different f-scale values, they needed different emission rates. In MOVES201X, we can now specify different road-load coefficients, vehicle weights and f-scale values by source type and regulatory class. Thus, we can now model regClass 41 in both the light-duty and heavy-duty sourcetypes using the same f-scale value and the same emission rates, and regClassID 40 is no longer needed. The vehicles that were previously classified as regClassID 40 in MOVES are now classified as regClassID 41 in MOVES_CTI_NPRM.
[2] see CFR § 86.091(2).

1.2 Emission Pollutants and Processes

MOVES models vehicle emissions from fourteen different emission processes as listed in Table 1-2. This report covers the emission rates for the exhaust emission processes (running exhaust, start exhaust, extended idle exhaust, auxiliary power exhaust, crankcase running exhaust, crankcase start exhaust, and crankcase extended idle exhaust) for HC, CO, NO_x and PM.

1. The running process occurs as the vehicle is operating on the road either under load or in idle mode. MOVES_CTI_NPRM includes off-network idling as a new source of vehicle activity, but it is not a new emission process. Off-network idling is classified as idle mode activity within the running emission process. The running process is further delineated by 23 operating modes as discussed in the next subsection.
2. The start exhaust process includes the incremental emissions that occur when starting a vehicle, including the incremental emissions that occur after the engine start before the aftertreatment system is fully functional.
3. The extended idle process in MOVES occurs during periods of hotelling, when long-haul trucks are used during rest periods, such as when a vehicle is parked for the night and left idling. Extended idle in generally defined to cover idling periods for longer than one hour. Extended idle can result in different emissions than incidental idle that occurs during running operation because the engine may be operated at a higher engine speed and the exhaust aftertreatment system may be too cool to operate at its full efficiency.
4. Auxiliary power exhaust are emissions that come from diesel-powered generators that power the truck's accessory loads, sometimes are used in place of the main engine during periods of hotelling. Documentation of the extended idle and auxiliary power exhaust emissions for heavy-duty diesel trucks are in Section 2.3.
5. Crankcase emissions (for running, start, and extended idle) include combustion products and oil that are vented from the engine crankcase to the atmosphere. Crankcase emissions are significant sources of emissions from heavy-duty compression ignition engines and are discussed for all heavy-duty source types and fuels in Section 5.

Estimation of energy consumption rates for heavy-duty vehicles is also covered in this report. Energy consumption (in units of kJ) is modeled for running exhaust, start exhaust, extended idle exhaust, and auxiliary power exhaust. Estimation of the emissions of nitrous oxide (N_2O), and ammonia (NH_3) for diesel, gasoline, and CNG heavy-duty vehicles are unchanged from MOVES2014 and are documented in separate reports.[7, 8] The methane (CH_4) emissions are estimated as a fraction of total hydrocarbon (THC) emissions. The CH_4/THC fractions are documented in the MOVES speciation report.[44]

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.[9] 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.[9] Brake and tire wear emission rates from heavy-duty vehicles are discussed in the Brake and Tire Wear Report.[12]

Table 1-2 Emission Processes for Onroad Heavy-Duty Vehicles

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

1.3 Operating Modes

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

For example, the activity basis for running process is source hours operating (SHO). The running process is divided into 23 operating modes (as shown in Table 1-3). Using Equation 2-1, the total running emissions is calculated by summing the product of the emission rates with the fraction of time spent in each operating mode (the operating mode distribution). This is multiplied by the total hours (SHO) spent in this emission process.

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

MOVES performs the calculations shown illustrated in Equation 1-1, at a detailed level that accounts for each factor that impacts the emission rates (e.g. model year, vehicle age, fuel type, regulatory class) and the operating mode distribution (source type, roadtype, average speed (which varies across hour of the day)). Then, the emissions can be aggregated to different levels (e.g., by sourcetype). Similar equations can be constructed for other process, the equation for starts is shown in Equation 1-2, where the starts are classified into eight operating modes (Table 1-5).

$$Start\ Emissions = Starts \times \sum_{i=1}^{8}(Operating\ Mode\ Distribution_i \times Emission\ Rate_i) \quad \textbf{Equation 1-2}$$

Operating modes for running exhaust are defined in terms of power output (with the exception of the idle and braking modes). For light-duty vehicles, the parameter used is known as vehicle-specific power (VSP), which is calculated by normalizing the continuous power output for each vehicle to its own weight as shown in Equation 1-3. As discussed in the light-duty emission rate report,[10] VSP is a robust predictor of vehicle emissions. In the laboratory, light-duty vehicles are tested on full chassis dynamometers, and emission standards are in units of grams per mile. The emission standards are largely independent of the weight (and other physical characteristics) of the vehicle.

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

Where:

VSP_t = vehicle specific power at time *t* [kW/ton]

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

B = the rotational resistance coefficient [kW·sec^2/m^2],

C = the aerodynamic drag coefficient [kW·sec^3/m^3],

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

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

a_t = instantaneous vehicle acceleration [m/s^2]

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

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

For heavy-duty vehicles, we classify running exhaust using scaled-tractive power (STP) as shown in Equation 1-4 using road-load coefficients. STP is similar to VSP, except the power for all vehicles within the same regulatory class and model year are scaled using a fixed mass factor, rather than the individual weight of the vehicle.

$$STP_t = \frac{Av_t + Bv_t^2 + Cv_t^3 + m \cdot v_t(a_t + g \cdot sin\theta_t)}{f_{scale}} \quad \textbf{Equation 1-4}$$

Where:

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

f_{scale} = fixed mass factor (see Table 1-4)

Other variables as previously defined in Equation 1-3

Equation 1-4 is used by MOVES to estimate the operating mode distribution from average speed and second-by-second driving cycles. The default average speed and driving cycles, and the load road parameters are discussed in the Population and Activity Report.[11]

The equation for STP is generalized below in Equation 1-5, with units in scaled kW or skW:

$$STP = \frac{P_{axle}}{f_{scale}}$$ **Equation 1-5**

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

As presented in Equation 1-4, P_{axle} can be estimated using the road-load coefficients from chassis-dynamometer tests (For example, pre-2010 heavy-duty diesel HC, CO, and PM emission rates in Section 2.1.2 and 2.1.3). Road-load coefficients can also be used to estimate power demand from onroad tests when more accurate power demand measurements are not available (For example the 2010+ heavy-duty gasoline emission rates in Section 3.1).

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

For onroad tests, measuring power from the ECU is generally more accurate than estimating power from road-load coefficients. Unlike a generic road-load equation where vehicle characteristics, such as aerodynamic drag and rolling resistance are assumed, the ECU measures engine speed and calculates torque directly during the test, avoiding the need to capture the impact of wind speed and wind direction, as well as weight and the road grade throughout the entire test cycle and route. Wind can have a significant impact on power needs, and the payload of heavy-duty vehicles can be greater than the vehicle weights itself, while also varying significantly over the test. Thus, for onroad tests, we generally use power calculated from the ECU measurements, because the vehicle and environmental characteristics determine the axle power (Section 2.1.1.2).

The operating modes bins for running exhaust are shown in Table 1-3.

Table 1-3 Operating Mode Definition for Running Exhaust for Heavy-Duty Vehicles

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

Notes:
[1] The units of vehicle acceleration for determining the braking mode are in units of mph/sec. MOVES converts the acceleration in meters/sec^2 to mph/sec using 0.4470 meter*hours = 1 mile*second.
[2] The deceleration/braking definition will overlap with some of the other operating modes. In these cases, the deceleration/braking categorization takes precedence over other definitions.

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

The f_{scale} values can be considered as a surrogate for the average mass of heavy-duty vehicles within each regulatory class, as reported in Table 1-4. For the pre-2010 emission rates, we used an f_{scale} equivalent to the average mass of the light-commercial trucks (2.06) for the LHD2b3 and LHD45 emission rates. For the other heavy-duty source types, a single 17.1 f_{scale} was used, which provided emissions within each operating mode bin for the largest heavy-duty truck vehicles.

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

Table 1-4 Fixed Mass Factor, f_{scale}

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

NOTE: OpMode-based emission rates **CANNOT** be compared directly between regClasses or model years (MYs) with different f_{scale} values. For example, the OpMode 14 emission rates for MY 2012 regClass 46 (f_{scale} = 7) cannot be directly compared to the same OpMode rates from MY 2009 regClass 46 (f_{scale} = 17.1) or MY 2012 regClass 47 (f_{scale} = 10). That is because data assigned to an OpMode based on different f_{scale} values will have different absolute power (numerator of Equation 1-4 and Equation 1-5). When using vehicle mass in the denominator (Equation 1-3), this is not an issue because the unit is kW/ton and the power is normalized to the mass of the vehicle. However, when using f_{scale} in the denominator, as is the case for all heavy-duty vehicles, the unit is scaled kW and there is no normalization to a physical quantity.

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

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

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

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

1.4 Vehicle Age

In MOVES, the start and running emission rates for HC, CO, NO_x, and PM are stored in the "emissionRateByAge" table by age group, meaning that different emission rates can be assigned to different aged vehicles of the same model year, regulatory class, fuel type and operating mode.

MOVES uses six different age classes to model the age effects, as shown in Table 1-6. The effects of age on the emission rates were developed separately for gasoline and diesel vehicles. For diesel vehicles, we estimated the effects of tampering and mal-maintenance on emission rates as a function of age. We adopted this approach due to the lack of adequate data to directly estimate the deterioration for heavy-duty vehicles. Based on surveys and studies, we developed estimates of frequencies and emission impacts of specific emission control component malfunctions, and then aggregated them to estimate the overall emissions effects for each pollutant (Appendix B). For gasoline vehicles, the age effects are estimated directly from the emissions data, or are adopted from light-duty deterioration as discussed in Section 3.1.1.1.

Table 1-6 MOVES Age Group Definitions

ageGroupID	Lower bound (years)	Upper bound (years)
3	0	3
405	4	5
607	6	7
809	8	9
1014	10	14
1519	15	19
2099	20	~

Energy rates are stored in the "EmissionRate" table, where rates are not distinguished by age. This table also includes HC, CO, NO_x, PM, and ammonia (NH_3) emission rates for extended idle and auxiliary power units (APU), nitrous oxide (N_2O) rates for start and running emissions, and tire and brake wear emission rates. This report documents the HC, CO, NO_x, and PM emissions from extended idle and APU usage, however the documentation of heavy-duty nitrous oxide and ammonia[8] and tire and brake wear[12] emission rates are documented elsewhere.

2 Heavy-Duty Diesel Emissions

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

2.1 Running Exhaust Emissions

The analysis for running exhaust emissions requires accurate second-by-second measurements of emission rates and parameters that can be used to estimate the tractive power exerted by a vehicle. This section describes how we analyzed continuous second-by-second heavy-duty diesel emissions data to develop emission rates applied within the predefined set of operating modes (Table 1-3). 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 1-4.

2.1.1 Nitrogen Oxides (NO_x)

For NO_x rates, we stratified heavy-duty vehicles into the model year groups listed in Table 2-1. These groups were defined based on changes in NO_x emissions standards and the outcome of the Heavy-Duty Diesel Consent Decree[13], which required additional control of NO_x emissions during highway driving for model years 1999-and-later. This measure is referred to as the "Not-to-Exceed" (NTE) limit.

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

Model year group	Standard (g/bhp-hr)	NTE limit (g/bhp-hr)
Pre-1988	None	None
1988-1989	10.7	None
1990	6.0	None
1991-1997	5.0	None
1998	4.0	None
1999-2002	4.0	7.0 HHD; 5.0 other reg. classes
2003-2006	2.4[1]	1.5 times the standard or family emission limit (FEL) (or 1.25 standard or FEL, when FEL > 1.50 g/bhp-hr)
2007-2009	1.2[1,2]	
2010+	0.2	

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

2.1.1.1 Data Sources

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

ROVER. This dataset includes measurements collected during onroad operation using the ROVER system, a portable emissions measurement system (PEMS) developed by the EPA. The measurements were conducted by the U.S. Army Aberdeen Test Center on behalf of U.S. EPA.[14] This program started in October 2000. Due to time constraints and data quality issues, we used only data collected from October 2003 through September 2007. The data was compiled and reformatted for MOVES analysis by Sierra Research.[15] 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).[16,17,18] This program was initiated as a result of the consent decree between the several heavy-duty engine manufacturers and the US government, requiring the manufacturers to test in-use trucks over the road. Data was collected from 2001 through 2006. The data we used represented approximately 1,100 hours of operation by 188 trucks of model years 1994 through 2003. Trucks were heavily loaded and tested over numerous routes involving urban, suburban, and rural driving. Several trucks were re-acquired and tested a second time after 2-3 years. Data were collected at 5-Hz frequency, which we averaged around each second to convert the data to a 1.0-Hz basis.

Heavy-Duty Diesel In-Use Testing (HDIUT). The in-use testing program for heavy-duty diesel vehicles was promulgated in June 2005 to monitor the emissions performance of heavy-duty engines operated under a wide range of real world driving conditions, within the engine's useful life.[19] It requires each manufacturer of heavy-duty highway diesel engines to assess the in-use exhaust emissions from their engines using onboard, portable emissions measurement systems (PEMS) during typical operation while on the road. The PEMS unit must meet the requirements of 40 CFR 1065 subpart J. The in-use testing program began with a mandatory two-year pilot program for gaseous emissions in calendar years 2005 and 2006. The fully enforceable program began in calendar year 2007 and is ongoing. The vehicles selected for participation in the program are within the engine's useful life, and generally, five unique vehicles are selected for a given engine family. This dataset includes results for HHD, MHD, and LHD vehicles. The data available for use in MOVES2014 were collected during calendar years 2005 through 2010 and represent engines manufactured in model years 2003 to 2009. For MOVES_CTI_NPRM, we looked at data from engines selected for testing in calendar years 2010 through 2016. These engines cover model years 2010 to 2015. The MY 2010+ data set included 38 unique engine families and 291 vehicles. There are about 8 million seconds of quality-assured second-by-second data and during this time the vehicles travelled about 68,000 miles. The operational conditions include a wide range of driving speeds, transient and steady-state conditions, engine loads, and exhaust temperature conditions that have implications for emissions control efficacy, particularly for NO_x.[20] For the HHD class, out of a total 159 vehicles, 109 were line-haul, 46 were delivery, and the remaining were marked as "Other" in the metadata. We plan to expand the characterization of the MY 2010+ HDIUT data set, in a future update to this report, by adding summary information on vehicle age distribution, odometer reading, idling time duration, and OpMode based time and miles travelled.

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.[21] The trucks studied were diesel-fueled, heavy heavy-duty trucks used to transport containers, bulk and break-bulk goods to and from ports and intermodal rail yards to other locations. These trucks conducted the majority of their travel on short-haul runs, repeatedly moving containers across fixed urban routes. Note that only small fractions of trucks involved in drayage service are dedicated solely to this function, with most trucks spending large fractions of their time performing other types of short-haul service. No specific drive cycles were used and all PEMS testing was based on actual in-use loads and speeds.

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

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

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

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

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

		Regulatory Class			
Data Source	**MYG**	**HHD**	**MHD**	**LHD**	**BUS**
ROVER and Consent Decree Testing	**1991-1997**	19	-	-	2
	1998	12	-	-	-
	1999-2002	78	30	-	25
	2003-2006	91	32	-	19
HDIUT	**2003-2006**	40	25	15	-
	2007-2009	68	71	24	-
	2010+[1]	159	58	64	10
Houston Drayage	**1991-1997**	8	-	-	-
	1998	1	-	-	-
	1999-2002	10	-	-	-
	2003-2006	8	-	-	-

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

2.1.1.2 Calculate STP from 1-Hz data

As discussed in Section 1.3, we prefer to estimate tractive power from engine data collected during real-world operation, rather than using the road-load equation. To do so, we first identified the seconds in the data that the truck was either idling or braking based on acceleration and speed criteria shown in Table 1-3. 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.

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

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

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

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

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

		Vehicle Speed (mph)		
		Low (0-25)	**Mid (25-50)**	**High (50+)**
Engine Load Map	**Low**	Cooling Fan 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*."[22]

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 pre-2010 model years, LHD losses were set to zero. The losses for MY 2010+ LHD vehicles were estimated by adjusting the MHD vehicle losses as such: (1) removed the loss for air compressor; (2) no change to air condition loss; (3) scaled the losses for cooling fan, alternator, and engine accessories by 5/7 (where 5 and 7 are rough estimates of the average engine displacement in liters for LHD and MHD engines, respectively). Based on these adjustments, the LHD losses are estimated to be approximately 60 percent for low power band and 70 percent for mid and high power bands of the MHD losses for the corresponding power bands. We acknowledge this assumption is not data driven, but we believe it is a step forward from having LHD losses equal to zero for all model years (as was the case in MOVES2014).

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

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

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

We then accounted for the driveline efficiency. The driveline efficiency accounts for losses in the wheel bearings, differential, driveshaft, and transmission. The efficiency values were determined through literature searches. Driveline efficiency $\eta_{driveline}$ varies with engine speed, vehicle speed, and vehicle power requirements. Using sources available in the literature, we estimated an average value for driveline efficiency.[23,24,25,26,27,28,29,30,31] Table 2-5 summarizes our findings.

Table 2-5 Driveline Efficiencies Found in the Literature

General truck:	
Barth (2005)	80-85%
Lucic (2001)	75-95%
HDT:	
Rakha	75-95%
NREL (1998)	91%
Goodyear Tire Comp.	86%
Ramsay (2003)	91%
21st Century Truck (2000)	94%
SAE J2188 Revised OCT2003:	
Single Drive/direct	94%
Single Drive/indirect	92%
Single Drive/double indirect	91%
Tandem Drive/direct	93%
Tandem Drive/indiriect	91%
Tandem Drive/double indirect	89%
Bus:	
Pritchard (2004): Transmission Eff.	96%
Hedrick (2004)	96%
MIRA	80%

Based on this research, we used a driveline efficiency of 90 percent for all HD regulatory classes. Equation 2-2 shows the translation from engine power P_{eng} to axle power P_{axle}.

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

Finally, we scaled the axle power using Equation 2-3, and the STP-scaling factors f_{scale} presented in Table 1-4.

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

We then constructed operating mode bins defined by STP and vehicle speed according to the methodology outlined earlier in Section 1.3.

We plan to revisit the accessory load losses and driveline efficiency numbers used here as additional data, particularly for MY 2010+ vehicles, becomes available. It is possible that future test programs might acquire accessory load information from the ECU and axle efficiency data is available through certification information during the HD GHG Phase 2 compliance program.

2.1.1.3 Calculate emission rates

2.1.1.3.1 *Emission Rates for pre-2010 Model Years*

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

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

Where:

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

We calculated a mean emission rate, denoted as the "meanBaseRate" in the MOVES emissionRateByAge table, for each combination of regulatory class, model year group, and operating mode bin combination. Examples of mean emission rates derived using this method are displayed in Section 2.1.1.8, starting with Figure 2-7.

2.1.1.3.2 *Emission Rates for 2010-and-beyond Model Years*

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

1. For a given regulatory class (HHD, MHD, LHD), and irrespective of engine model year (as long as it is MY 2010+), we grouped the vehicles in the HDIUT data set into three NO_x family emission limit (FEL)[a] groups as detailed below. We first calculated the OpMode-based average emission rate for each vehicle by regulatory class and NO_x FEL group (Equation 2-5). Then, we calculated the OpMode-based average emission rate for all vehicles in the NO_x FEL group (Equation 2-6). This means, for a given regulatory class and NO_x FEL group, we are not distinguishing between manufacturers or model years.
2. We weighted the OpMode-based average emission rates for each of the three NO_x FEL groups within a regulatory class by the, per model year, production volume of the engines in the NO_x FEL group to the total production volume of the regulatory class (Equation 2-7). Thus, we created OpMode-based average emission rates for each model year and regulatory class.

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

---

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

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

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

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

Where:

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

Creation of NO_x FEL Groups

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

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

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

Each test vehicle, within a regulatory class, was assigned to one of these three groups. These groupings were applied not only to NO_x, but to all pollutants for emission rate calculations. We chose to use NO_x as the basis for creation of these groups because data for NO_x FEL is most abundant in the heavy-duty engine certification database and, for MY 2010+ engines, the biggest technology changes and tailpipe exhaust emissions impacts are due to emissions control measures for NO_x. We arrived at the specific group bins based on the spread of NO_x FELs for all MY 2010+

engine families reported in the certification database (and not just the engine families tested under the HDIUT program). The NO_x FELs for all MY 2010+ HD diesel engine families in the certification database are shown in Figure 2-1. As highlighted by the shaded rectangles, most of the engine families are concentrated in the 0.05–0.20, 0.30–0.35, and 0.45–0.50 bands and this trend guided our bin choices, represented by the curly braces, for the three NO_x FEL groups.

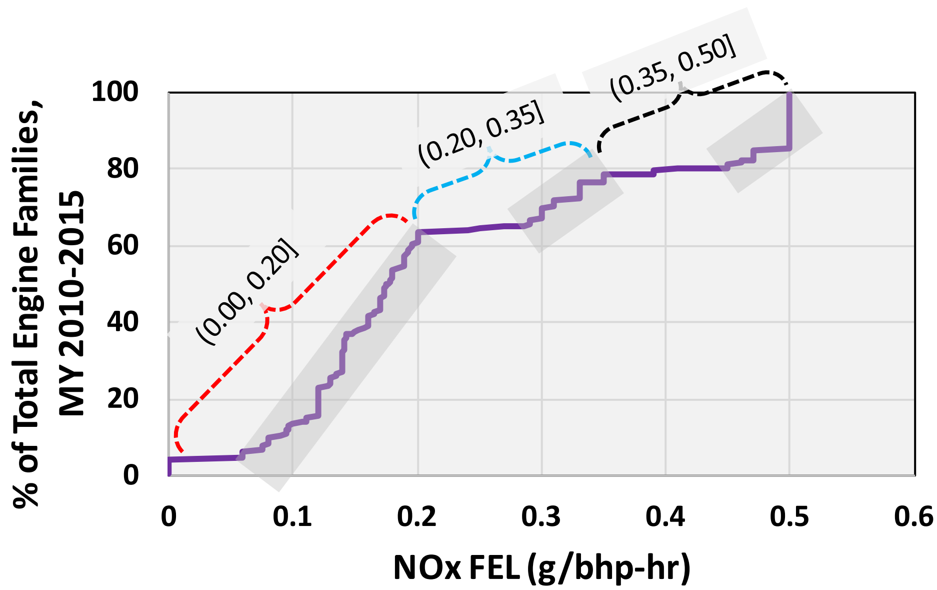


Figure 2-1 Distribution of NO_x Family Emission Limit (FEL) for Model Year 2010 and Beyond Heavy-Duty Diesel Engine Families, as Reported in the Certification Database

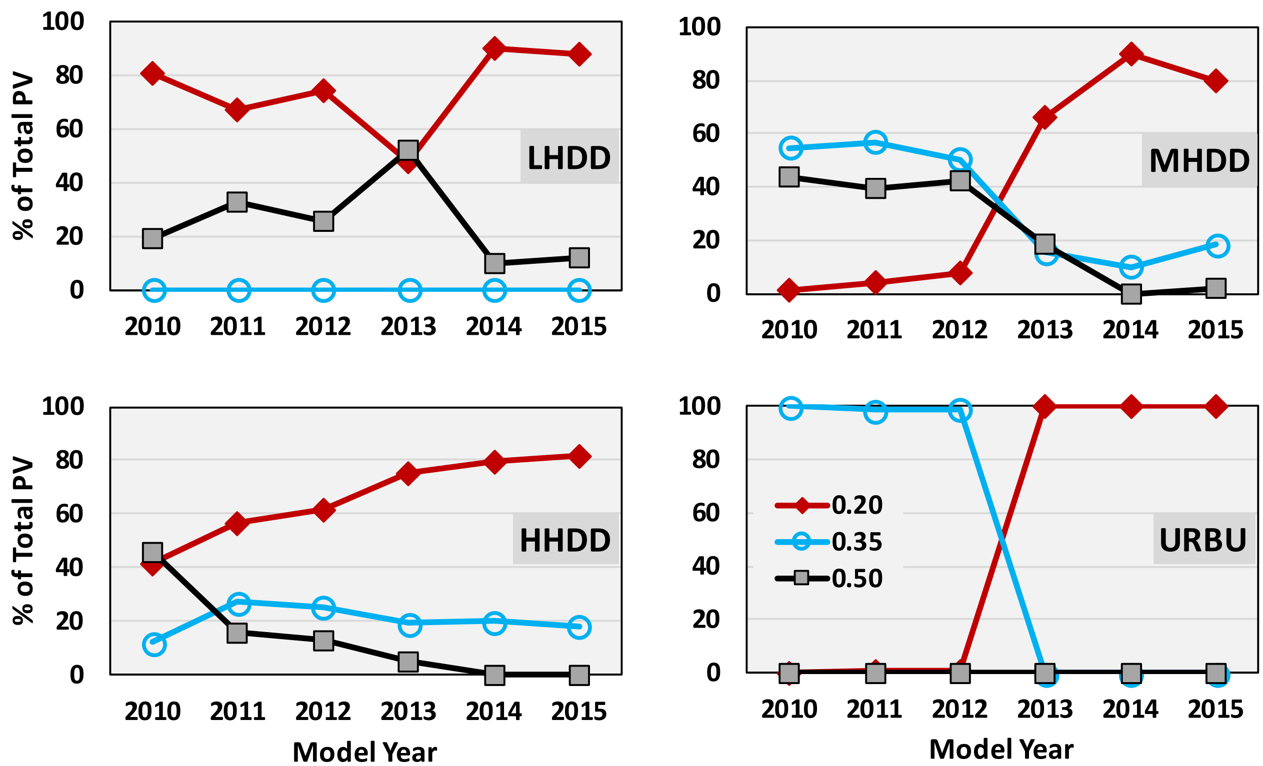
Table 2-7 shows the number of vehicles by regulatory class and NO_x FEL group for MY2010+ engines in the HDIUT program. The number of vehicles by regulatory class in this table match the number of vehicles in Table 2-2.

Table 2-7 Number of Diesel Vehicles with MY 2010+ Engines by NO_x FEL Group from the HDIUT Program Used for Emission Rate Analysis

Regulatory Class	NO_x FEL Group			Total
	0.20	0.35	0.50	
LHD	49	0	15	64
MHD	26	23	9	58
HHD	93	31	35	159
Urban Bus	0	10	0	10
Total	168	64	59	**291**

Weighting by Production Volume

We collected production volume data by the same regulatory classes (LHD, MHD, HHD, Urban Bus) and NO_x FEL groups (0.20, 0.35, 0.50) that we used for the emission rate analysis. We then combined the NO_x FEL group-based rates (averaged across all 2010+ model years) with the production volume data (distinct for each model year) to create emission rates unique to each model year. We did this for each model year from 2010 and up to 2015 (the last model year for which we have production volume data). For MY 2016+, we used the production volume weighting from MY 2015. The per-model-year production volume weighting, by regulatory class and NO_x FEL groups, is shown in Figure 2-2. This method allows us to better represent the technology adoption landscape in the heavy-duty domain. For example, for HHDD, model years 2010 through 2013 had engines with NO_x FEL in the 0.50 group (0.35 g/bhp-hr < NO_x FEL ≤ 0.50 g/bhp-hr), but starting with model year 2014, there are no engines in the 0.50 group. Compared to engines in the 0.20 group and 0.35 group, engines in the 0.50 group predominantly use a different emissions control strategy to reduce tailpipe NO_x emissions. Thus, our approach using the NO_x FEL groups and per-model-year production volume correctly captures the prevalence and influence (on emissions) of different technologies in the fleet.



Production volume percent contributions of the three NO_x FEL groups, in a given regulatory class and model year; these sum to 100 percent of the production volume for the regulatory class and model year.

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

Other Considerations

One aspect in our current approach is that for FEL group average emission rates, we do not differentiate between manufacturers and engine model years. Thus, a HHD MY 2010 engine from manufacturer A with NO_x FEL of 0.20 and a HHD MY 2015 engine from manufacturer B with NO_x FEL of 0.10 are both put in the HHD 0.20 group and averaged. If future data shows significant differences in real-world performance of engines with similar NO_x FEL but different model years, a possible area of improvement would be to differentiate between model years when calculating the FEL group based average emission rate (which then gets weighted by production volume). Or, we could create two model year groups, such as MY 2010-2013 and 2014+ to capture improvements in emissions control devices, such as better catalyst formulation and thermal management for SCR systems. Similarly, we could additionally differentiate between manufacturers or even between engine families by the same manufacturer. Each of these additional steps may provide increased ability to distinguish the differences, however, the drawbacks are more complex analysis and the need to make assumptions due to lack of data (for example, we do not have emissions data from each engine family or even each manufacturer for each model year). We believe the approach adopted here provides emissions rates, for MY 2010+, that are sufficiently representative of the real-world while working within the constraints of resources and technical data.

2.1.1.3.3 *Statistics*

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

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

Where:

s_j^2 = the variance within each vehicle, and

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

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

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

Then, we estimated the total variance by combining the within-vehicle and between-vehicle variances to get the standard error $s_{\bar{r}_p}$ (Equation 2-10) and dividing the standard error by the mean emission rate to get the coefficient-of-variation of the mean c_p (Equation 2-11). We used the standard error to estimate the 95 percent confidence intervals of the mean emission rate, which are displayed in Figure 2-7 through Figure 2-14 and Appendix C for a subsample of the NO_x heavy-duty emission rates. For each emission rate, the coefficient of variation is stored in the emissionRateByAge table.

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

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

2.1.1.4 Hole-filling Emission Rates

The data included in the emissions analysis does not cover all operating modes or vehicle-type and model year combinations needed for MOVES. In this section, we discuss the "hole-filling" methodology used to fill missing operating mode bins, and missing vehicle-type and model year combinations. To do so, we rely on the heavy-duty diesel emission standards, as well as engineering knowledge and test data of emission control technologies that were implemented or forecasted to be implemented to meet the standards.

2.1.1.4.1 *Hole-filling Missing Operating Modes*

Hole-filling is required for the high-power OpModes (mostly in the medium- and high-speed bins) because the test vehicles do not typically operate in those power-speed bins. In MOVES01X, for MY 2010+ criteria pollutant and energy emissions rates, we adopted new f_{scale} values, by regulatory class, such that the real-world data used to estimate emissions rates covers all OpModes. Thus, hole-filling was no longer necessary for MY 2010+ running exhaust emission rates update. The f_{scale} values are shown in Table 1-4. The method to select the new f_{scale} values is described Appendix G.

Criteria pollutants and energy rates for MY 1960-2009

As described in Section 1.3, f_{scale} values were not updated for model years 2009-and-earlier. Thus, for MHD and HHD trucks, the maximum operating mode (opModeID = 40) represents a tractive power greater than 513 kW (STP= 30 skW × 17.1). This value exceeds the capacity of most HHD vehicles, 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, mode 27 or 28 for the middle speed range, and mode 37 or 38 for the highest speed range. For each of these operating modes, work-specific emissions factors (g/kW-hr) were calculated using the midpoint STP (Table 1-3). Then, these emissions factors were multiplied by the midpoint STP of the higher operating modes (e.g., modes 39 and 40 for speed>50 mph) to input emission rates for the modes lacking data. For the highest bins in each speed range, a "midpoint" STP of 33 skW (564.3 kW) was used. Equation 2-12 displays an example calculation of the emission rate for opModeID 40, using a mean emission rate from opModeID 37, for a given regulatory class and model year group.

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

Criteria pollutants and energy rates for MY 2010+

For the updates to THC, CO, NO_x, $PM_{2.5}$, and energy rates for MY 2010+ HD vehicles, we used new f_{scale} values (see Table 1-4 and Appendix G that resulted in all OpModes being populated with rates. Thus, there was no need for hole-filling.

Figure 2-3 to Figure 2-5 show the effect of the new f_{scale} values on OpMode coverage using the example of NO_x emission rates for the vehicles in the NO_x FEL=0.20 group for LHD, MHD, and HHD regulatory classes, respectively. Note that the absolute mass/time OpMode-based emissions rates between two series based on different f_{scale} cannot be compared. The main benefit of the new f_{scale} values is that all the OpModes are populated even if the trends may not be perfectly monotonically increasing for each pollutant in a regulatory class. The comparison is similar for the 0.35 and 0.50 NO_x FEL groups. Note the final rates are estimated as production volume weighted rates from each of the NO_x FEL groups.

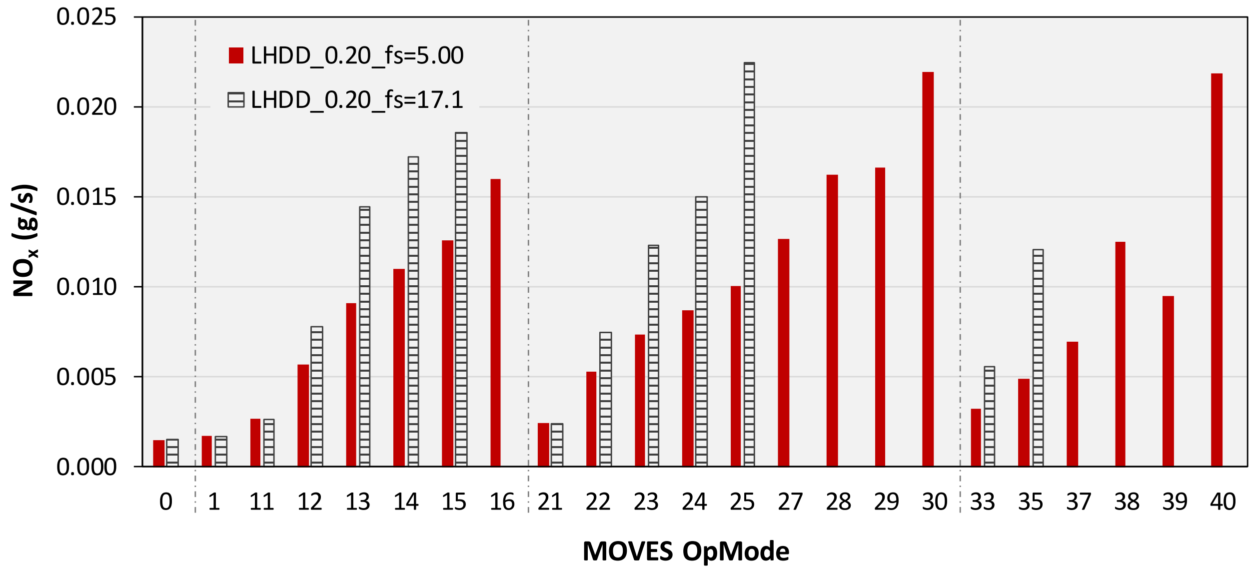


Figure 2-3 Effect of f_{scale} Value on OpMode Coverage for NOx Emission Rates for Light Heavy-Duty Vehicles in the NOx FEL = 0.20 Group

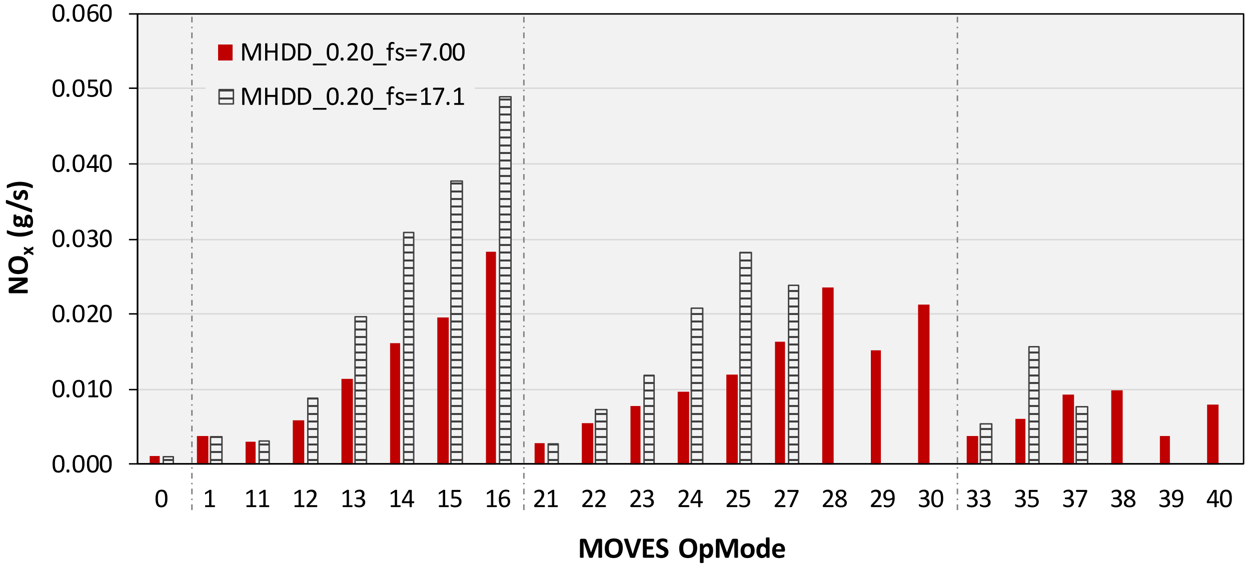


Figure 2-4 Effect of *f_{scale}* Value on OpMode Coverage for NOx Emission Rates for Medium Heavy-Duty Vehicles in the NOx FEL = 0.20 Group

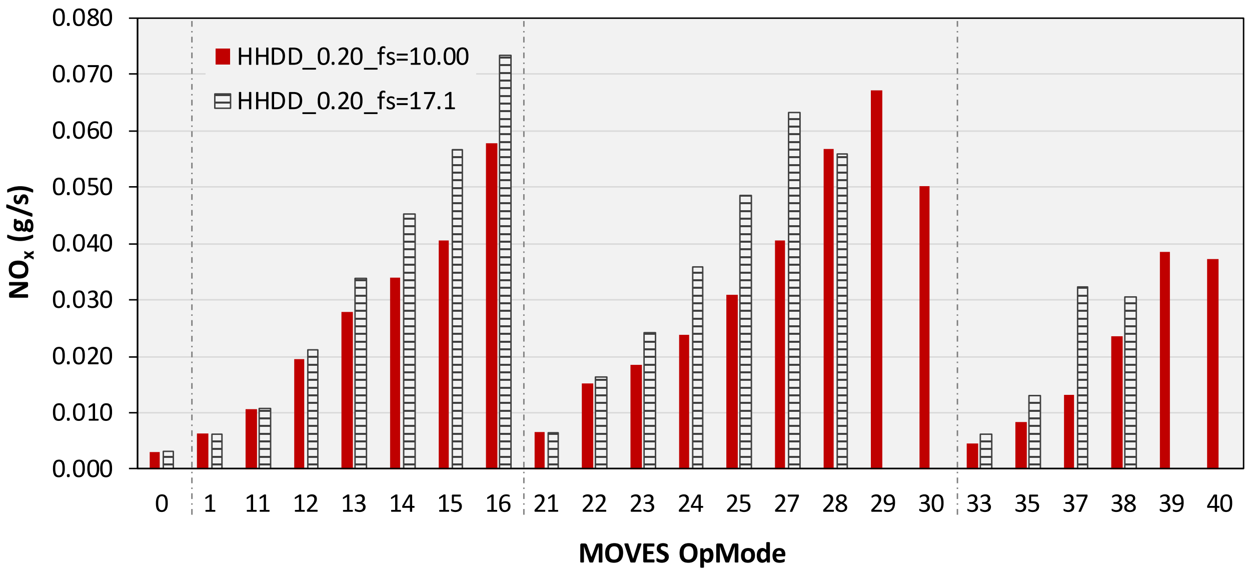


Figure 2-5 Effect of *f_{scale}* Value on OpMode Coverage for NOx Emission Rates for Heavy Heavy-Duty Vehicles in the NOx FEL = 0.20 Group

2.1.1.4.2 *Pre-2007 HHD, MHD, Urban Bus, LHD45 and LHD2b3*

For regulatory class/model year combinations with missing data, we proportionally adjusted the existing emissions data using ratios of certification data or vehicle emission standards as specified in Table 2-1. For MHD and HHD, 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 as analyzed for MOBILE6.[32] On average, the MY 1990 and MY 1988-1989 rates are 1.055 times and 1.367 times the baseline rates of MY 1991-1997, respectively. We applied the 1988-1989 emission rates to model years 1987 and earlier.

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

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

For LHD2b3 vehicles, MY 1998 emission rates were used as base rates to back-cast emission rates for the 1991-1997 model years, using the ratio of emission standards between these two model-year groups (5.0 g/bhp-hr over 4.0 g/bhp-hr) such that the 1991-1997 rates are 1.25 times the rates for MY 1998. LHD45 use the same emission rates as LHD45 for these model years.

Table 2-9 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 *2007-2009 Model Year HHD, MHD, and Urban Bus*

The 2007 Heavy-Duty Rule[107] required the use of ultra-low sulfur diesel fuel; this fuel was 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[107] established much tighter NO_x emission standards (0.2 g/bhp-hr). While the NO_x standard went into effect for MY 2007 at 0.2 g/bhp-hr, it was phased in over a three-year period ending in 2010. Rather than phasing in the aftertreatment technology needed to meet the new standard, most manufacturers chose to meet a 1.2 g/bhp-hr standard for MY2007-2009 (down from 2.4 g/bhp-hr in 2006), which did not require NO_x aftertreatment. For the 2007-2009 HHD, we used the data from the HDIUT program as discussed in Appendix C. For the NO_x emission rates within the 2007-2009 model year group for MHD and Urban Bus we estimated the NO_x emission rates were 50 percent lower than the corresponding 2003-2006 emissions (proportional to the reduction in the NO_x emission standards mentioned above). In Appendix C.3, we confirmed that the MHD rates were consistent with NO_x emission rates measured from 2007-2009 MHD trucks measured in HDIUT.

2.1.1.4.4 *2007-2009 LHD45 and LHD2b3 Emissions*

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

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

Emissions from this vehicle were not directly used to calculate emission rates, because only one vehicle was tested. Rather, adjustments were made from the MOVES2010[b] MY 2003-2006 model year group to develop emission rates for this model year group and regulatory class. During PM regeneration, we assumed that the LNT did not reduce emissions from 2003-2006 levels. During all other times, we assumed that emissions were reduced by 90 percent from 2003-2006 levels. These assumptions result in an estimated NO_x reduction of 81 percent for LNT equipped trucks between 2003-2006 and 2007-2009, as shown in Equation 2-14.

$$\frac{LNT\ NOx\ emissions}{Baseline\ LHD2b3\ (2003-2006)\ NOx\ emissions} = (normal\ op.frequency) \times \left(\frac{LNT\ normal\ emissions}{baseline\ emissions}\right) + (DPF\ reg.frequency) \times \left(\frac{baseline\ emissions}{baseline\ emission}\right)$$

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

Equation 2-14

Because we assume that LNT-equipped trucks account for about 25 percent of the LHDDT market in model years 2007-2009, we again weighted the rates for the LHD2b3 regulatory class (regClassID 41) for model years 2007 and later. For MY 2007-09, we assume that the remaining 75 percent of LHD2b3 diesel trucks will not have aftertreatment and will exhibit the 2007-2009 model year emission rates described earlier in this section. Overall, these assumptions result in a 58 percent reduction in NO_x emission rates in 2007-2009 from the MOVES2010 MY 2003-2006 NO_x emission rates as shown in Equation 2-15.

$$\frac{2007-2009\ LHD2b3\ NOx\ emissions}{2003-2006\ LHD2b3\ NOx\ emissions} = (LNT\ market\ share)\left(\frac{LNT\ NOx\ emissions}{2003-2006\ LHD2b3\ NOx\ emissions}\right) + (non-LNT\ market\ share)\left(\frac{2007-2009\ emission\ standerds}{2003-2006\ NOx\ emissions\ standerds}\right)$$

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

Equation 2-15

[b] In MOVES2014, we updated the diesel NOx emission rates for 2003-2006 on the HDIUT program

In the absence of other data, we apply the LHD2b3 emission rates to LHD45 vehicles. Newer data shows that LNT is not being used in LHD45 vehicles, however, we have not updated this assumption because the results compare well to the HDIUT data; see Appendix C.

For MOVES_CTI_NPRM, the MY 2010 and beyond emission rates for LHD45 and LHD2b3 are based on analysis of the LHD engine family equipped vehicles in the HDIUT data and production volume weighting (as described in Section 2.1.1.3.2.

2.1.1.4.5 2010+ HHD, MHD, Urban Bus, LHD45, and LHD2b3

For MOVES_CTI_NPRM, the MY 2010-and-later emission rates for HHD, MHD, Urban Bus, and LHD45, and LHD2b3 are based on analysis of the HDIUT data and model-year specific production volume weighting (as described in Section 2.1.1.3.2) for each model year from 2010 through 2015. The rates for HHD, MHD, and the two LHD classes use data from vehicles with HHD, MHD, and LHD engines, respectively. The rates for Urban Bus are the same as HHD rates because: urban buses are in the same GVWR class as HHD; some engines certified under HHD are used in the urban bus application; and there is no separate NO_x standard (for MY 2010+) for the Urban Bus regulatory class. The NO_x emissions are projected to remain constant for MY 2015 and later vehicles for regulatory classes HHD, MHD, Urban Buses, and LHD45. The LHD2b3 trucks are projected to have a further decrease in NO_x emissions through the implementation of the Tier 3 program as discussed in Section 2.1.1.4.6.

2.1.1.4.6 *Incorporation of Tier 3 Standards for LHD2b3*

In addition to regulating light-duty vehicles, the Tier 3 vehicle emission standards[33] will affect light heavy-duty diesel vehicles, i.e., vehicles in regulatory classes LHD2b3 (regClassID 41). For these LHD diesel vehicles, reductions in emission rates attributable to the introduction of Tier 3 standards are applied only to rates for NO_x.

For HC and CO emissions, the emission rates currently in MOVES imply that current levels on the FTP cycle are substantially below the Tier 3 HC and CO standards. For example, when MOVES rates are combined to estimate a simulated FTP estimate for NMHC, the result is a rate of approximately 0.05 grams per mile, while the simulated FTP estimate for CO is less than 1.0 gram/mile. Consequently, we assumed that no additional reductions in HC and CO emissions would be realized through implementation of the Tier 3 standards on LHD diesel vehicles. By contrast, we estimate that the Tier 3 NO_x standard will result in a reduction of emissions from diesel vehicles in regulatory classes LHD2b3. 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 2-8. The derivation of the phase-in assumptions is discussed in Appendix I.

Table 2-8 Phase-in Assumptions for Tier 3 NOx Standards for Light Heavy-Duty Diesel Vehicles

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

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

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

In addition to tightening emission standards, the Tier 3 regulations require an increase in the regulatory useful life. 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, the diesel 2b3 rates estimated for the 0-3 year ageGroup are replicated to the 4-5 year ageGroup, i.e., the onset of deterioration is delayed until the 6-7 year ageGroup (as shown in Figure 2-6). This effect is phased-in for model years 2018-2021 and fully implemented for MY2022+.

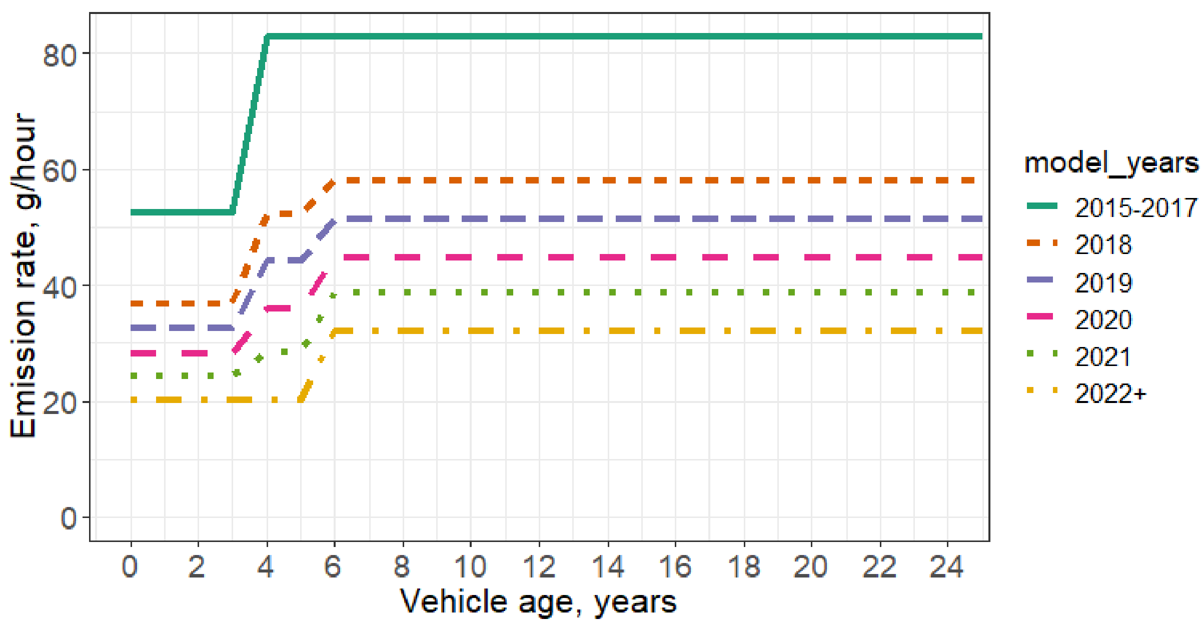


Figure 2-6 NOx: Emission Rates for Running Exhaust Operation in a Single Operating Mode (27) vs. Age for LHD2b3 Diesel Trucks for 2017 through 2022 and Later Model Years.

2.1.1.5 Summary

Table 2-9 summarizes the methods used to estimate emission rates for each regulatory–class/model-year-group combination. The emission rates in MOVES are based on the analysis of ROVER, Consent Decree testing data, and HDIUT data. Using the HDIUT data, we updated the HHD rates for model year group 2007-2009 in MOVES2014 and updated the HHD, MHD, LHD, and Urban Bus rates for MY 2010+ vehicles in MOVES_CTI_NPRM. MOVES also includes the impact of the Tier 3 regulations on the LHD2b3 regulatory classes.

Table 2-9 Summary of Methods for Heavy-Duty Diesel NO_x Emission Rate Development for Each Regulatory Class and Model Year Group

Model year group	HHD (regClass 47)	MHD (regClass 46)	Urban Bus (regClass 48)	LHD45 (regClass 42)	LHD2b3 (regClass 41)
1960-1989, 1990	HHD 1991-1997 rates proportioned to ratio of certification levels	Same rates as HHD	Urban Bus 1991-1997 rates proportioned using ratio of HHD certification levels	Same rates as LHD2b3	LHD2b3 1991-1993 rates proportioned to LHD certification levels
1991-1997	Data analysis[a,c]	Same rates as HHD	Data analysis[a]	Same rates as LHD2b3	LHD2b3 1999-2002 rates proportioned to 1991-1997 FTP standards per Table 2-1
1998	Data analysis[a,c]	Same rates as HHD	Urban Bus 1999-2002 rates proportioned using ratio of HHD 1998 rates to HHD 1999-2002 rates	Same rates as LHD2b3	Same rates as 1999-2002
1999-2002	Data analysis[a,c]	Data analysis[a]	Data analysis[a]	Same rates as LHD2b3	MHD engine data with 2.06 fixed mass factor
2003-2006	Data analysis[a,c]	Data analysis[a,c,d]	Data analysis[a]	Same rates as LHD2b3	Data analysis with 2.06 mass factor[b]
2007-2009	Data analysis[b]	MHD 2003-2006 rates proportioned to FTP standards per Table 2-1[c]	Urban Bus 2003-2006 rates proportioned to FTP standards per Table 2-1	Same rates as LHD2b3[e]	Percent reductions from the MOVES2010 2003-2006 rates (Section 2.1.1.4.4)[c]
2010 - 2015	HHD data analysis[b] with MY specific production volume weighting	MHD data analysis[b] with MY specific production volume weighting	Same as HHD	LHD data analysis[b] with MY specific production volume weighting and T&M specific to LHD45	LHD data analysis[b] with MY specific production volume weighting and T&M specific to LHD2b3
2016-2050	Same as HHD MY 2015	Same as MHD MY 2015	Same as Urban Bus (= HHD) MY 2015	Same as LHD45 MY 2015	Same as LHD2b3 MY 2015 with Tier 3 reductions phase-in from MY 2018-2022

Notes:

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

[b] Analysis based on HDIUT data

[c] Confirmed by HDIUT and Houston Drayage data

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

[e] Newer data shows that LNT is not being used in LHD45 vehicles, however, we have not updated this assumption because the results compare well to the HDIUT data; see Appendix C.

2.1.1.6 Tampering and Mal-maintenance

Table 2-10 shows the estimated aggregate NO_x emissions increases due to Tampering and Mal-maintenance (T&M) by regulatory class and model year group. As described in Appendix B, the T&M emission increases in Table 2-10 are calculated by combining information regarding the assumed frequency rate of an equipment failure at the useful life of the engine with the estimated emission impact of the equipment failure. The emission increases are reduced for ages that are younger than the useful life of the engine, as shown in Table B-2, and the emission increases by age differ for the LHD, MHD, HHD and Urban Bus regulatory classes. Thus, the aged emission rates for regulatory classes with the same zero-mile emission rates (Table 2-9) may be different due to the T&M NO_x effects (Table 2-10) and phase-in of T&M effects by age (Table B-2).

The LHD vehicles have different T&M NO_x increases than HHD, MHD, and Urban Bus vehicles due to the 25 percent assumed penetration of lean NO_x trap (LNT) aftertreatment within the LHD2b3 vehicles in MY 2007-2009, consistent with the assumptions previously made in Section 2.1.1.4.4. Newer data shows that LNT is not actually being used in LHD45 vehicles, however, we have not updated this assumption because the resulting LHD45 2007-2009 rates compare well to the HDIUT data (see Appendix C).

The T&M values for 2010-and-later vehicles account for implementation of heavy-duty on-board diagnostics (OBD). For LHD2b3 trucks, OBD systems were assumed to be fully implemented in MY 2010. For Class 4 through 8 trucks, (LHD45, MHD, HHD), we assumed there would be a phase-in period from MY 2010 to 2012 where one-third of those trucks were equipped with OBD systems. In MY 2013 and later, all trucks have OBD systems. These OBD adoption rates have been incorporated into the tampering and mal-maintenance emission increases in Table 2-10 with the assumptions and calculations detailed in Appendix B.

Table 2-10 Fleet-average NO_x Emissions Increases in MOVES from Zero-mile Levels over the Useful Life due to Tampering and Mal-maintenance (T&M)

Model years	NO_x increase (TM_{NOx}) for LHD2b3 trucks [%]	NO_x increase (TM_{NOx}) for LHD45 trucks [%]	NO_x increase (TM_{NOx}) for all other HD trucks [%]
1994-1997	0	0	0
1998-2002	0	0	0
2003-2006	0	0	0
2007-2009	4	4	0
2010-2012	56	77	77
2013+	56	58	58

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

- The WVU MEMS data did not show an increase in NO_x emissions with odometer (and consequently, age) during or following the regulatory useful life.[34] 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 in proportion to the zero-mile level, because, in order to meet the more stringent 2010 and later emission standards, these engines rely on aftertreatment emission control systems such that a control system failure will substantially increase emissions.

The NO_x deterioration value for SCR-equipped MY 2015 HHD vehicles is a 58 percent increase. It should be noted that the 58 percent increase is over a baseline emission rate that is significantly lower compared to a MY 2009 non-SCR equipped HHD vehicle. On a per OpMode basis, the NO_x emission rate for age 0-3 MY 2015 HHD vehicle is 33 percent to 89 percent lower than age 0-3 MY 2009 HHD vehicle, while the average reduction across OpModes is 65 percent. Using the average across OpMode metric for simplicity, a fully-deteriorated MY 2015 HHD vehicle is still about 51 percent lower than a MY 2009 HHD age 0-3 vehicle. Since the reduction is not a constant percent value across OpModes, the actual reduction is dependent on the OpMode time distribution and is best compared on a cycle average basis (such as gram/mile).

2.1.1.7 Defeat Device and Low-NO_x Rebuilds

The default emission rates in MOVES for model years 1991 through 1998 are intended to include the effects of defeat devices as well as the benefits of heavy-duty low-NO_x rebuilds (commonly called reflash) that occurred as the result of the heavy-duty diesel consent decree. Reflashes reduce NO_x emissions from these engines by reconfiguring certain engine calibrations, such as fuel injection timing. The MOVES database also includes a set of alternate emission rates for model years 1991 through 1998 assuming a hypothetical fully reflashed fleet.

Since defeat devices were in effect mostly during highway or steady cruising operation, we assumed that NO_x emissions were elevated for only the top two speed ranges in the running exhaust operating modes (>25mph). To modify the relevant emission rates to represent reflash programs, we first used emission rates from model year 1999 (the first model year with not-to-exceed emission limits) to calculate baseline ratios of the emission rates for operating modes 27 and 37 to the rate for opMode 16. We then multiplied the MY 1999 ratios by the emission rates in mode 16 for model years 1991 through 1998, to get estimated "reflashed" emission rates for operating modes 27 and 37. This step is described in Equation 2-16 and Equation 2-18. To estimate "reflashed" rates in the remaining operating modes, we multiplied the reflashed rates by ratios of the remaining operating modes to mode 27 for MY 1991-1998, as shown in Equation 2-17 and Equation 2-19.

.

Where: Operating modes (OM) 21-30

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

Equation 2-16

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

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

Where: Operating modes (OM) 31-40

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

Because the reflash occurred over time after the engines were sold, we phase-in the reflash rates with age. An EPA assessment shows that about 20 percent of all vehicles eligible for reflash had been reflashed by the end of 2008.[35] We assumed that vehicles were reflashed at a steady rate from the time of the consent decree (1999/2000 calendar year), such that in 2008, about 20 percent had been reflashed. We approximated a linear increase in reflash rate from age zero.

2.1.1.8 Sample results

The charts in this sub-section show examples of heavy-duty diesel emission rates in MOVES. Not all rates are shown; the intention is to illustrate the most common trends and hole-filling results.

Figure 2-7 through Figure 2-9 show that NO_x emission rates increase with STP for HHD trucks. Figure 2-10 adds the MHD and Urban Bus regulatory classes, with the error bars removed for clarity. As expected, the emissions increase with power, with the lowest emissions occurring in the idling/coasting/braking bins.

The highest operating modes, for pre-2010 model years that have f_{scale} = 17.1, 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.

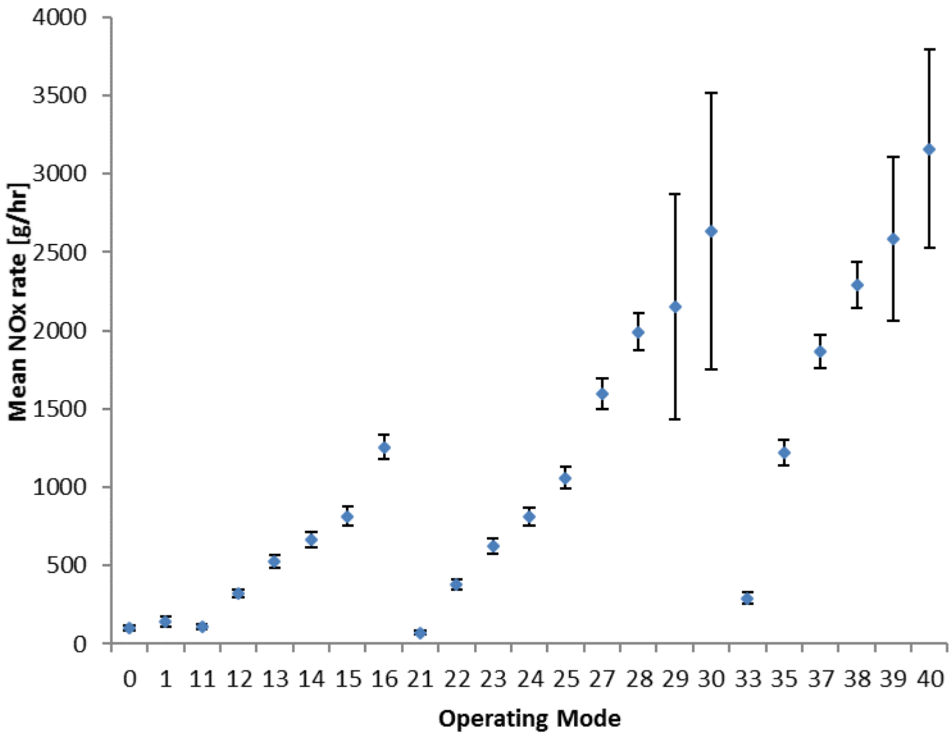


Figure 2-7 Trends in NO_x Emissions by Operating Mode from HHD Trucks for Model Year 2002. Error Bars represent the 95 percent confidence interval of the Mean

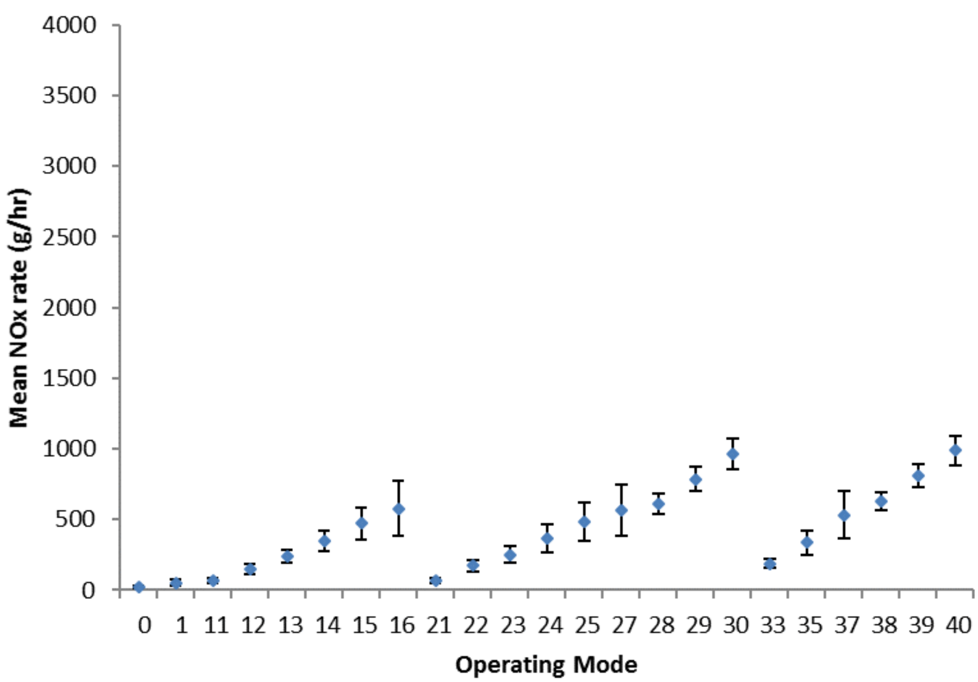


Figure 2-8 Trends in NO_x Emissions by Operating Mode from HHD Trucks for Model Year 2007. Error Bars represent the 95 percent confidence interval of the Mean

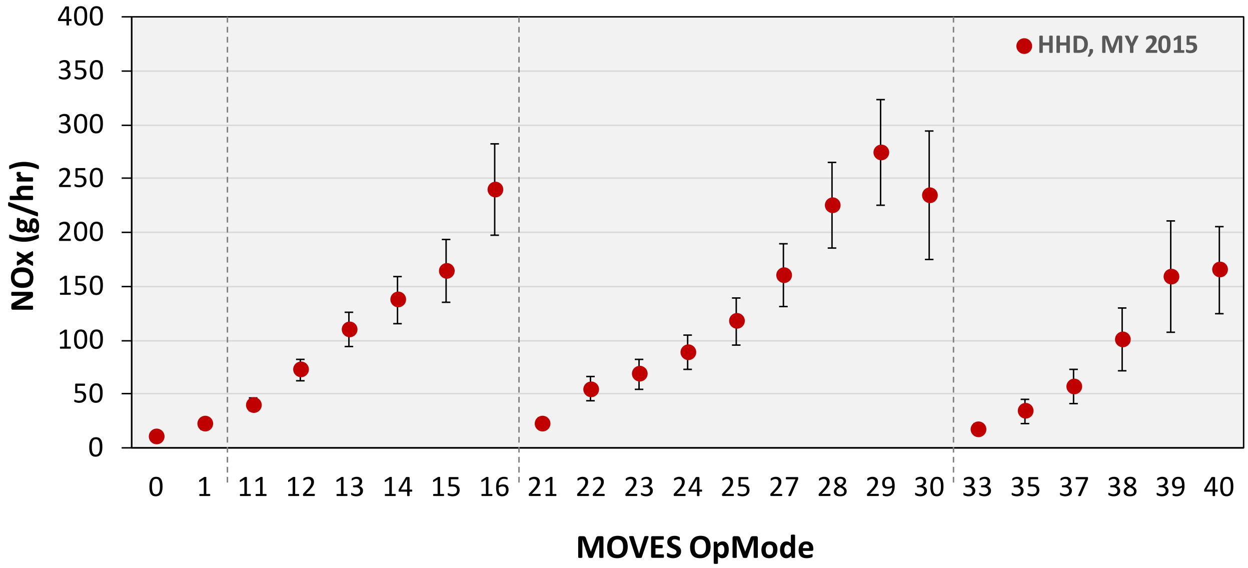


Figure 2-9 Trends in NO_x Emissions by Operating Mode from HHD Trucks for Model Year 2015. Error Bars represent the 95 percent confidence interval of the Mean

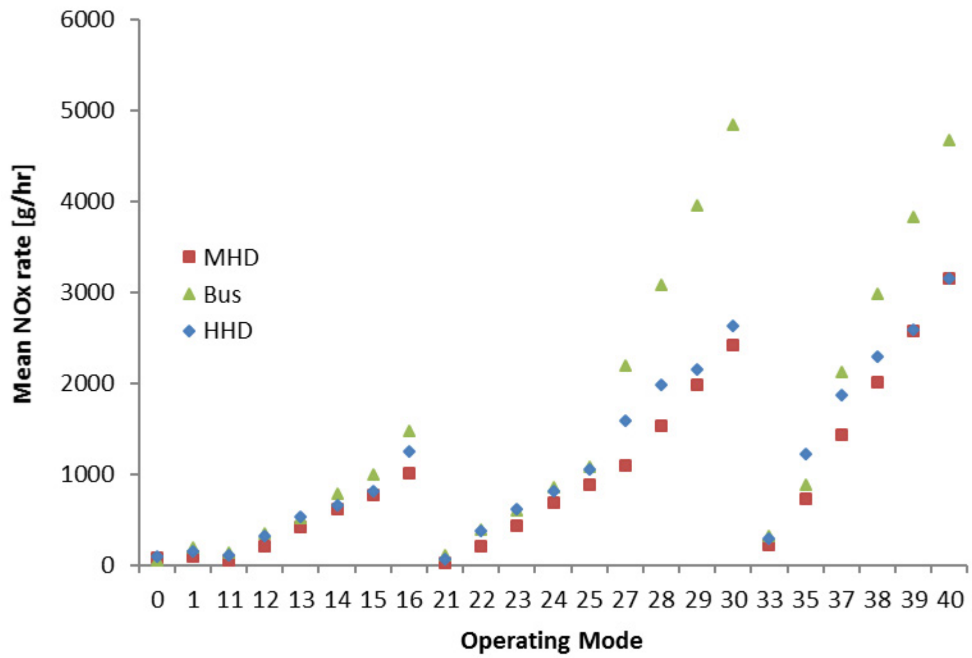


Figure 2-10 Trends in NO_x Emissions by Operating Mode from MHD, HHD, and Urban Bus Regulatory Classes for Model Year 2002.

The effects of model year, representing a rough surrogate for technology or standards, can be seen in Figure 2-11, which shows decreasing NO_x rates by model year group for a sample operating mode (opModeID 24) for HHD trucks. Other regulatory classes show similar trends. The rates in this chart were derived with a combination of data analysis (model years 1991 through 2009) and hole-filling. The trends in the data are expected, since the model year groups were formed on the basis of NO_x standards. Increasingly stringent emissions standards have caused NO_x emissions to decrease significantly.

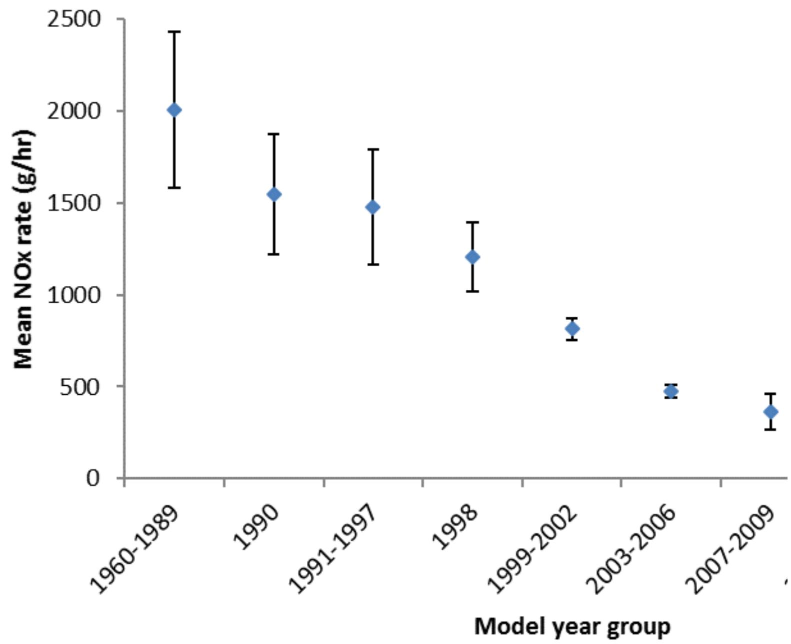


Figure 2-11 Trends in NO_x by Model Year for HHD Trucks in Operating Mode 24. Error Bars represent the 95 percent confidence interval of the Mean. Note: The MY 2010+ rates are not included because they are based on a different fscale than the pre-2010 model years. We will update this plot to display g/mile emissions which are not based on fscale like the Operating Mode specific rates.

Age effects were implemented for aftertreatment-equipped trucks only (mostly model year 2010 and later) based on an analysis of tampering and mal-maintenance effects. Due to faster mileage accumulation, the heavy heavy-duty trucks reach their maximum emission at the youngest ages, as shown in Figure 2-12. Standard Errors (based on coefficients-of-variation for means) from previous model year groups were used to estimate uncertainties for MY 2010.

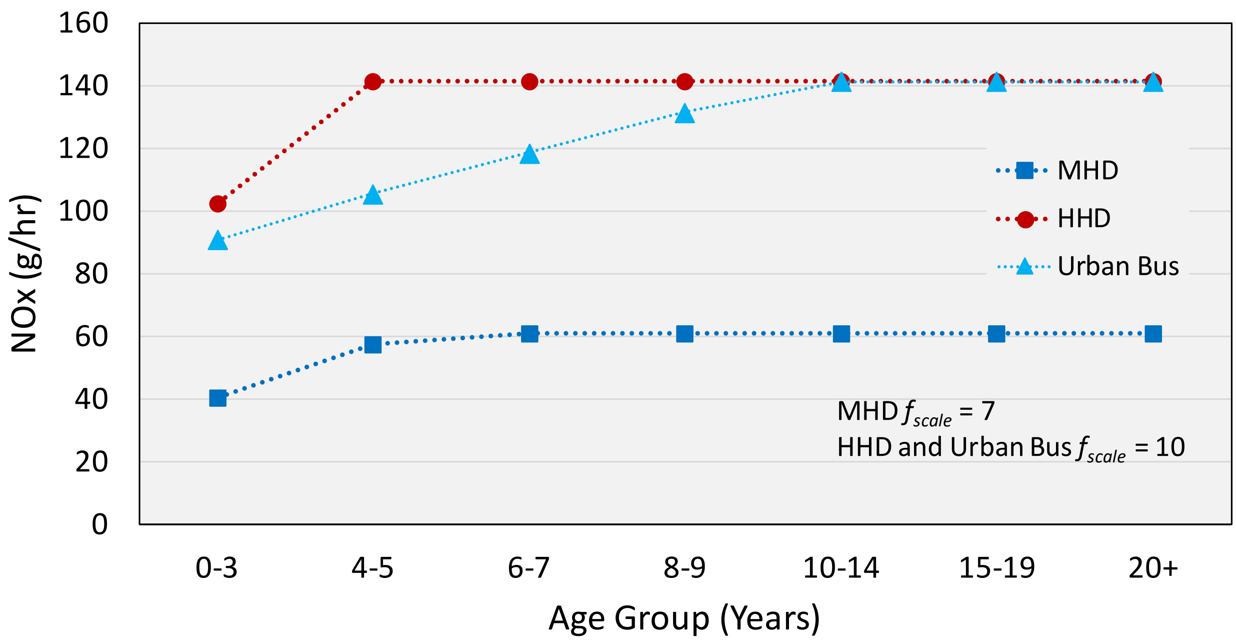


Figure 2-12 Trends in NOx by Age for Model Year 2015 for Operating Mode 24 for MHD, HHD, and Urban Bus Regulatory Classes.

Figure 2-13 and Figure 2-14 show the mean emission rates for LHD2b3 trucks for model years 2003-2006 and 2007-2009, respectively. The estimated uncertainties are greater than for the other heavy-duty regulatory classes, since there were fewer vehicles in our test data. As described previously, model years 2007-2009 vehicles include vehicles with LNTs (with NO_x increases during PM regeneration) and vehicles without any aftertreatment.

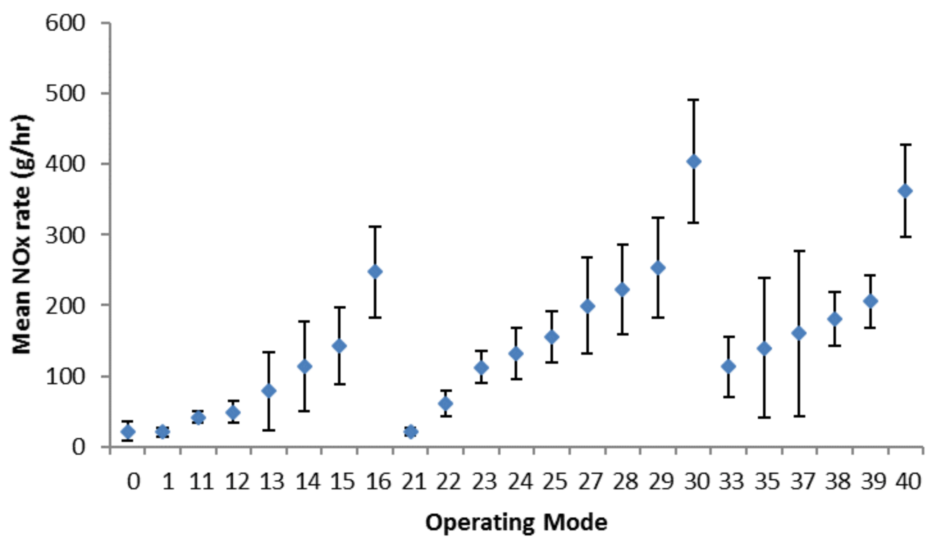


Figure 2-13 Mean NO_x rates by operating mode for model years 2003-2006 LHD2b3 (regClassID 41) trucks age 0-3. Error bars represent the 95 percent confidence interval of the mean

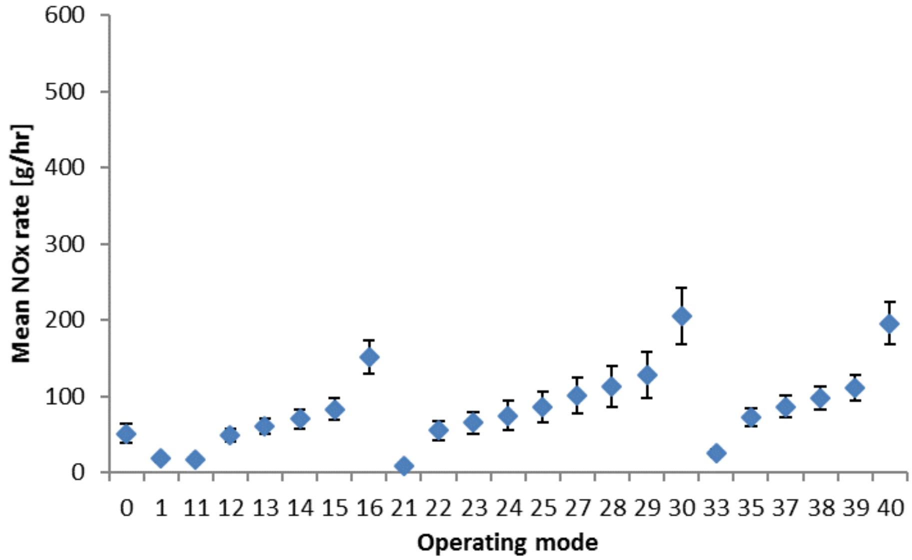


Figure 2-14 Mean NO_x rates by operating mode for model years 2007-2009 LHD2b3 (regClassID 41) trucks age 0-3. Error bars represent the 95 percent confidence interval of the mean

2.1.2 Particulate Matter (PM)

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

Measurements of total $PM_{2.5}$ emission rates are typically filter-based, including the mass of all the chemical components in the particle-phase. As described above for NO_x, the heavy-duty diesel PM emission rates in MOVES are a function of: (1) source bin, (2) operating mode, and (3) age group. We classified heavy-duty PM emission data into the following model year groups for purposes of emission rate development. These groups are generally based on the introduction of emissions standards for heavy-duty diesel engines. They also serve as a surrogate for continually advancing emission control technology on heavy-duty engines. For example, MY 2010 and beyond is mentioned as a separate group even though the PM standard is unchanged from the previous group MY 2007-2009. This is because, starting MY 2010, the wide adoption of SCR systems and improvements in DPFs likely resulted in a shift in tailpipe PM emissions. Other, secondary, reasons are wider availability of PM data in the HDIUT data set (section 2.1.1.1) starting MY 2010-2011 and the f_{scale} updates to all HD regClasses for MY2010+ (see section 2.1.1.4.1 and Appendix G). Table 2-11 shows the model year group ranges and the applicable brake-specific emissions standards.

Table 2-11 Model Year Groups Used for Analysis Based on the PM Emissions Standard

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

2.1.2.1 Data Sources

MY 1960-2009: All of the data used to develop the MOVES $PM_{2.5}$ emission rates for MY 1960-2009 was generated in the CRC E-55/59 research program.[36] The following description by Dr. Ying Hsu and Maureen Mullen of E. H. Pechan, in the "*Compilation of Diesel Emissions Speciation Data – Final Report*"[37] provides a good summary of the program:

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

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

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

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

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

The tables below provide a greater detail on the data used in the analysis. Vehicles counts are provided by number of vehicles, number of tests, model year group, and regulatory class (46 = MHD, 47=HHD) in Table 2-12.

Table 2-12 Vehicle and Test Counts by Regulatory Class and Model Year Group

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

Counts of tests are provided by test cycle in Table 2-13.

Table 2-13 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

MY 2010+: The HDIUT data set, briefly described in section 2.1.1.1 and Table 2-2, was used for tailpipe PM rates update for MY 2010+. The analysis method for PM was different from the gaseous pollutants and these differences are described in section 2.1.2.3.

2.1.2.2 Data Analysis for MY 1960-2009 Rates

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 1-4 , and then subsequently classified to one of the 23 operating modes defined above in Table 1-3.

The values of coefficients *A*, *B*, and *C* are the road-load coefficients pertaining to the heavy-duty vehicles[38] 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 1-4.

Note that this approach differs from the NO_x emission rates analysis described in Section 2.1.1.2, since the particulate data was collected on a chassis dynamometer from vehicles lacking electronic control units (ECU). We have not formally compared the results of the two methods of calculating STP. However, on average, we did find the operating-mode distributions to be similar between the two calculation methods for a given vehicle type. For example, we found that the maximum STP in each speed range was approximately the same.

2.1.2.2.2 Compute Normalized TEOM Readings

The TEOM readings were obtained for a subset of tests in the E-55/59 test program. Only 29 vehicles had a full complement of 1-hz TEOM measurements. However, the continuous particulate values were modeled for the remaining vehicles by West Virginia University, and results were provided to EPA. In the end, a total of 56 vehicles (out of a total of 75) and 470 tests were used in the analysis out of a possible 75 vehicles. Vehicles and tests were excluded if the total TEOM $PM_{2.5}$ reading was negative or zero, or if corresponding full-cycle filter masses were not available. Table 2-14 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 2-14 Vehicle and Test Counts by Heavy-Duty Class and Model Year

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

Since the development of MOVES emission rates is cycle independent, all available cycles/tests which met the above requirements were utilized. As a result, 488,881 seconds of TEOM data were used. The process required that each individual second by second TEOM rate be normalized to its corresponding full-cycle filter mass, available for each combination of vehicle and test. This step was necessary because individual TEOM measurements are highly uncertain and vary widely in terms of magnitude (extreme positive and negative absolute readings can occur). Equation 2-20 shows the normalization process for a particular one second TEOM measurement.

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

Where:

i = an individual 1-Hz measurement (g/sec),

j = an individual test on an individual vehicle,

$PM_{TEOM,j,i}$ = an individual TEOM measurement on vehicle j at second i,

$PM_{filter,j}$ = the Total $PM_{2.5}$ filter mass on j,

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

Kinsey et al. (2006) [39] demonstrated that time-integrated TEOM measurements compare well with gravimetric filter measurements of diesel-generated particulate matter.

2.1.2.2.3 Compute Average Normalized TEOM Measures by MOVES Bin

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

2.1.2.2.4 Missing Operating Modes

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

2.1.2.2.5 LHD and Urban Bus Emission Rates

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

The following steps were needed to adjust the emissions estimated from the MHD and HHD regulatory classes because the data were not analyzed for the f_{scale}.used for LHD. The emission rates of pre-2010 LHD (LHD2b3 and LHD45 (regClassID 41 and 42) are based on an f_{scale} of 2.06 as discussed in Section 1.3, whereas MHD and HHD are based on an f_{scale} of 17.1. The $PM_{2.5}$ emission rates for the pre-2010 LHD regulatory classes are based on the VSP-based MHD $PM_{2.5}$ emission factors derived from the E55/59 TEOM data. With VSP-based emission rates, the power of the vehicle is scaled to the mass of the individual tested vehicle. Because LHD have lower vehicle weights and power outputs from the MHD and HHD vehicles, we scaled the VSP-emission rates down to the power requirements of the LHD vehicles. To estimate the LHD2b3 and LHD45 $PM_{2.5}$

emission rates, we multiplied the VSP-based MHD $PM_{2.5}$ emission rates by a factor of 0.46 obtained from the MOBILE6.2 heavy-duty conversion factors[40], which accounts for the lower power requirements per mile (bhp-hr/mile) of light heavy-duty trucks versus MHD trucks. This scaling is estimates VSP-based emissions rates for LHD vehicles, which is compatible with the f_{scale} of 2.06, which is the average source mass of light-duty trucks in metric tons. Equation 2-21 used to derive the $PM_{2.5}$ emission rates for LHD regulatory class is shown below:

$$LHDPM_{2.5}\ emission\ rate = 0.46 \times MHD\ (VSP_{based})PM_{2.5}\ emission\ rate$$ **Equation 2-21**

Where the MHD VSP-based emission rates are obtained from MOVES2009.[41]

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 2-15 displays the model years for which the Urban Bus regulatory class has different PM emission standards from other heavy-duty compression-ignition engines. For these model years (1991-2006), the Urban Bus PM emission standards are equal to the HHD emission rates multiplied by the ratio in emission standards. In addition, the Urban Bus emissions have different emission deterioration effects as discussed in Appendix B.1.

Table 2-15 Urban Bus PM Standards in Comparison to Heavy-Duty Highway Compression Engine Standards

Engine Model Year	Heavy-Duty Highway Compression-Ignition Engines	Urban Buses	Ratio in standards
1991-1993[a]	0.25	0.1	0.4
1994-1995	0.1	0.07	0.7
1996-2006	0.1	0.05	0.5

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

2.1.2.2.6 Model Year 2007-2009 Vehicles (with Diesel Particulate Filters)

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

At the time of analysis for MOVES2014, no continuous PM emissions data were available for analysis on the 2007-2009 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 was applied to the existing, OpMode-based, 1998-2006 model year PM emission rates to estimate in-use rates for MY 2007-2009 vehicles.

An analysis of the available certification data is shown in Table 2-16 below. It suggests that the actual ratio of improvement due to the particulate trap is reduction of a factor of 27.7. This factor is considerably higher than the relative change in the certification standards (i.e., a factor of 10). The reason for the difference is that the new trap-equipped vehicles certify at emission levels which are much lower than the standard, and thus, create a much larger 'margin of safety' than previous technologies could achieve.

As an additional check on the effectiveness of the trap technology, EPA conducted some limited in-house testing of a Dodge Ram truck, and carefully reviewed the test results from the CRC Advanced Collaborative Emission Study (ACES) phase-one program, designed to characterize emissions from diesel engines meeting 2007 standards. The results from these studies demonstrated that the effectiveness of working particulate traps is very high.[42]

Table 2-16 Average Certification Results for Model Years 2003-2007

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

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

2.1.2.2.7 Tampering and Mal-maintenance

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

The primary data set was collected during a limited calendar year period, yet MOVES requires data from a complete range of model year/age combinations. As a result, the T&M factors shown below in Table 2-17 were used to forecast or back-cast the basic PM emission rates to predict model year group and age group combinations not covered by the primary data set. For example, for the 1981 through 1983 model year group, the primary dataset contained data which was in either the 15 to 19 or the 20+ age groups. However, for completeness, MOVES must have emission rates for these model years for ageGroups 0-3, 4-5, 6-7, etc. As a result, unless we assume that the higher emission rates which are were measured on the older model year vehicles have always prevailed – even when they were young, a modeling approach such as T&M must be employed. Likewise, more recent model years could only be tested at younger ages. The T&M methodology used in the MOVES analysis allows for the filling of age and model year group combinations for which no data is available.

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

We followed the same tampering and mal-maintenance methodology and analysis for PM as we did for NO_x, as described in Appendix B.8. The overall MOVES tampering and mal-maintenance effects on PM emissions over the fleet's useful life are shown in Table 2-17. The value of 89 percent for 2010-2012 model years reflects the projected effect of heavy-duty on-board diagnostic deterrence/early repair of Tampering and Mal-maintenance effects. It is an eleven percent improvement from model years which do not have OBD (i.e., 2007-2009). The 67 percent value for 2013+ is driven by the assumed full-implementation of the OBD in 2013 and later trucks, which assumes a 33 percent decrease in tampering and mal-maintenance emission effects.

Table 2-17 Tampering and Mal-maintenance Effects for PM over the Useful Life

Model Year Group	Increase in PM Emissions (%)
Pre-1998	85
1998 - 2002	74
2003 – 2006	48
2007 – 2009	100
2010 – 2012[1]	89 (HHD, MHD, LHD45, and Bus) 67 (LHD2b3)
2013+	67

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

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

Particulate matter from conventional diesel engines is dominantly composed of elemental carbon. Elemental carbon is often used synonymously with soot and black carbon. Black carbon is important because of its negative health effects and its environmental impacts as a climate forcer.[43] Elemental carbon from vehicle exhaust is measured with filter-based measurements using thermal optical methods. Continuous surrogate measures of elemental carbon can also be made with available photoacoustic instruments.

MOVES models Total $PM_{2.5}$ emissions by vehicle operating mode using elemental carbon (EC) and non-elemental particulate matter carbon (NonECPM), as shown in Equation 2-22.

$$PM_{2.5} = EC + NonECPM \quad \text{Equation 2-22}$$

By having emission rates for EC and nonECPM for each operating mode, the MOVES design permits the EC/PM to vary for each operating mode. In practice, the data used to develop EC and nonECPM emission rates does not support such fine resolution, and the EC/PM is the same within each emission processes, except for the idle operating mode.

For pre-2007 diesel trucks, we developed EC and nonECPM emission rates by applying EC/PM ratios to the modal-based emission rates. For the idle operating mode (opModeID 1), we applied an EC/PM fraction of 46.4 percent from the $PM_{2.5}$ Speciation profile developed from the idle mode from the UDDS tests from the E55/59 program. For all the other operation modes within the running emission process, we used an EC/PM fraction of 79.0 percent from the $PM_{2.5}$ speciation profile developed from the transient mode of the UDDS tests from the E55/59 program. The development of the pre-2007 $PM_{2.5}$ speciation profiles from the E55/59 program are documented in the Onroad Speciation Report.[44]

For 2007-2009 model year DPF-equipped diesel engines, we used the elemental carbon fraction of 9.98 percent measured in Phase 1 of the Advanced Collaborative Emissions Study (ACES) Report.[45] Diesel particulate filters preferentially reduce elemental carbon emissions, resulting in the low percentage of elemental carbon emissions. The average EC/PM fraction is based on four engines run on the 16-hour cycle which composes several different operating cycles. Because the fraction is based upon a range of driving conditions, we applied the constant 9.98 percent EC/PM fraction across all operating modes for the 2007+ diesel emissions rates, including the idle operating mode (opModeID 1).

The nonECPM fraction of emissions contains organic carbon (OC), sulfate, and other trace elements and ions. MOVES uses the fuel sulfur content to adjust the sulfate emission contribution to NonECPM as discussed in the MOVES Fuel Adjustment Report.[46] MOVES uses speciation profiles to estimate the composition of organic carbon, ions, and elements in NonECPM as discussed in the MOVES PM Speciation Report.[44]

2.1.2.3 Data Analysis for MY 2010+ Rates

The MY 2010+ HDIUT data set described in section 2.1.1.1 and Table 2-2 was used to update $PM_{2.5}$ emissions rates for MY 2010+ vehicles. OpModes (Table 1-3) were assigned to the 1 hz data using the method to calculate STP described in section 2.1.1.2. The analysis used updated f_{scale} values, same as NO_x analysis, described in section 2.1.1.4.1 and Appendix G and thus, there was no need for hole-filling of missing OpModes. One key difference between the $PM_{2.5}$ and NO_x methods is that the $PM_{2.5}$ analysis did not use the NO_x FEL based grouping (described in section 2.1.1.3.2). The PM data is missing or reported as zero for many vehicles and when distributed over FEL groups, some or all OpModes within a group had very sparse data. We addressed the issue of data sparsity by not using NO_x FEL based grouping and production volume weighting. Thus, unlike NO_x, the $PM_{2.5}$ rates for zero-mile (or age 0) for a given regClass do not vary by model year between 2010 and 2015. Note that, for regClass 42-47, the PM emission rates in the MOVES database for all age groups (except age 0-3 for regClass 42) for MY 2013+ are lower than their counterpart rates for MY 2010-2012 because of lower T&M impact due to HD OBD phase-in (see Appendix B).

The per-OpMode PM emission rates are estimated using Equation 2-23 and Equation 2-24, which are comparable to Equation 2-5 and Equation 2-6 used for the development of NOx emission rates except the FEL grouping part is removed.

$$ER_{pol,OM,C,veh} = \frac{\sum_{sec} ER_{pol,OM,C,veh,sec}}{sec_{count}} \quad \textbf{Equation 2-23}$$

$$ER_{pol,OM,C} = \frac{\sum_{veh} ER_{pol,OM,C,veh}}{veh_{count}} \quad \textbf{Equation 2-24}$$

Where:

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

While using the same method as used in the NO_x analysis would capture any variations across model years, the inability to capture this variation is less of a concern for PM because the DPF technology had matured more than NO_x control technology by MY 2010, and year-over-year variations between 2010-2015 are a very small contributor to overall PM inventory. The effect of tampering and mal-maintenance on emissions rates is based on the methodology described in section 2.1.2.2.7 and the values are shown in Table 2-17. The EC (9.98 percent) and non-EC (90.02 percent) fractions are unchanged from MY 2007-2009 analysis described in section 2.1.2.2.8.

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

We compared our HHD $PM_{2.5}$ rates against values reported in the literature. For a MOVES national scale run, the $PM_{2.5}$ rate for a MY 2015, age 0-3, HHD vehicle was about 2.3 mg/mi. Other studies have reported PM rates in the range of 1-7 mg/mi for MY 2010+ vehicles equipped with DPF and SCR and certified to NO_x standard of 0.20 g/bhp-hr.[157,158,159] The rates from the MOVES-run and other studies are dependent on driving cycle, however, since the MOVES rates are within the range of reported values, we decided to use the HDIUT based $PM_{2.5}$ data for the update. For the same MOVES run, the $PM_{2.5}$ rates for LHD2b3, LHD45, MHD, and Urban Bus were 4.9 mg/mi, 4.8 mg/mi, 14.6 mg/mi and 2.2 mg/mi. The OpMode based $PM_{2.5}$ rates for MHD vehicles are higher compared to other regClasses. We do not have a reason to suspect the MHD data nor do we have a confirmed explanation of why the emission rate is comparatively higher.

DPF Regeneration Events:

MOVES does not separately model the change in emissions, for any pollutant, from DPF regeneration events. However, the HDIUT data set used to update the MY 2010+ PM rates includes DPF regeneration events. Thus, the emission rates, for PM and other pollutants, includes the effects of DPF regen events. Modern DPFs have catalyzed substrate that allow them to undergo passive regeneration when the vehicle is operating at high-speeds and/or high-loads such that the exhaust temperature is sufficient to induce the regeneration. The passive regen events are "silent" and happen in the background without any regeneration code in the ECU data. On the other hand, the active regeneration events are where the ECU actively raises the temperature in the exhaust so that the soot captured in the DPF can be combusted. One way to increase the temperature is to inject additional fuel which gets burned off and raises the temperature. We analyzed the "Regen_Signal" column in the quality-assured 1 hz emissions data files for 77 vehicles in the HHD 0.20 NO_x FEL group to estimate the frequency and count of regen events. It is our understanding that the "Regen_Signal" flag only accounts for active regen events. There were 11 vehicles with the Regen_Signal set to "Y" and the regen events totaled 60,576 seconds, which is about 18% of the data from just those 11 vehicles and 3% of the data from all 77 vehicles.

Ideally, we would like to have detailed information on the frequency of regeneration events, by OpMode, in the real-world and the effect of the regeneration event on emission rates. Until we have that level of detailed data, we conclude that the emission rates in MOVES for MY 2010+ HD vehicles are somewhat representative, on average, of the effect of DPF regeneration events.

2.1.2.4 Sample Results

Figure 2-15 and Figure 2-16 show the trend of increasing PM rates with STP. As with NO_x, the highest operating modes in each speed range will rarely be attained due to the power limitations of heavy-duty vehicles, but are included in the figures for completeness. At high speeds (greater than 50 mph; operating modes ≥ 30), the overall PM rates are lower than the other speed ranges. For pre-2007 model years, the PM rates are dominated by EC (except for the idle operating mode, opModeID 1). With the introduction of DPFs in model year 2007, we model the large reductions in overall PM rates and the smaller relative EC contribution to PM emissions.

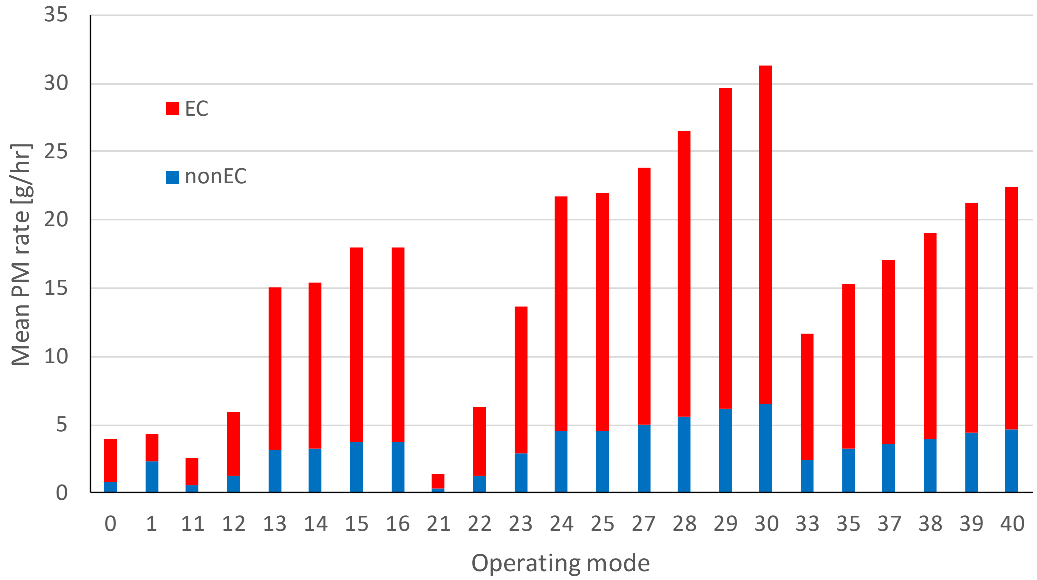


Figure 2-15 Particulate Matter Rates by Operating Mode Representing Medium Heavy-Duty Vehicles (model year 2006 at age 0-3 years)

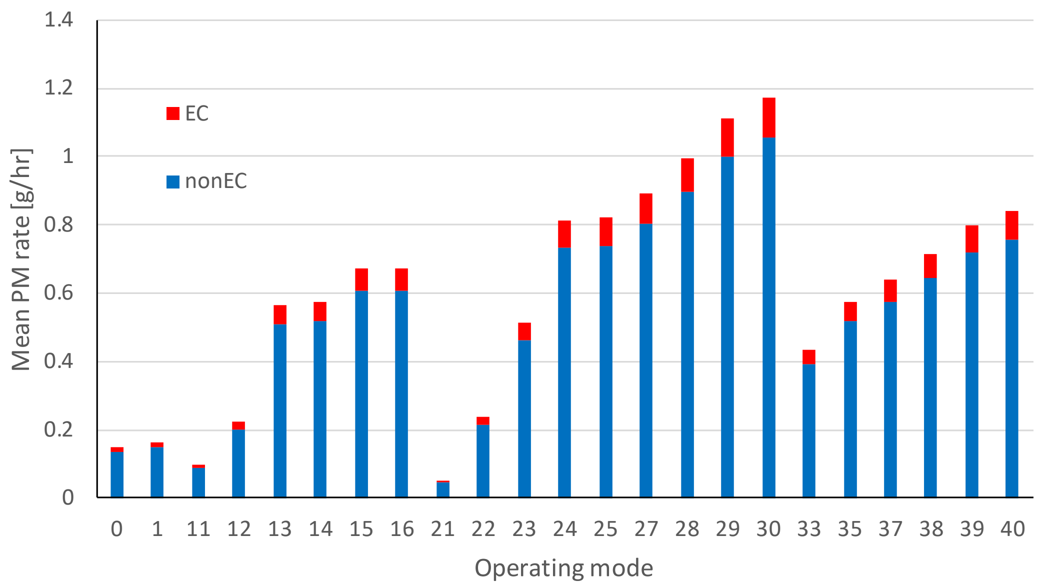


Figure 2-16 Particulate Matter Rates by Operating Mode for Medium Heavy-Duty Vehicles (model year 2007 at age 0-3 years)

Figure 2-17 shows an example of how tampering and mal-maintenance estimates increase PM with age. The EC/PM proportion does not change by age, but the overall rate increases and levels off after the end of useful life. The rate at which emissions increase toward their maximum depends on regulatory class.

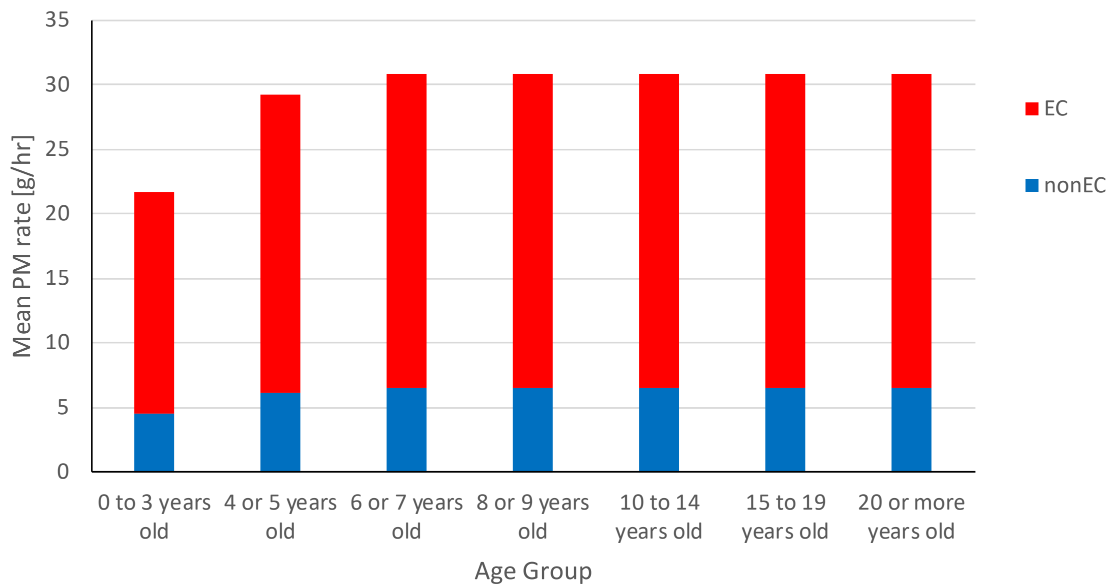


Figure 2-17 Particulate Matter Rates by Age Group for Medium Heavy-Duty Vehicles (model year 2006, operating mode 24)

Figure 2-18 shows the effect of model year on emission rates from a single operating mode (opModeID 24) from medium heavy-duty truck in MOVES. Emissions generally decrease with new PM standards, however there is variability within each operating mode. The EC fraction stays constant until model year 2007, when it is reduced to less than ~10 percent due the implementation of diesel particle filters. The overall PM level is substantially lower starting in model year 2007. The emission rates shown here for earlier model years are an extrapolation of the T&M analysis since young-age engines from early model years could not be tested in the E-55 program.

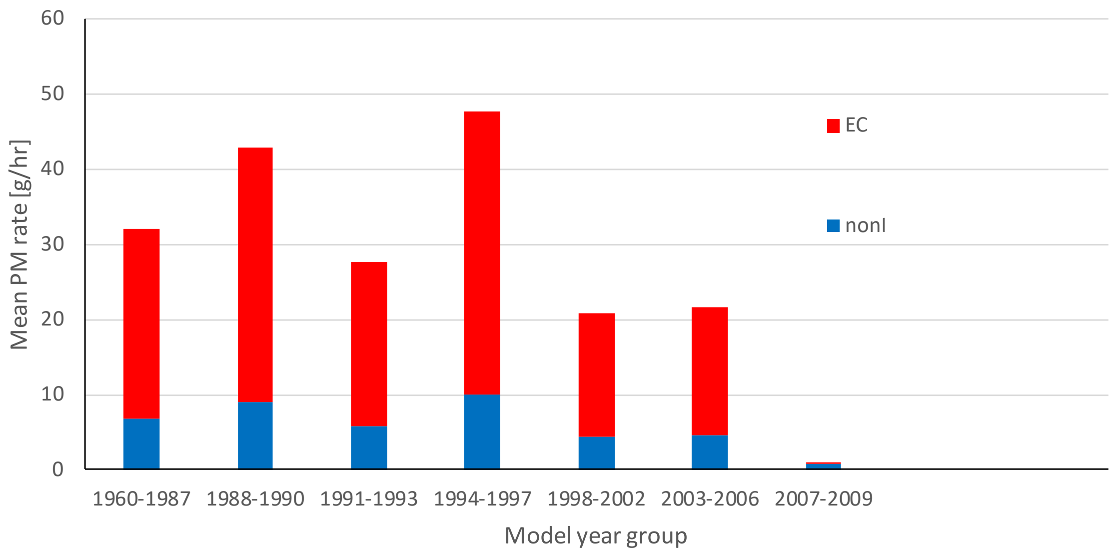


Figure 2-18 Particulate Matter Rates for Medium Heavy-Duty Vehicles by Model Year Group (age 0-3 years, operating mode 24).

Note: The MY 2010+ emission rates are not shown because they have a different f_{scale} and cannot be directly compared to the pre-2010 rates. We will update this figure to display g/mile rates that are not dependent on the f_{scale}.

2.1.3 Hydrocarbons (HC) and Carbon Monoxide (CO)

While diesel engine emissions of HC and CO are important, they are not the largest contributors to mobile source HC and CO emission inventories. Regulations of non-methane hydrocarbons (NMHC), combined with the common use of diesel oxidation catalysts have yielded reductions in both HC and CO emissions from later model year heavy-duty diesel engines. As a result, data collection efforts do not focus on HC or CO from heavy-duty engines, and less data is available. In this report, hydrocarbons are sometimes referred to as total hydrocarbons (THC).

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

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

2.1.3.1 Data Sources

MY Pre-2010 base rates

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

1. **CRC E-55/59[36]: As** mentioned earlier, this program represents the largest volume of heavy-duty emissions data collected from chassis dynamometer tests. All tests were used, not just those using the TEOM. Overall, 75 trucks were tested on a variety of drive cycles. Model

years ranged from 1969 to 2005, with testing conducted by West Virginia University from 2001 to 2005.

2. **Northern Front Range Air Quality Study (NFRAQS)[47]:** 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)[48]:** NYSDEC sponsored this study to investigate the nature and extent of heavy-duty diesel vehicle emissions in the New York Metropolitan Area. West Virginia University tested 25 heavy heavy-duty and 12 medium heavy-duty diesel trucks under transient and steady-state drive cycles.
4. **West Virginia University:** Additional historical data collected on chassis dynamometers by WVU is available in the EPA Mobile Source Observation Database.

The pre-2010 onroad data used for the NO_x analysis was not used since 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.

MY 2010 and later base rates

We used the MY 2010+ HDIUT data set, using the same vehicles as used for NO_x and described in Section 2.1.1.1 and Table 2-2. Past concerns regarding the quality of HC or CO measurements are not applicable here since the HDIUT measurements are made using instruments that conform to the requirements described in 40 CFR Part 1065.

The numbers of vehicles in the data sets are shown in Table 2-18.

Table 2-18 Numbers of Vehicles by Model Year Group, Regulatory Class, and Age Group

Model year group	Regulatory class	Age group						
		0-3	4-5	6-7	8-9	10-14	15-19	20+
1960-2002	HHD	58	19	16	9	16	6	7
	MHD	9	6	5	4	12	15	6
	LHD45	2			1			
	LHD2b3	6						
	Bus	26			1	3		
2003-2006	HHD	6						
2007-2009	HHD, MHD, LHD45, LH2b3, Bus	No vehicles for this model year group. Rates for this model year group are based on MY 2003-2006 with 80 percent reduction.						
2010+	HHD, MHD, LHD45, LH2b3, Bus	See “HDIUT 2010+” row in Table 2-2. All vehicles for MY 2010+ are in the 0-3 age group.						

2.1.3.2 Analysis

Pre-2010 base rates

Similar to the analysis done for PM, for each second of operation on the chassis-dynamometer, the instantaneous scaled tractive power (STP_t) was calculated using Equation 1-4 and then subsequently classified to one of the 23 operating modes defined in Table 1-3. We used the same track-load coefficients, A, B, and C pertaining to heavy-duty vehicles that were used in the PM analysis.

Using a method similar to that used in the NO_x and PM analysis, we averaged emissions by vehicle and operating mode. We then averaged across all vehicles by model year group, age group, and operating mode. Estimates of uncertainty for each mean rate were calculated using the same equations and methods described in Section 2.1.1.3.3. In populating the emission rates in MOVES, we used the age group that was most prevalent in each regulatory class and model year group combination. These age groups are shown in Table 2-19. We used the MHD to represent the LHD45 and LHD2b3 emission rates analyzed with a fixed mass factor of 2.06.

2010 and later base rates

We used the HDIUT data and followed the analysis methodology used for MY 2010+ NO_x rates. The dataset is described in section 2.1.1.1 and Table 2-2 while the methodology is described in Sections 2.1.1.2 (calculation of STP and assignment of operating modes), 2.1.1.3.2 (calculation of mean emission rates), 2.1.1.4.1 (hole-filling missing operating modes), and Appendix G (selection of f_{scale}). HDIUT data set is predominantly vehicles in the 0-3 age group with only a handful vehicles in the 4-5 age group. Since the HDIUT data is measured and submitted by the manufacturer and the test vehicles are required to be free of any tampering or mal-maintenance, we can safely assume that they represent age 0 vehicles for the purpose of assigning base rates and applying the tampering and mal-maintenance effects.

A comparison of HDIUT based THC and CO emission rate for MY 2010+ MHD and HHD vehicles, for OpMode 24, with older model years is shown in Figure 2-25 and Figure 2-26, respectively. The THC rates, generally low for diesel vehicles, for both MHD and HHD are comparable to MY 2007-2009 rates. However, for CO, the HHD rates for MY 2010+ are significantly higher compared to MY 2007-2009 but MHD rates are comparable. In a previous review of this report, we received the comment that single-cell NDIR based CO measurements suffer from severe drift that is not corrected by zero and span checks because the calibration gases are dry, while vehicle tailpipe exhaust gases are not dry (Appendix K.4). Based on the HDIUT data it is not possible for us to determine if MY 2010+ CO emission rates are affected by the said drift in the CO measurements. We looked at the CO emissions for each of the 93 vehicles in the HHD 0.20 FEL group and confirm the high average CO rate is not due to a few outliers. Further, the CO emission rate for the MHD vehicles is not as high and that for the LHD vehicles (= 13.45 g/hr for OpMode 24) is even lower. Based on the available data and trends, we are unable to confirm whether or not the high CO emissions for the HHD vehicles is real or an artifact of CO sensor drift. Thus, we decided to accept the reported CO emission rates as valid.

Table 2-19 Age Groups for which Emission Rates are Populated Directly Based on the Data

Regulatory class	Model year group	Age group
HHD	1960-2002	0-3
MHD	1960-2002	15-19
LHD2b3	1960-2002	0-3
BUS	1960-2002	0-3
HHD	2003-2006	0-3
HHD, MHD, LHD[1], BUS[2]	2010+	0-3

Notes:
[1] LHD2b3 and LHD45 emission rates are based on the vehicles with "LHD" service class in the HDIUT data set
[2] Urban Bus emission rates are based on HHD vehicles in the HDIUT data set

Effect of Tampering and Mal-maintenance

For all model years, we then applied tampering and mal-maintenance effects to adjust emissions from the measured age to all age groups, lowering emissions for younger ages and raising them for older ages, using the methodology described in Appendix B. We applied the same tampering and mal-maintenance effects for CO as HC, which are shown in Table 2-20.

Table 2-20 Tampering and Mal-maintenance Effects for HC and CO over the Useful Life

Model years	Increase in HC and CO Emissions (%)
Pre-2003	300
2003 – 2006	150
2007 – 2009	150
2010 – 2012[1]	29 (HHD, MHD, LHD45, and Bus) 22 (LHD2b3)
2013+	22

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

While LHD2b3 and LHD45 and MHD vehicles share the same pre-MY 2010 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 multiplied these increases by the T&M age-based adjustment factors shown in Table B-2 and applied the result to the zero-mile (or age 0) emissions rate to get the emissions rate by age group.

We did not analyze emissions data for 2007-2009 heavy-duty trucks. With the increased use of diesel oxidation catalysts (DOCs) in conjunction with DPFs, we assumed an 80 percent reduction in zero-mile emission rates for both HC and CO starting with model year 2007. The derivation of the T&M effects for 2007 and later trucks presented in Table 2-20 are discussed in appendix section B.9

2.1.3.3 Sample results

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

In Figure 2-19 through Figure 2-22, we see that HC and CO mean emission rates increase with STP, though there is much higher uncertainty than for the NO_x rates. This pattern could be due to the smaller data set or may truly reflect a less direct correlation between HC, CO, and STP. For the MY 2002 figures, data for HHD and bus classes were combined to generate one set of rates for HHD and buses. Figure 2-20 and Figure 2-22 show the rates for HHD for MY 2015, based on the methods described in section 2.1.1.3.2 and 2.1.1.4.1 and Appendix G.

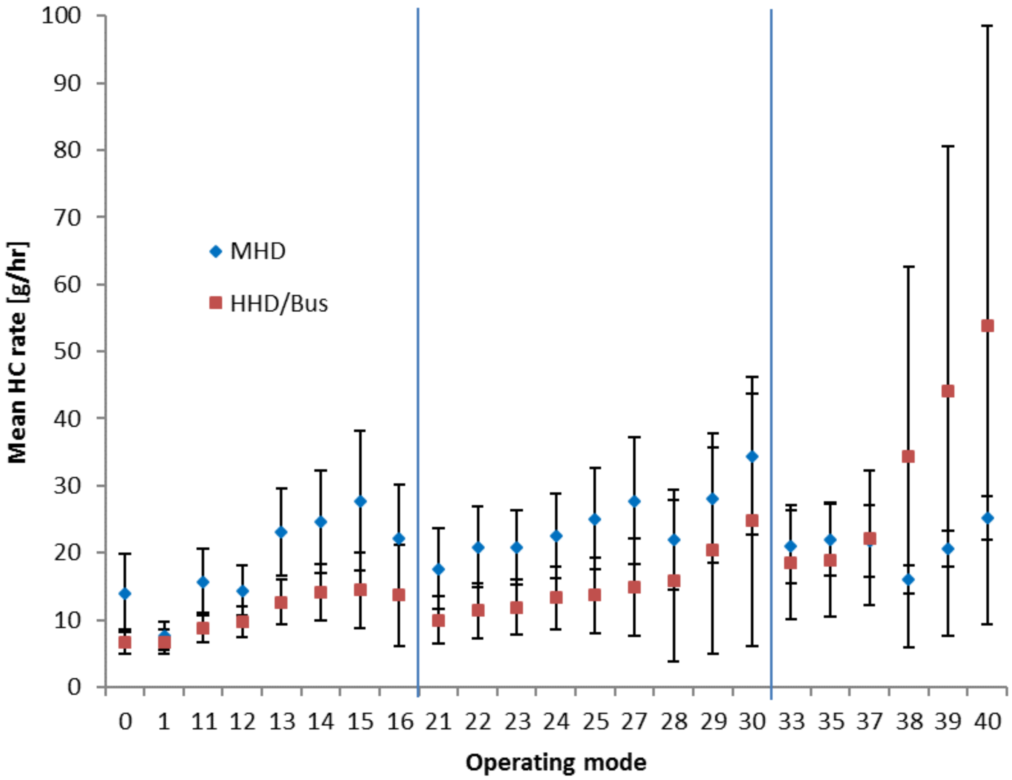


Figure 2-19 THC Emission Rates [g/hr] by Operating Mode for Model Year 2002 and Age Group 0-3. Error Bars Represent the 95 Percent Confidence Interval of the Mean

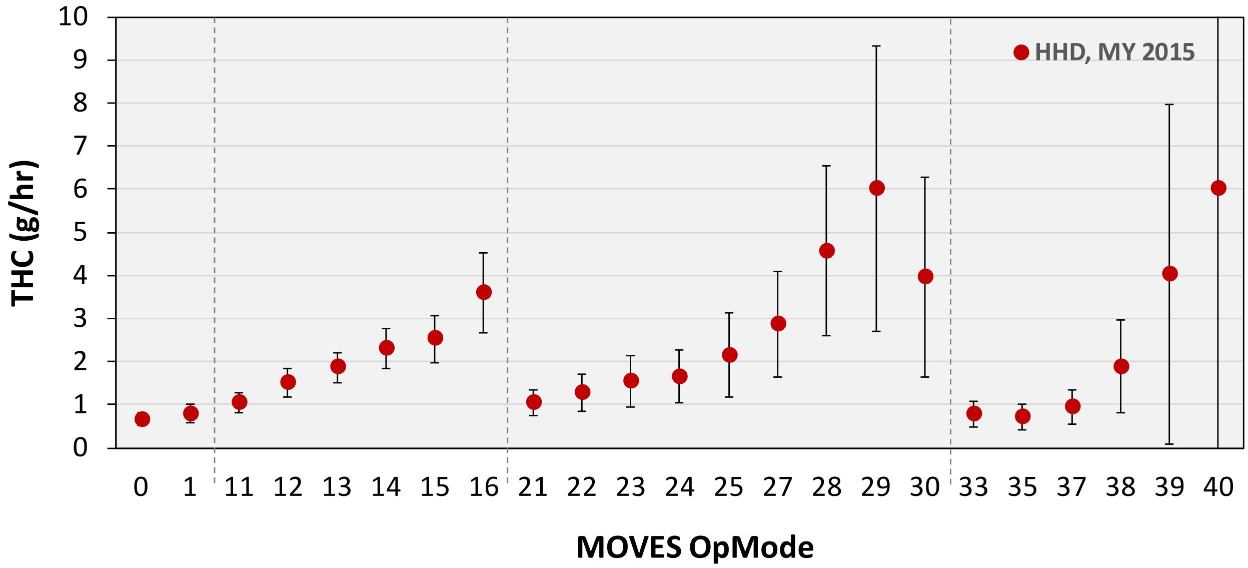


Figure 2-20 THC Emission Rates [g/hr] by Operating Mode for HHD, Model Year 2015, and Age Group 0-3. Error Bars Represent the 95 Percent Confidence Interval of the Mean

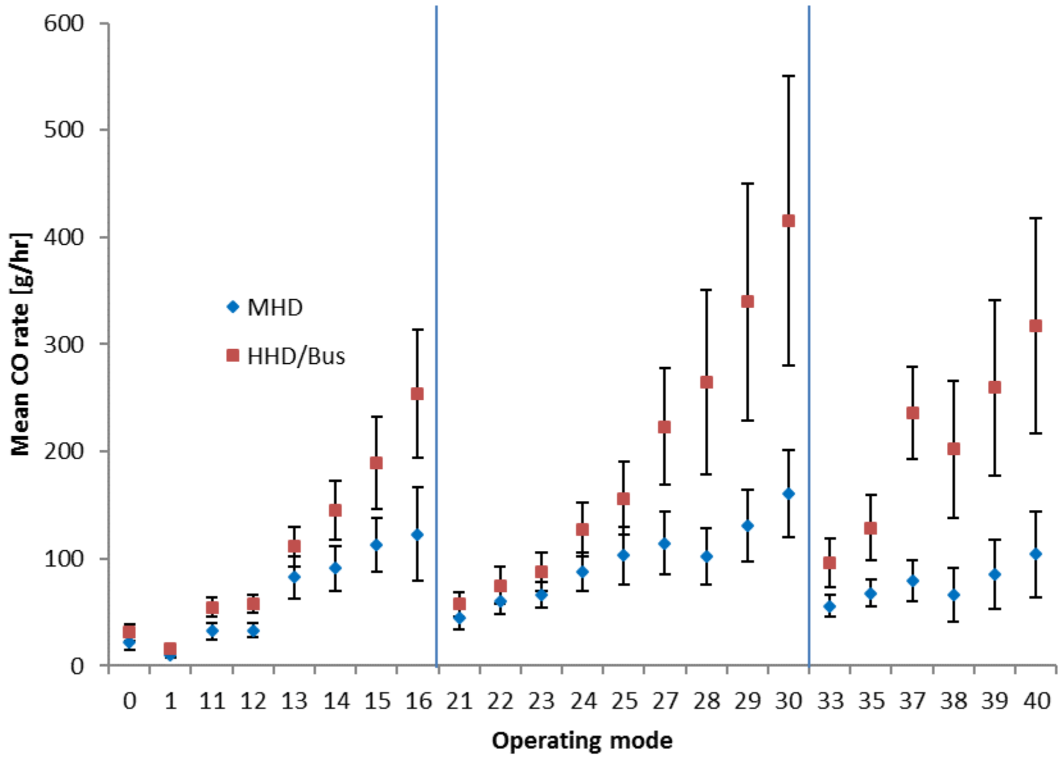


Figure 2-21 CO Emission Rates [g/hr] by Operating Mode for Model Year 2002 and Age Group 0-3. Error Bars Represent the 95 Percent Confidence Interval of the Mean

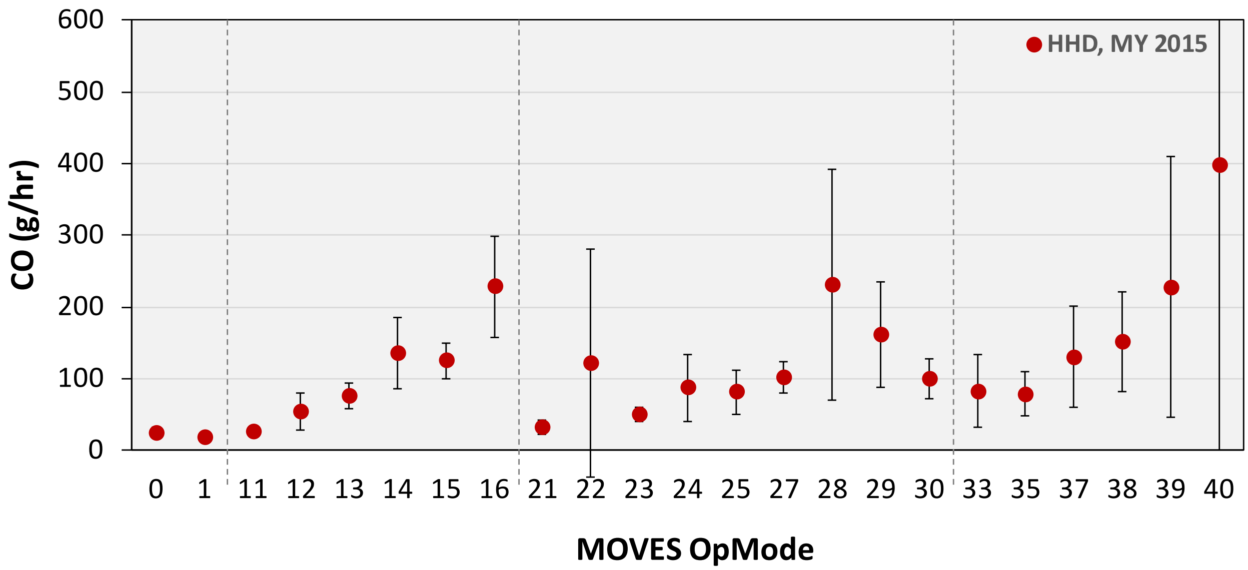


Figure 2-22 CO Emission Rates [g/hr] by Operating Mode for HHD, Model Year 2015, and Age Group 0-3. Error Bars Represent the 95 Percent Confidence Interval of the Mean

Figure 2-23 and Figure 2-24 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).

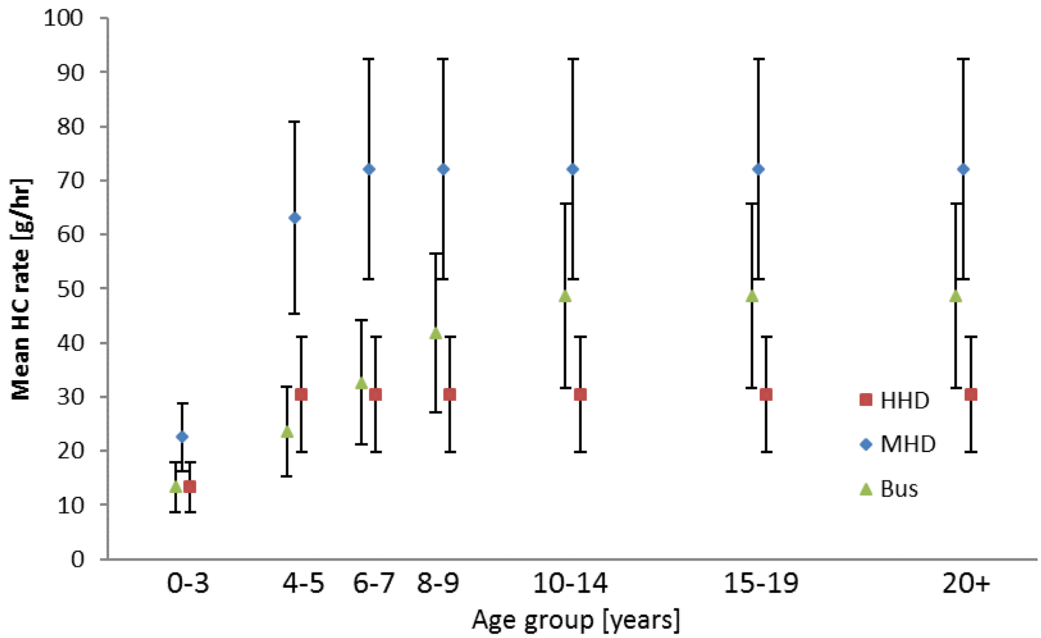


Figure 2-23 THC Emission Rates [g/hr] by Age Group for Model Year 2002 and Operating Mode 24. Error Bars Represent the 95 Percent Confidence Interval of the Mean

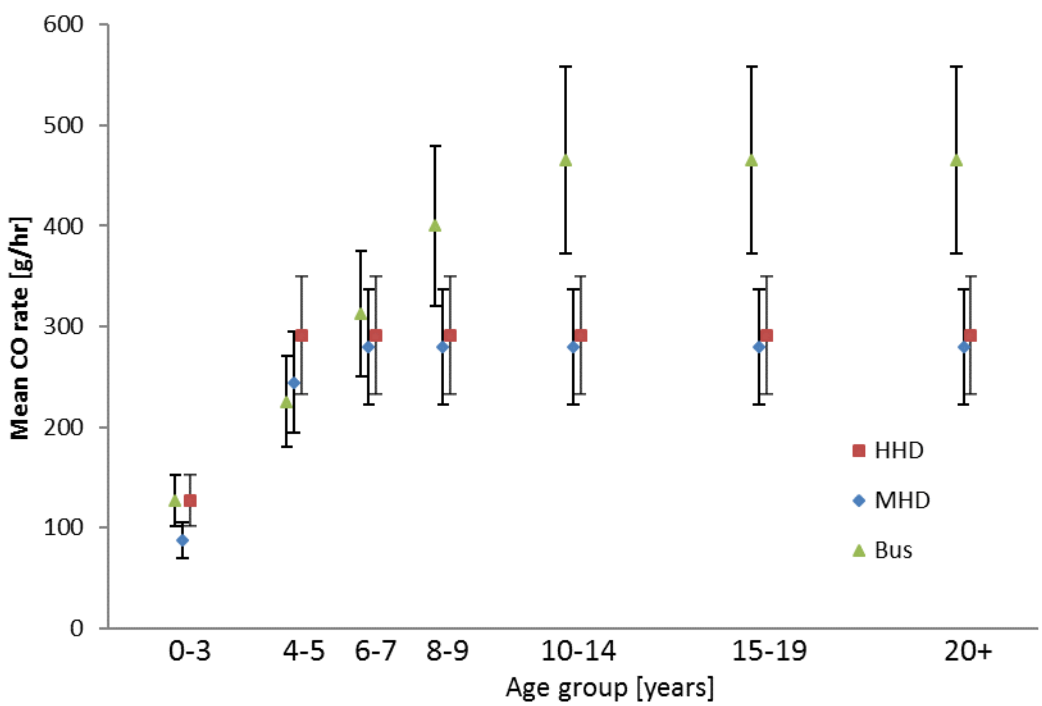


Figure 2-24 CO Emission Rates [g/hr] by Age Group for Model Year 2002 and Operating Mode 24. Error Bars Represent the 95 Percent Confidence Interval of the Mean

Figure 2-25 and Figure 2-26 show sample HC and CO emission rates by model year group for OpModeID 24. For MY 2003–2006, we only analyzed data from vehicles within the HHD regulatory class and thus, the zero-mile emission rates derived for HHD regulatory class are used as the basis for the zero-mile emission rates for the other HD regulatory classes. The MY 2007–2009 emission rates reflect the use of diesel oxidation catalysts and are derived by reducing the CO and HC emissions in MY 2003-2006 by 80 percent and applying the model-year and regulatory class specific T&M adjustment factors. For MY 2010–2060 group, the rates are shown for MY 2015 since between 2010 and 2015 they vary per model year production volume. Further, the 2010+ rates are based on the new f_{scale} value and thus an absolute quantitative OpMode-based comparison with pre-2010 model year rates is not possible. However, qualitatively, compared to MY 2007–2009, THC rates are similar, while for HHD, the CO rates are considerably higher for 2010+.

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

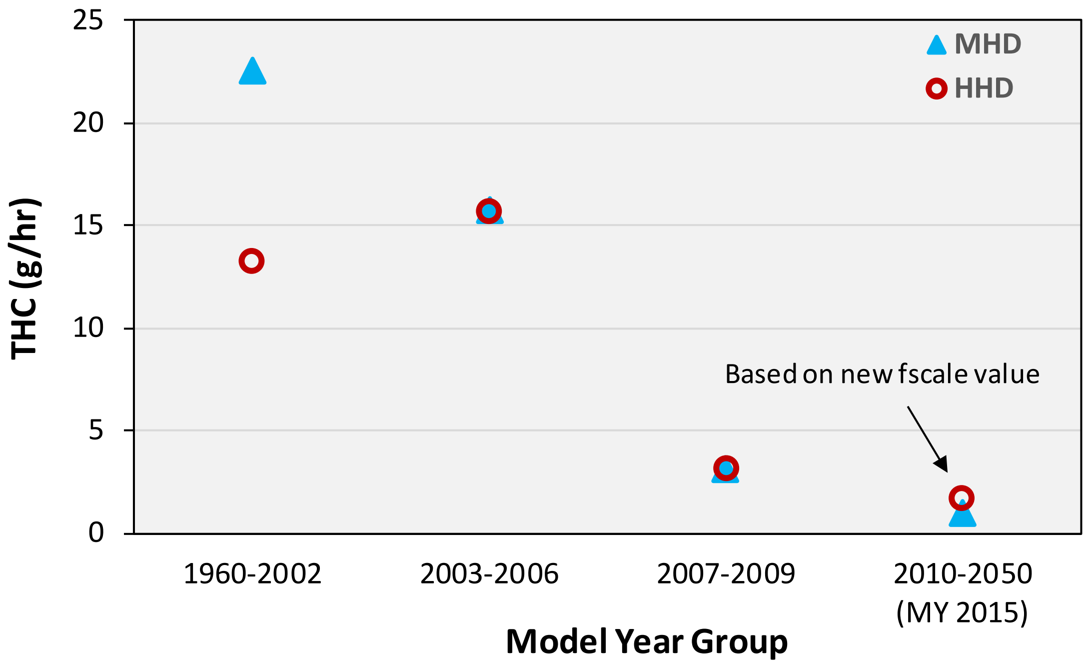


Figure 2-25 THC Emission Rates by Model Year Group for Operating Mode 24 and Age Group 0-3

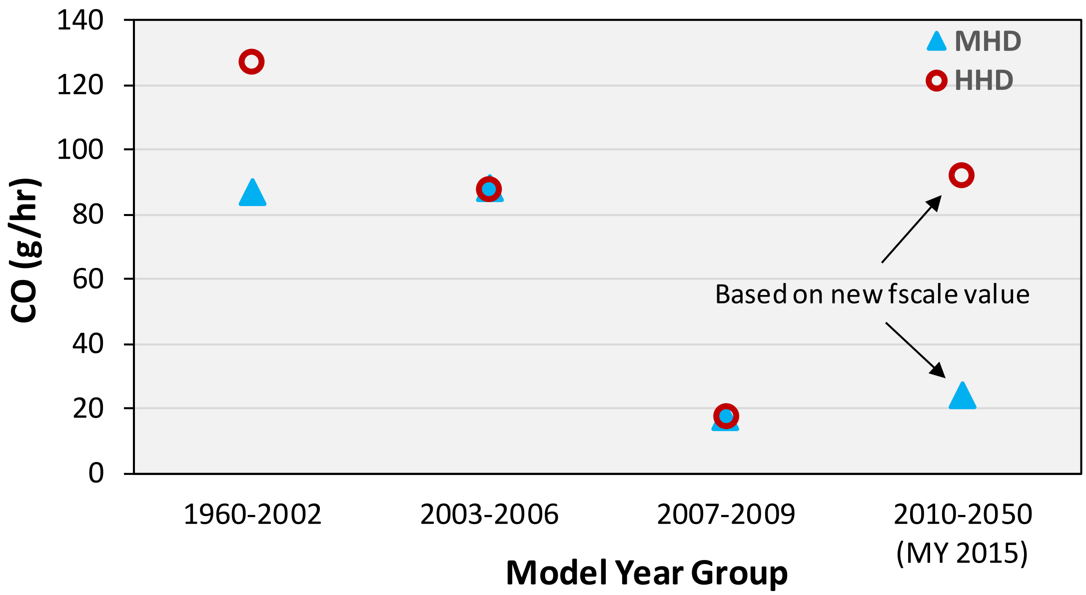


Figure 2-26 CO Emission Rates by Model Year Group for Operating Mode 24 and Age Group 0-3

2.1.4 Energy

2.1.4.1 LHD Energy Rates for Model Years 1960-2009

In MOVES_CTI_NPRM, the energy rates for LHD (LHD2b3 and LHD45) for pre-2010 diesel vehicles are unchanged from MOVES2014. The energy rates for LHD2b3 regulatory class, along with the light-duty regulatory classes (regClassIDs 20 and 30), vary by fueltype, model year group, and regulatory class, as discussed in the MOVES2010 energy updates report.[49] The energy rates were simplified to be single energy rates for regulatory class, fuel type and model year combinations by weighting across engine size, engine technology, and vehicle weight according to the default population in the MOVES2010 sample vehicle population table. Because this approach uses highly detailed data, coupled with information on the vehicle fleet that varies for each model year, variability was introduced into the aggregated energy rates used in MOVES_CTI_NPRM.

2.1.4.2 MHD, Urban Bus, and HHD Energy Rates for Model Years 1960-2009

The data used to develop NO_x rates was also used to develop running-exhaust energy rates for most of the heavy-duty source types. The energy rates were based on the same data (Section 2.1.1.1), STP structure and calculation steps as in the NO_x analysis (Sections 2.1.1.2 and 2.1.1.3); however, unlike NO_x, we did not classify the energy rates by model year, regulatory class, or by age, because neither variable had a significant impact on energy rates or CO_2.

In MOVES, CO_2 emissions were used as the basis for calculating energy rates. To calculate energy rates [kJ/hour] from CO_2 emissions (Equation 2-25), 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[50] for diesel fuel.

$$\bar{r}_{energy} = \bar{r}_{CO_2} \frac{HV}{f_{CO_2}}$$ **Equation 2-25**

The energy rates for the MHD, Urban Bus, and HHD vehicle classes are shown in Figure 2-27. Compared to other emissions, the uncertainties in the energy rates are smaller, in part because there is no classification by age, model year, or regulatory class. Thus, the number of vehicles used to determine each rate is larger, providing for a greater certainty of the mean energy rate.

OpMode-based energy consumption rates are the same across MHD, Urban Bus, and HHD regulatory classes. However, the distribution of time spent in the OpModes varies between these regulatory classes based on differences in their activity and tractive power demand. Thus, the aggregated energy rates (e.g., kJ/mile) calculated by MOVES differ by regulatory class.

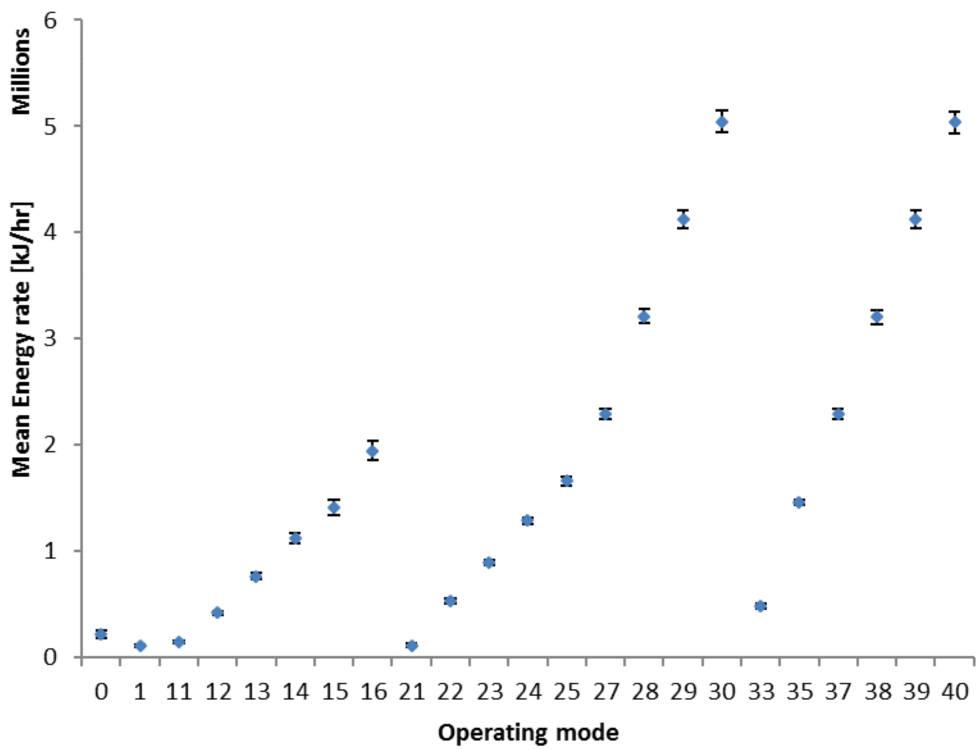


Figure 2-27 Diesel running exhaust energy rates for MHD, HHD, and Urban Buses for 1960-2009 model years. Error bars represent the 95 percent confidence interval of the mean

2.1.4.3 LHD2b3, LHD45, MHD, Urban Bus, and HHD Energy Rates for Model Years 2010-2013

The MY 2010+ HDIUT dataset described in section 2.1.1.1 and Table 2-2 included CO_2 emissions data, which was used to update the energy rates. The CO_2 rates were calculated using the analysis methodology for MY 2010+ NO_x rates. The methodology is described in Sections 2.1.1.2 (calculation of STP and assignment of operating modes), 2.1.1.3.2 (calculation of mean emission rates), 2.1.1.4.1 (hole-filling missing operating modes), and Appendix G (selection of f_{scale}). The energy rates are derived using the CO_2 rates and the conventional diesel specific values for carbon content (0.0202 g/KJ) and oxidation fraction (1.0) and the molecular mass of CO_2 (44), and atomic mass of Carbon (12). These values are described in the MOVES GHG and Energy Consumption report[7].

One artifact of the method to calculate the CO_2 rates is that the data used to develop the energy rates for MY 2010-2013 includes the data from MY 2014 and 2015 vehicles. Note that the rates for each model year are unique based on NO_x FEL based production volume weighting. The effect of MY 2014-2015 vehicles on MY 2010-2013 is not estimated but it is based on: (1) the measured rates from just the MY 2014-2015 vehicles (not documented in this report); (2) the fraction of MY 2014-2015 vehicles per NO_x FEL group per regulatory class (Table 2-21); and (3) the production volume weighting per NO_x FEL group per regulatory class (Figure 2-2). Overall, the effect is small because vehicles with MY 2010-2013 engines make up about 90% of the HDIUT dataset used for the MY 2010+ rates update, as shown in Table 2-21.

Table 2-21 Fraction of MY 2010-2013 out of all MY 2010+ Diesel Vehicles[1] in the HDIUT Dataset

Regulatory Class	MY 2010-2013 Fraction of MY 2010+ Vehicles by NOx FEL Group			Total
	0.20	**0.35**	**0.50**	
LHD	0.96		0.67	0.89
MHD	0.81	1.00	1.00	0.91
HHD	0.83	0.84	1.00	0.87
Urban Bus		1.00		1.00
Total	0.86	0.92	0.92	**0.89**

Note:
[1] Same vehicle set as used to show counts in Table 2-7

2.1.4.4 LHD45, MHD, Urban Bus, and HHD Energy Rates for Model Years 2014-2060

The energy rates for 2014 through 2018 model years reflect the impact of the Medium- and Heavy-Duty Greenhouse Gas (GHG) Phase 1 Rule.[51] The heavy-duty greenhouse gas program begins with 2014 model year and increases in stringency through 2018.

MOVES_CTI_NPRM also includes an update for the Medium and Heavy-Duty GHG Phase 2 rule.[52] The Phase 2 program begins in 2018 model year for trailers and in 2021 for the other categories, while phasing in through model year 2027. These Phase 2 standards continue indefinitely after model year 2027. The programs break the diverse truck sectors into three distinct categories, including:

- Line haul tractors and trailers (combination trucks in MOVES)
- Heavy-duty pickups and vans (3/4- and 1-ton trucks and vans)
- Vocational trucks (buses, refuse trucks, motorhomes, single-unit trucks)

The Phase 2 Rule sets 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.[c]

In MOVES, the improved fuel consumption from the HD GHG Rules is implemented in two ways. First, the running, start, and extended idle rates for total energy consumption are reduced. Second, the truck weights and road-load coefficients are updated to reflect the lower vehicle curb weights through lightweighting of materials, lower resistance tires, and improved aerodynamics of the vehicle chassis. Vehicle weights and road-load coefficients are discussed in the Population and Activity Report.[11]

The revised running, start, and extended idle rates for total energy consumption are drawn from the HD GHG rulemaking modeling.[52,53] The estimated reductions for heavy-duty diesel vehicles from the HD GHG Phase 1 rule, for running, start, and extended idle rates, are shown in Table 2-22. These reductions are generally for the 2014 through 2020 model years, and reflect the improvements expected from improved energy efficiency in the powertrain. The reductions from the MY 2013 baseline were applied to the appropriate regulatory classes and model years in the MOVES emissionRate table. In particular, for running emissions, the Phase 1 reductions were applied to the MY 2014 and MY 2015+ energy rates calculated from HDIUT dataset as described above for MY 2010-2013 (Section 2.1.4.3). Note that the inclusion of some vehicles with MY 2014+ engines (and thus subject to the HDGHG Phase 1 rule phase-in) in the base year estimates means that the application of the reductions in Table 2-22 slightly overstates the CO_2 and energy consumption impact of the Phase 1 phase-in. In the future, we plan to develop the rates for these model years directly based on available data.

Table 2-22 Estimated Reductions in Diesel Engine Energy Consumption Rates from the HD GHG Phase 1 Program[54]

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

Because the Phase 2 rulemaking set different standards for vocational vehicles and tractor-trailers and because single-unit vocational vehicles and tractor-trailers are mapped to the same regulatory classes (Class 7 and 8 trucks in regClassID 46 and 47) under the default MOVES framework, it was necessary to create a new EmissionRateAdjustment table with sourceTypeID as another primary key. The EmissionRateAdjustment table alllows MOVES_CTI_NPRM to model the final standards for vocational vehicles and tractor-trailers simultaneously. The EmissionRateAdjustment table includes the following data fields, many shared with the EmissionRate table:

1. polProcessID (primary key)

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

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

Table 2-23 includes the energy rate reductions stored in the EmissionRateAdjustment table which are applied to the running rates in MOVES_CTI_NPRM for MY 2020-and-later heavy-duty diesel vehicles. Thus, for LHD45, MHD, HHD and Urban Bus, the running energy rates for these model years are estimated with a chain of calculations starting with the HDIUT-based estimates by operating mode and regulatory class for MY 2015, reduced to a MY2017 rate by applying the HDGHG 1 reduction in Table 2-22, and further reduced by applying the HDGHG 2 reductions listed in Table 2-23. The reductions shown in Table 2-23 are a combination of improvements to the engine and other systems besides aerodynamics and tire rolling resistances. The projected improvements due to aerodynamics and tire rolling resistance are reflected in the road load coefficients, as described in the Population and Activity Report.[11]

Table 2-23 Estimated Reductions in Diesel Engine Energy Consumption Rates due to the HD GHG Phase 2 Program[52]

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

2.1.4.5 LHD2b3 Energy Rates for Model Years 2014-2060

LHD2b3 energy reductions are modelled slightly differently than the other heavy-duty vehicles. Unlike the HD standards for tractors and vocational vehicles, the HD pickup truck/van standards are evaluated in terms of grams of CO_2 per mile or gallons of fuel per 100 miles. Table 2-24 describes the expected changes in CO_2 emissions due to improved engine and vehicle technologies due to the HD GHG Phase 1 program. Similarly, Table 2-25 shows the projected improvements in CO_2 emissions due to the HD GHG Phase 2 program. Since nearly all HD pickup trucks and vans will be certified on a chassis dynamometer, the CO_2 reductions for these vehicles are not treated as separate engine and road-load reduction components, but represented as total vehicle CO_2 reductions. MOVES models the HD pickup truck/van standards by lowering the energy rates stored in the emissionRate table. No change is made to the road-load coefficients or weights of passenger or light-duty truck source types. Instead of using the EmissionRateAdjustment table, the energy consumption rates for LHD2b3 were lowered by the percentages shown in Table 2-24 and Table 2-25 for the corresponding model years.

The heavy-duty regulations apply to all the vehicles in the LHD2b3 regulatory class, with the exception of medium duty passenger vehicles (MDPVs). The fuel economy of MDPVs are covered by the Light-duty GHG rule.[55] However, MDPVs make up a minor contribution to the population of LHD2b3, and we apply the HD GHG energy reductions to all vehicles within LHD2b3.

Table 2-24 Estimated Total Vehicle Reductions in Energy Consumption Rates for HD Diesel and Gasoline Pickup Trucks and Vans due to the HD GHG Phase 1 Program

GVWR class	Fuel	Model years	Reduction from MY 2013 Energy Rates
LHD 2b3	Gasoline	2014	1.5%
		2015	2%
		2016	4%
		2017	6%
		2018-2020	10%
	Diesel	2014	2.3%
		2015	3%
		2016	6%
		2017	9%
		2018-2020	15%

Table 2-25 Estimated Total Vehicle Reductions in Energy Consumption Rates for HD Diesel and Gasoline Pickup Trucks and Vans due to the HD GHG Phase 2 Program

GVWR class	Fuel	Model years	Reduction from MY 2020 Emission Rates
LHD 2b3	Gasoline and Diesel	2021	2.50%
		2022	4.94%
		2023	7.31%
		2024	9.63%
		2025	11.89%
		2026	14.09%
		2027+	16.24%

2.1.4.6 Summary of Heavy-duty Phase 1 and Phase 2 reductions

Figure 2-28 displays the relative reductions in energy consumption for all heavy-duty vehicles from Phase 1 and Phase 2 rules. In Phase 1, regClassID 47 and 48 are treated as same. In Phase 2, regClassID 47 and 48 are separated and regClassID 47 is further separated in to vocational (“voc”), tractor-trailer short-haul (“short-haul”) and tractor-trailer long-haul (“long-haul”). A somewhat similar separation occurs for regClassIDs 42 and 46. The energy rates for a given vehicle type are constant from MY 2027 and beyond.

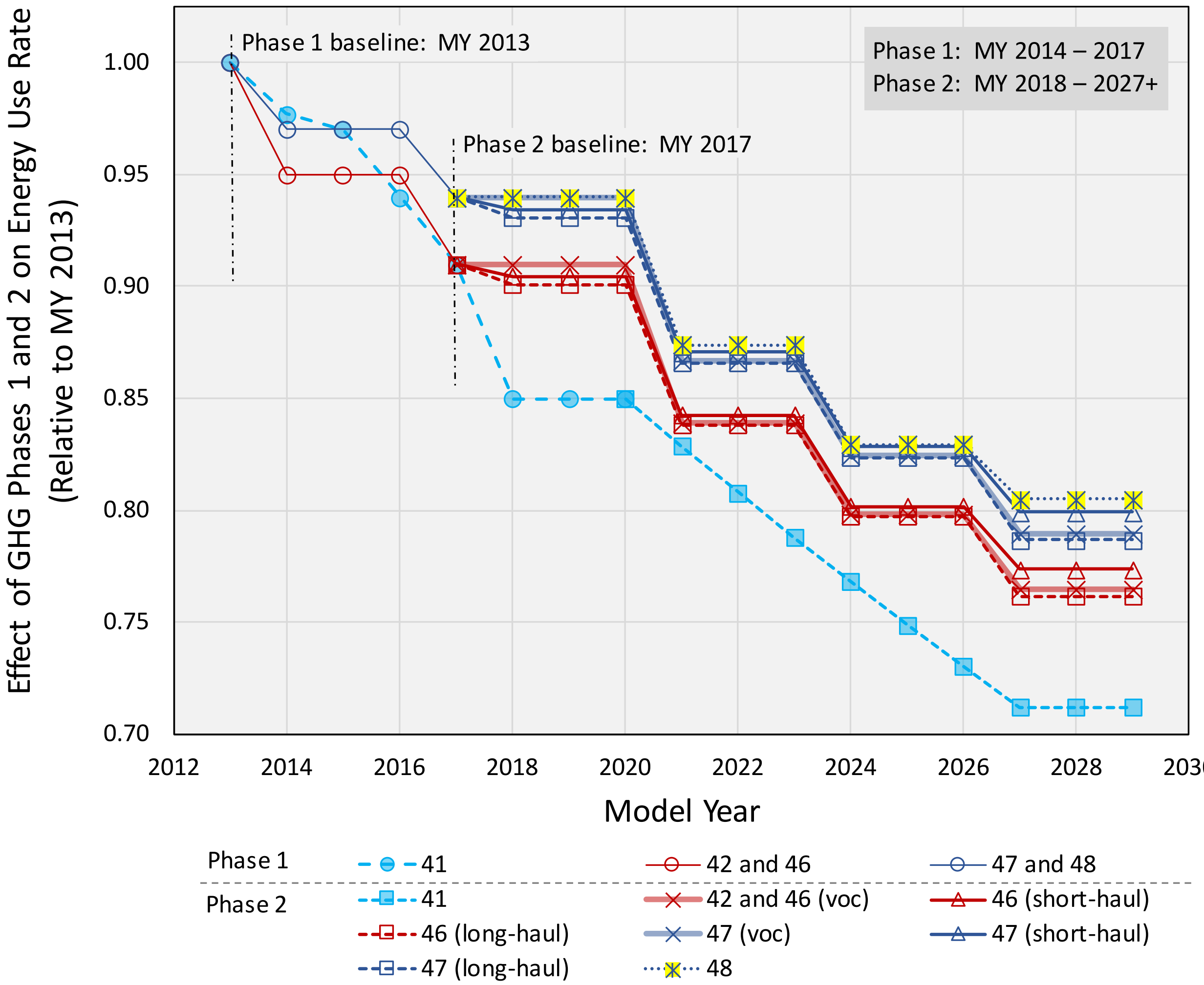


Figure 2-28 HD GHG Phase 1 and Phase 2 rule reductions in energy consumption rates for LHD2b3 (41), LHD45 (42), MHD (46), HHD (47), and Urban Bus (48) diesel vehicles

2.2 Start Exhaust Emissions

The ‘start’ process occurs when the vehicle is started and the engine is not fully warmed up. For modeling purposes, we define start emissions as the increase in emissions due to an engine start. Operationally, we use the difference in emissions between a test cycle with a cold start and the same cycle with a hot start. As explained in Section 1.3, 2e define eight intermediate stages which are differentiated by soak time length (time duration between engine key off and engine key on) between a cold start (> 720 minutes of soak time) and a hot start FTP (< 6 minutes of soak time). More details on how start emission rates are calculated as a function of soak time, can be found later in this section and in the MOVES light-duty emission rate document.[10] The impact of ambient temperature on cold starts is discussed in the Emission Adjustments MOVES report[56].

2.2.1 HC, CO, and NO_x

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

2.2.1.1 Pre-2010 Model Year

For light-duty diesel vehicles, start emissions are estimated by subtracting FTP bag 3 emissions from FTP bag 1 emissions. Bag 3 and Bag 1 are the same dynamometer cycle, except that Bag 1 starts with a cold start, and Bag 3 begins with a hot start. A similar approach was applied for LHD vehicles tested on the FTP and ST01 cycles, which also have separate bags containing cold and hot start emissions over identical drive cycles. Data from 21 LHD diesel vehicles, ranging from model years 1988 to 2000, were analyzed. No classifications were made for model year or age due to the limited number of vehicles. The results of this analysis for HC, CO, and NO_x are shown in Table 2-26.

Table 2-26 Average Start Emissions Increases for pre-2010 Model Year Light Heavy-Duty Diesel Vehicles (g) for Regulatory Class LHD2b3 and LHD45 (regClassID 41 and 42)

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

For pre-2010 model year HHD and MHD trucks, analogous data were unavailable. To provide at least a minimal amount of information, we measured emissions from a 2007 Cummins ISB 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 2-29. The biggest drop in emission rate over the test was with CO, whereas there was a slight increase in NO_x (implying that cold start NO_x is lower than running NO_x), and an insignificant change in HC.

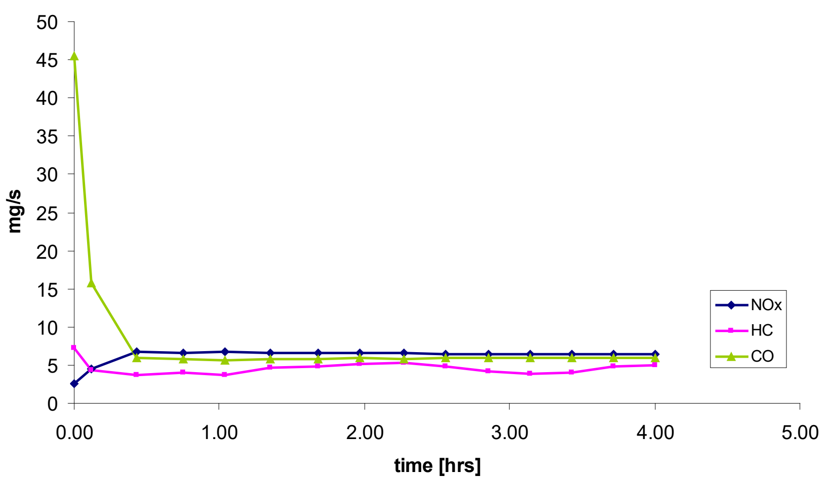


Figure 2-29 Trends in the Stabilization of Idle Emissions from a Diesel Engine Following a Cold Start (from a 2007 Cummins ISB Measured on an Engine Dynamometer)

We calculated the area under each curve for the first 25 minutes and divided by 25 minutes to get the average emission rate during the cold start idle portion. Then, we averaged the data for the remaining portion of the test, or the warm idle portion. The difference between cold start and warm idle is in Table 2-27. The measured HC increment is zero. The NO_x increment is negative since cold start emissions were lower than warm idle emissions.

Table 2-27. Cold-start Emissions Increases in Grams on the 2007 Cummins ISB

HC	CO	NO_x
0.0	16.0	-2.3

We also considered NO_x data from University of Tennessee[57], which tested 24 trucks with PEMS at different load levels during idling. Each truck was tested with a cold start going into low-RPM idle with air-conditioning on. We integrated the emissions over the warm-up period to get the total cold start idling emissions. We calculated the warm idling emissions by multiplying the reported warm idling rate by the stabilization time. We used the stabilization period from our engine dynamometer tests (25 minutes). Then we subtracted the cold start-idle emissions from the warm idle emissions to estimate the cold start increment. We found that several trucks produced lower NO_x emissions during cold start (similar to our own work described above), and several trucks produced higher NO_x emissions during cold start. Due to these conflicting results, and the recognition that many factors affect NO_x emission during start (e.g. air-fuel ratio, injection timing, etc.), we set the default NO_x cold-start increment to zero. Table 2-28 shows our final MOVES inputs for HHD and MHD diesel start emissions increases from our 2007 MY in-house testing. Due to the limited data, the emission rate is constant for all pre-2010 model years and ages.

Table 2-28. MOVES Inputs for Pre-2010 HHD and MHD Diesel Start Emissions (grams/start) for Regulatory Class 46, 47, and 48. No Differentiation by Model Year or Age.

HC	CO	NO_x
0.0	16.0	0.0

As discussed in the Emission Adjustments Report[56], MOVES applies an additive adjustment to diesel HC cold-start emissions for ambient temperatures below 72 F. Thus, despite a pre-2010 baseline HC start emission rate of zero, MOVES estimates positive HC start emissions from heavy-duty diesel vehicles at ambient temperatures below 72 F. No temperature adjustments are applied to CO, PM, or NO_x diesel start emissions because no clear trend was found with the data.

2.2.1.2 Model Year 2010 and Later

The cold start emissions for 2010 model year and later LHD, MHD, and HHD diesel engines have been updated for MOVES_CTI_NPRM based on new data. Similar to the approach taken for light-duty vehicles, the cold start emissions are defined as the difference in emissions between a test cycle with a cold start and the same test cycle with a hot start. Heavy-duty diesel engines are certified using the Heavy-Duty Diesel Engine Federal Test Procedure (FTP) cycle (40 CFR Part 86, Appendix I.f.2). The test procedure for certification requires that manufacturers run the engine over the FTP cycle with a cold start and then repeat the cycle with a warm start. Starting in model year 2016, EPA began collecting certification data that contained separate cold and hot results for each engine certified. The data that was analyzed for this MOVES_CTI_NPRM update includes the following engine families from 2016 and 2017 model years shown in Table 2-29.

Table 2-29: Engine Data Analyzed to Revise the Cold Start Emission Rates for HD Diesel Engines

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

The certification data was used to determine the grams emitted per cold start using Equation 2-26.

$$\begin{aligned} Grams\ per\ Start \\ &= [Cold\ FTP\ Emission\ Results\ (g/(hp - hr)) \\ &- Hot\ FTP\ Emission\ Results(g/(hp - hr))] \\ &* FTP\ Cycle\ Work\ (hp - hr) \end{aligned} \qquad \textbf{Equation 2-26}$$

However, the amount of work (hp-hr) performed over the FTP cycle is not provided as part of the certification data submitted by the manufacturers to EPA but is required to convert the FTP emission results in grams per horsepower-hour into grams. Furthermore, the FTP cycle work is unique to each engine because it is created based on the engine's maximum speed, curb idle speed, and the maximum torque curve. Therefore, we needed to develop a surrogate from the information that is provided by manufacturers for certification for each engine. We determined that the rated power of an engine correlates well to the FTP cycle work. This analysis was based on FTP cycle work and rated power data from ten HD engines. As shown in Figure 2-30, the FTP cycle work is approximately a linear function of the engine's Rated Power. For the calculation of cold start emissions for each engine analyzed, the FTP cycle work (hp-hr) was estimated for the engine based on its rated power using the equation 0.0599 times the Rated Power (hp) plus 4.4297.

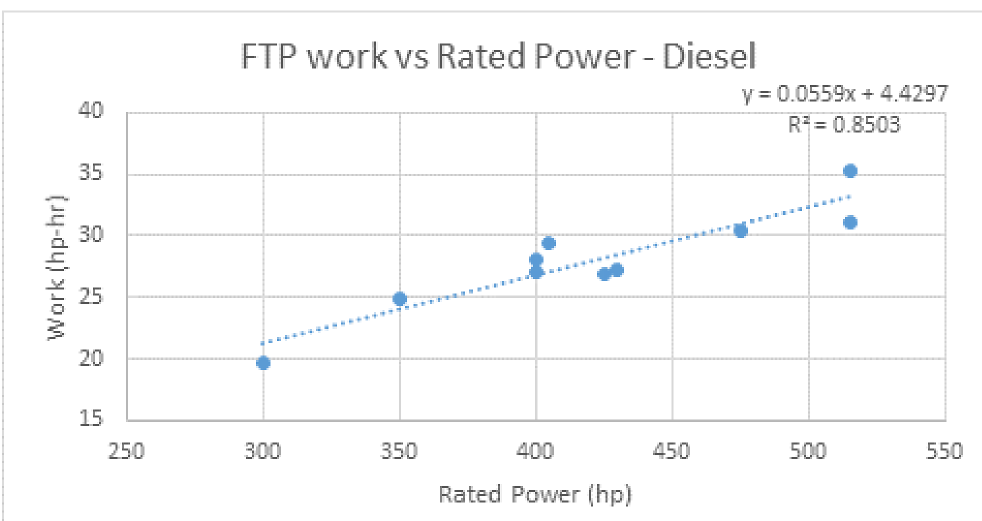


Figure 2-30: Relationship between HD Diesel Engine Rated Power and FTP Cycle Work

The analysis of cold and hot start FTP emissions data from eleven HHD diesel engines determined the grams per start for HC, CO, NO_x, and $PM_{2.5}$. The average and standard deviation of the HC, CO, and NO_x emission levels of the eleven engines are shown in Table 2-30. The $PM_{2.5}$ emissions are summarized in Table 2-33.The engines included MY2016 and MY2017, ranging in displacement between 7.7 and 14.9 liters, and in rated power between 260 and 605 HP. The new default cold start emissions values for MOVES_CTI_NPRM are the mean values shown in the table. The HC and NO_x cold start emissions for HHD diesel engines are increasing with this update, compared to what is currently in MOVES2014, while the CO emissions are decreasing.

Table 2-30: Cold Start Emissions for MY2010 and Later Heavy Heavy-Duty Diesel Engines

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

Six MHD diesel engines were used to determine the HC, CO, and NO_x grams emitted per start. The average and standard deviation of the emissions from the six engines are shown in Table 2-31. The engines included MY2016 and MY2017, ranging in displacement between 5.1 and 8.9 liters, and in rated power between 230 and 380 HP. The new default values for MOVES_CTI_NPRM are the mean values shown in the table. Similar to the HHD engines, the HC and NO_x cold start emissions for the MHD diesel engines are increasing with this update, compared to what is currently in MOVES2014, while the CO emissions are decreasing.

Table 2-31 Cold Start Emissions for MY2010 and Later Medium Heavy-Duty Diesel Engines

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

Analysis of five LHD diesel engines determined that the grams per start for HC, CO, and NO_x are the values shown in Table 2-32. The engines included MY2016 and MY2017, ranging in displacement between 3.0 and 6.7 liters, and in rated power between 161 and 330 HP. The new default values for MOVES_CTI_NPRM are the mean values. The CO and NO_x cold start emissions are increasing with this update for the LHD diesel engines, compared to what is currently in MOVES2014, while the HC emissions are lower.

Table 2-32 Cold Start Emissions for MY2010 and Later Light Heavy-Duty Diesel Engines (regClassID=41) & 42)

Grams per Start	HC	CO	NO_X
Mean	0.005	2.47	6.77
Standard Deviation of Data	0.11	2.61	2.24

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

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

The Tier 3 exhaust emission standards affect light heavy-duty diesel vehicles in the LHD2b3 regulatory class (regClassID 41). 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 2.1.1.4.6.

2.2.2 Particulate Matter

2.2.2.1 Pre-2010 Model Year

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

Data for model year 2009-and-earlier vehicles was only available from engine dynamometer testing performed on one heavy heavy-duty diesel engine, using the FTP cycle with particulate mass collected on filters. The engine was manufactured in MY2004. The cycle was repeated six times, under both hot and cold start conditions (two tests for cold start and four replicate tests for hot start). The average difference in $PM_{2.5}$ emissions (filter measurement - FTP cycle) was 0.10985 grams. The data are shown here:

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

We applied this value to 1960 through 2006 model year vehicles. For 2007 through 2009 model years, we applied a 90 percent reduction to account for the expected use of DPFs, leading to a corresponding value of 0.01099 g. The value is the same for all heavy-duty diesel regulatory classes.

As introduced in Section 2.1.2.2.8, in MOVES, the $PM_{2.5}$ emission rates are estimated as the elemental carbon (EC) and non-elemental carbon PM (nonEC). We estimated the EC and nonEC from the total PM starts rates by applying the EC/PM fraction of 46.4 percent from the $PM_{2.5}$ Speciation profile developed from the idle mode from the UDDS tests from the E55/59 program for pre-2007 trucks.[44] For all 2007+ trucks, we apply the EC/PM fraction of 9.98 percent from the $PM_{2.5}$ speciation profile developed from trucks equipped with diesel particulate filters[44].

2.2.2.2 Model Year 2010 and Later

The cold start emissions for 2010 model year and later LHD, MHD, and HHD diesel engines have been updated for MOVES_CTI_NPRM based on new data. We updated the cold start particulate matter emission rates based on the certification data and data analysis methods discussed in Section 2.2.1.2. The resulting cold start emission rates for each HD diesel engine regulatory group are shown in Table 2-33.

Table 2-33: Cold Start PM2.5 Emission Rates for Heavy-Duty Diesel Emissions for 2010+ MY

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

Note:
[a] The value for the light heavy-duty diesel PM emission rate in MOVES_CTI_NPRM will not be zero, as indicated by the test data. Instead, the emission rate will be represented by the medium heavy-duty diesel emission rate because of the overlap in engines and aftertreatment systems between the two categories.

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

2.2.3 *Adjusting Start Rates for Soak Time*

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

In the MOVES input database, “operating modes” for start emissions are defined in terms of soak time preceding an engine start. The “cold-start” is defined as a start following a soak period of at least 720 minutes (12 hours) and is represented as opModeID=108. An additional seven modes are defined in terms of soak times ranging from 3 min up to 540 min (opModeID = 101-107). Table 2-34 describes the different start-related operating modes in MOVES as a function of soak time.

Table 2-34. 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

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

The soak fractions we used for HC, CO, and NO_x for MY 2009 and older HD diesel vehicles are illustrated in Figure 2-31 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.[10] The soak fractions are taken from the non-catalyst soak fractions derived in a CARB report[58] and reproduced in a MOBILE6 report.[59]

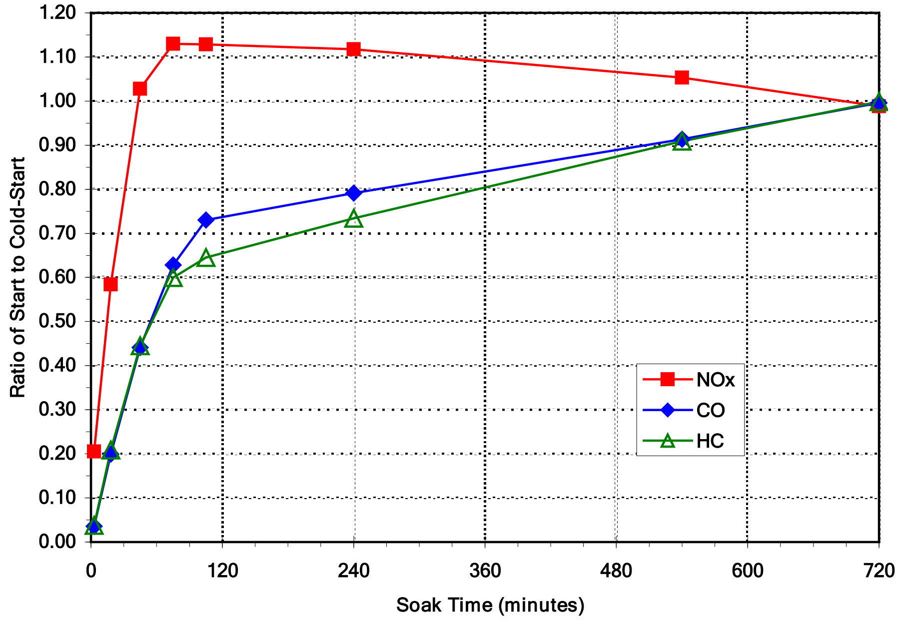


Figure 2-31. Soak Fractions Applied to Cold-Start Emissions (opModeID = 108) to Estimate Emissions for shorter Soak Periods (operating modes 101-107). This figure is reproduced from the Light-Duty Emissions Report[10]

For light heavy-duty vehicles (regulatory classes LHD2b3 and LHD45), the soak distributions apply to the cold starts for HC, CO and NO_x. For medium and heavy heavy-duty vehicles (regulatory classes MHD, HHD, and Urban Bus) only the CO soak fractions are applied to the cold-start emissions, because the base cold start HC and NO_x emission rates for medium and heavy heavy-duty emission rates are zero (see Section 2.2.1.1). The start emission rates used for 2009 MY and older heavy-duty vehicles, derived from applying the soak fractions are displayed in Table 2-35 for HC, CO, and NO_x.

Table 2-35. Heavy-Duty diesel HC, CO, and NO_x Start emissions (g/start) by operating mode for 2009MY and older vehicles and all ages in MOVES

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

Notes:
[1] LHD refers to LHD2b3 and LHD45 (regClassID 41 and 42)
[2] Other HD refers to the medium heavy-duty, heavy heavy-duty, and urban bus regulatory classes (46, 47, 48)

The PM start rates by operating mode are given in Table 2-36 below. They are estimated by assuming a linear decrease in emissions with time between a full cold start (>720 minutes) and zero emissions at a short soak time (< 6 minutes).

Table 2-36. Particulate Matter Start Emission Rates by Operating Mode (soak fraction) for all HD Diesel vehicles through MY 2009 (regClassID 41 through 48)

Operating Mode	$PM_{2.5}$ (grams per start) 1960-2006 MY	$PM_{2.5}$ (grams per start) 2007-2009 MY
101	0.0000	0.00000
102	0.0009	0.00009
103	0.0046	0.00046
104	0.0092	0.00092
105	0.0138	0.00138
106	0.0183	0.00183
107	0.0549	0.00549
108	0.1099	0.01099

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

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

The first test program included a MY 2015 day-cab tractor with a MY 2015 HHD diesel engine tested on a heavy-duty chassis.[60] The vehicle was relatively new and had 10,000 miles on the odometer. The testing consisted of running two repeats of a transient drive cycle developed by the National Renewable Energy Laboratory (NREL). The vehicle speed trace is shown below in Figure 2-32. Prior to each soak test, the vehicle was first run through two of the NREL cycles. Then the engine was shut off for a specified amount of time to reflect the soak periods shown in Table 2-34. At least two repeats were conducted for each soak period. The emission measurements included dilute gaseous measurements and triplicate particulate matter filters.

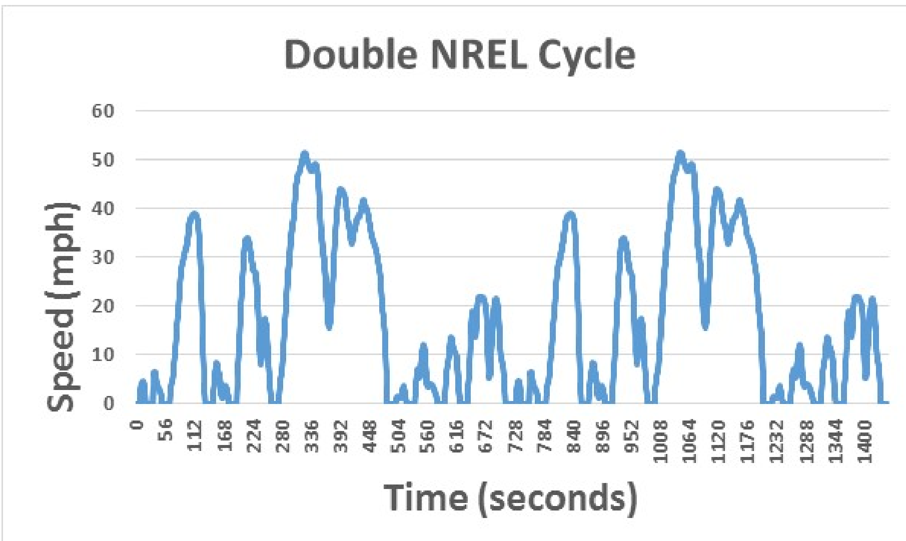


Figure 2-32 National Renewable Energy Laboratory's Heavy-Duty Vocational Transient Cycle

The NO_x, CO, HC, and PM emission results in terms of grams or mg per mile from the tests over a range of soak periods are shown in Figure 2-33 through Figure 2-36.

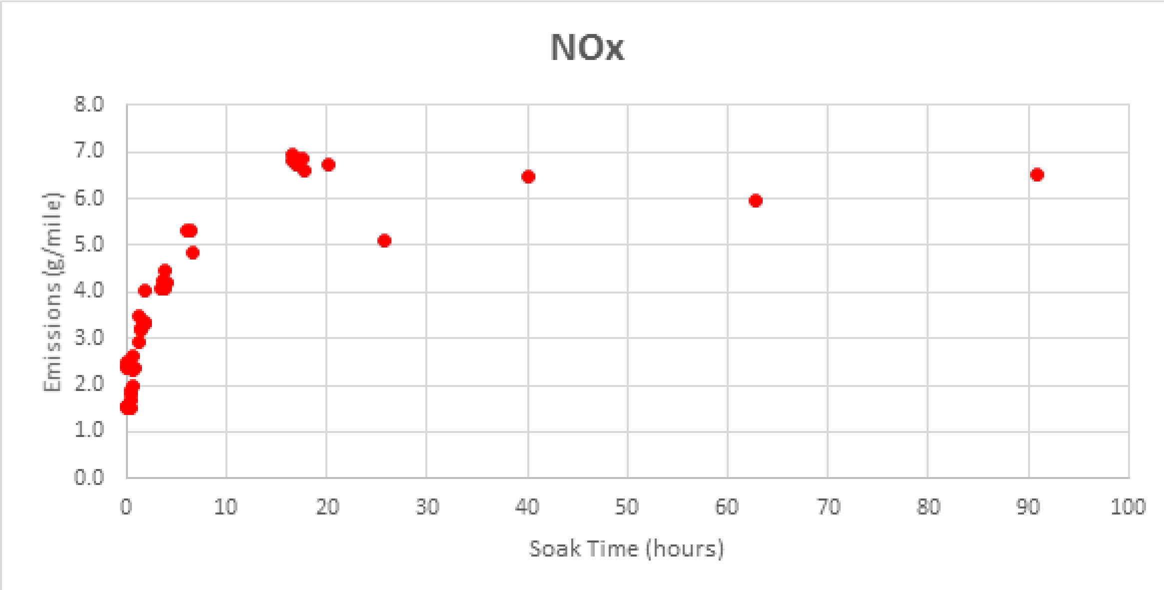


Figure 2-33 MY 2015 Heavy-Duty Vehicle NO_x Emissions by Soak Time

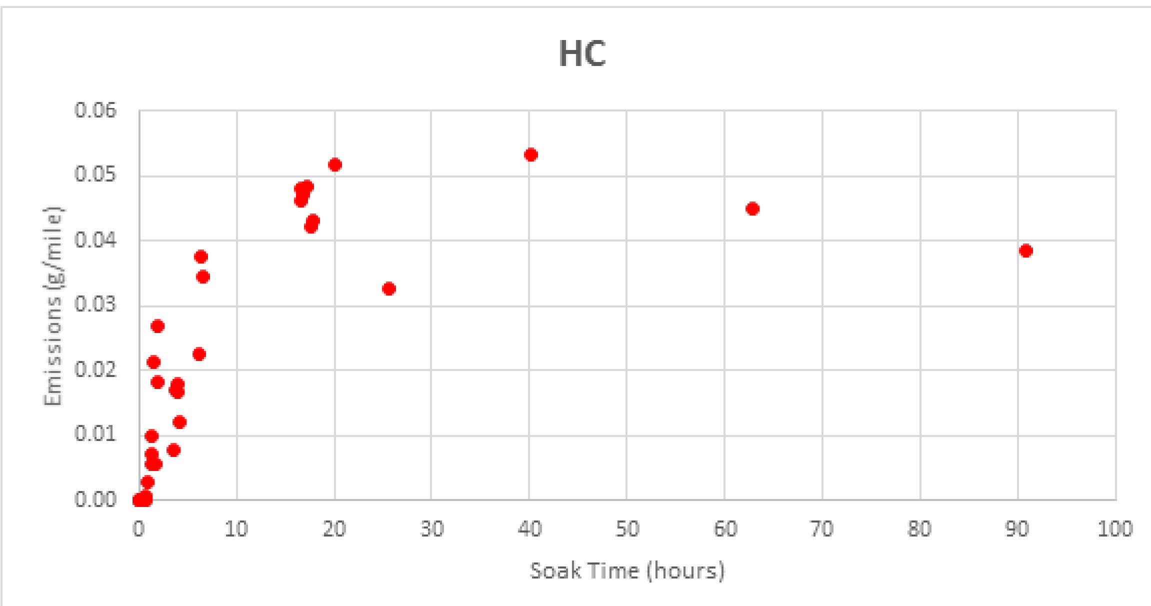


Figure 2-34 MY 2015 Heavy-Duty Vehicle HC Emissions by Soak Time

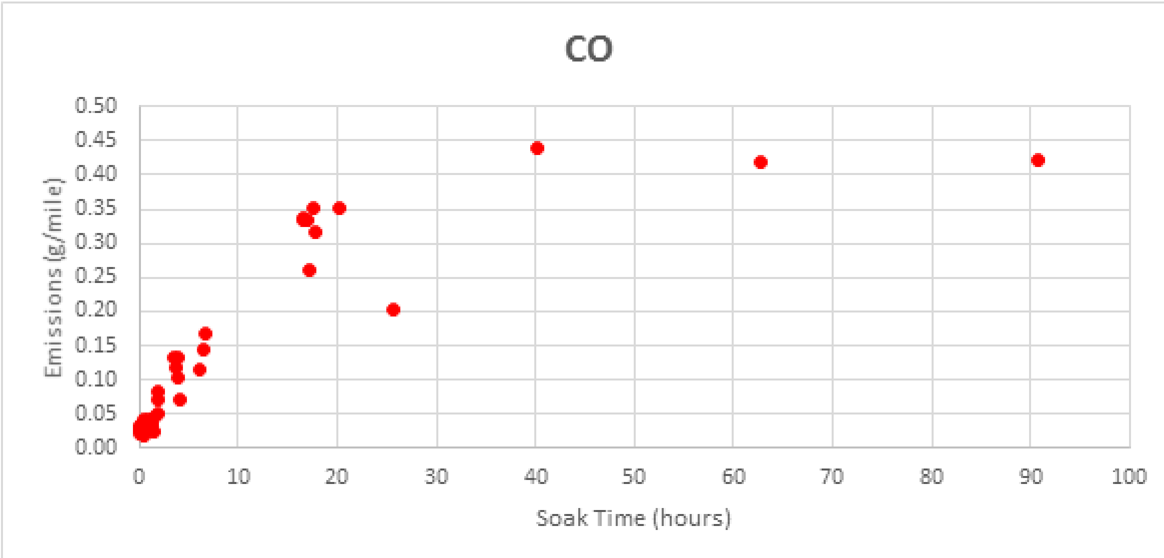


Figure 2-35 MY 2015 Heavy-Duty Vehicle CO Emissions by Soak Time

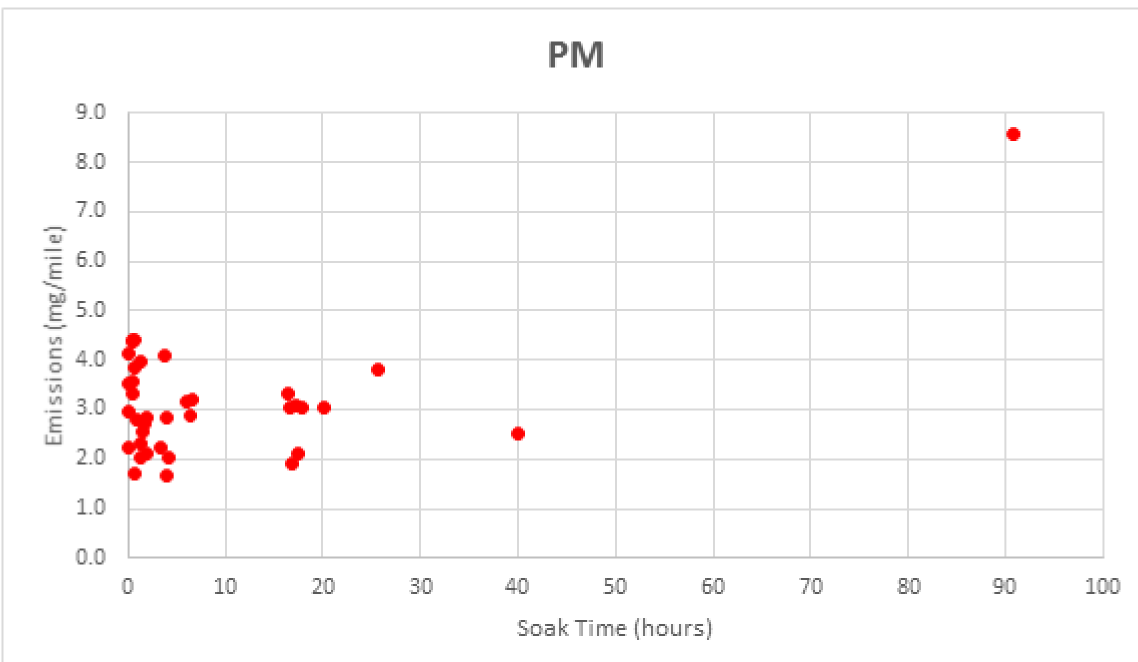


Figure 2-36 MY 2015 Heavy-Duty Vehicle PM Emissions by Soak Time

In addition to the chassis testing, onroad testing was conducted using a portable emissions measurement system (PEMS).[61] The emissions data gathered by the PEMS in this test program only included the gaseous emissions, not PM data. A MY 2016 work van with a diesel engine was tested on the road. The vehicle was soaked and started within a laboratory under controlled temperatures. All onroad testing occurred with ambient temperatures over 50 degrees F. Each test began with 10 seconds of idle followed by driving a defined “soak route.” A typical vehicle speed profile from the route is shown in Figure 2-37. The route consisted of approximately 700 seconds of driving in a neighborhood/urban environment over approximately 2.7 miles.

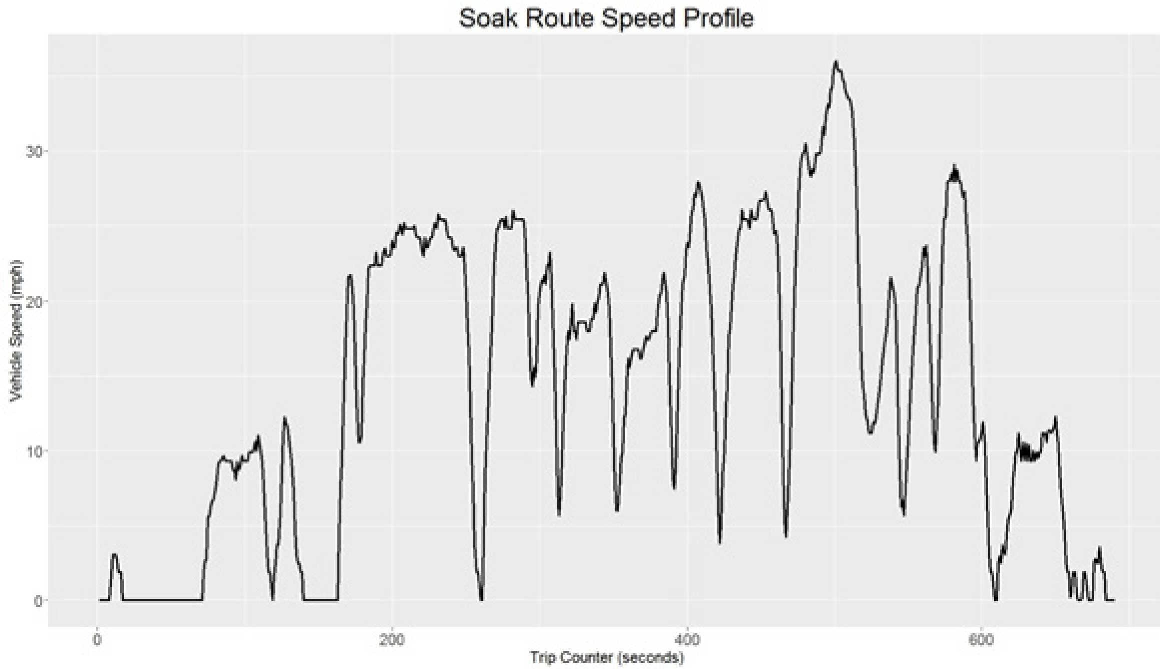


Figure 2-37 Onroad Soak Drive Route

The emission results, in terms of total emissions over the route, from the onroad tests are shown in Figure 2-38 through Figure 2-40.

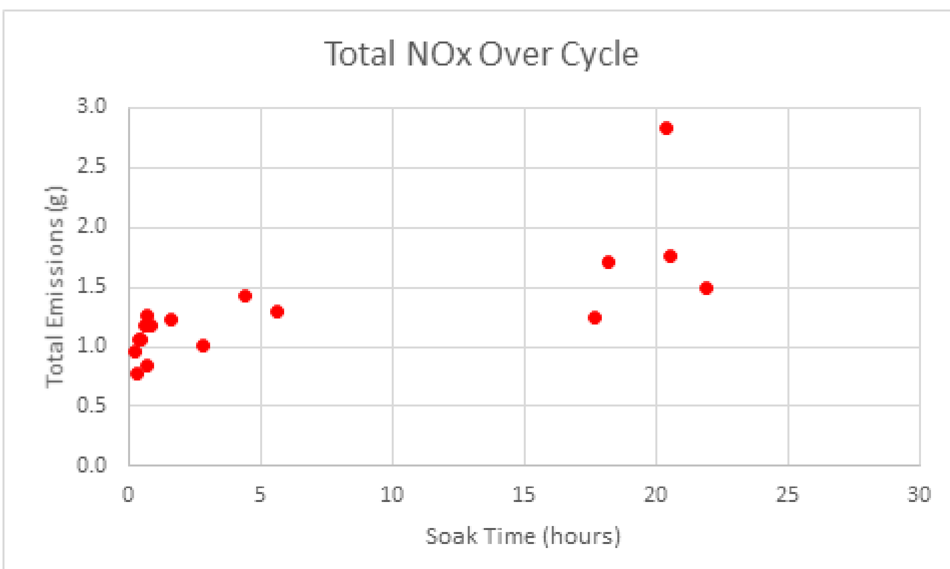


Figure 2-38 MY 2016 Heavy-Duty Vehicle NO_x Emissions by Soak Time

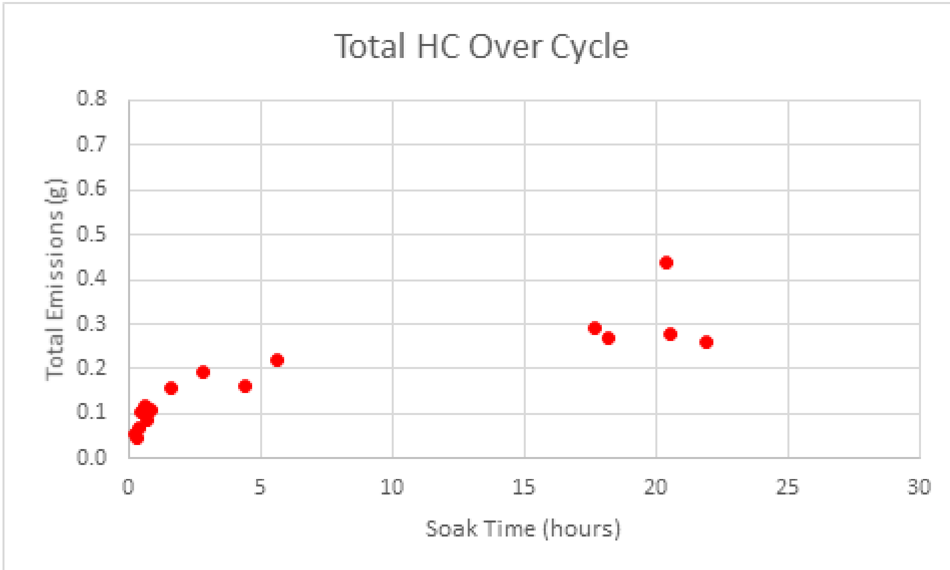


Figure 2-39 MY 2016 Heavy-Duty Vehicle HC Emissions by Soak Time

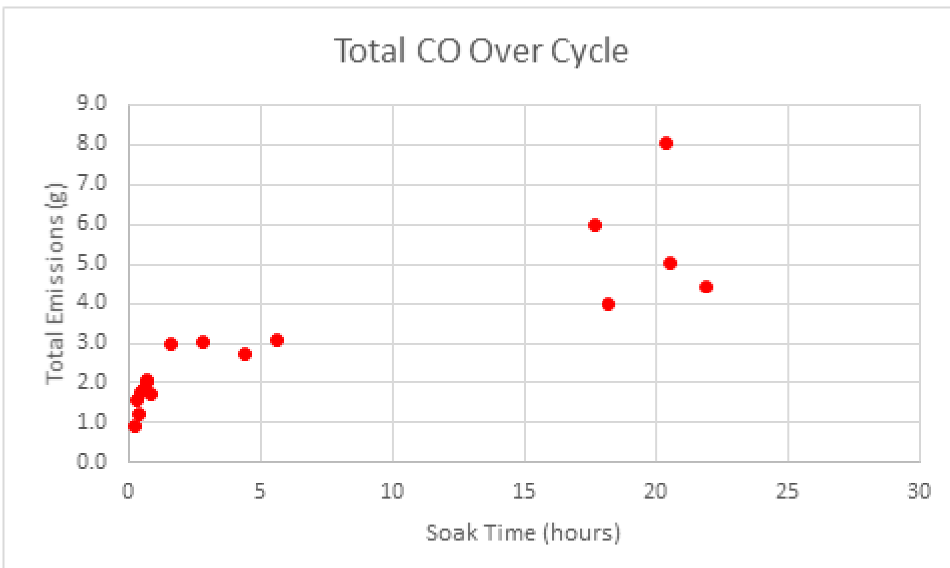


Figure 2-40 MY 2016 Heavy-Duty Vehicle CO Emissions by Soak Time

The soak emission ratios were calculated using a multi-step process based on the chassis test and onroad test results. First, the total emissions over the route or drive cycle were averaged for each soak period for each pollutant (NO_x, HC, CO) for each vehicle. Then the start emissions for each soak period were determined by subtracting the average total emissions from the tests with the 3 minute soak time from the emissions from the specific soak period. The ratios for soak period operating modes 102 through 108 were calculated based on the average start emissions of the soak period divided by the average start emissions of the cold start (>12 hours) soak period. The soak fractions for the Operating Mode 101 were determined by extrapolating the value from the Operating Mode 102 result using the proportional difference in time between the midpoints of each OpMode 101 and 102 soak times. In other words, soak fraction for OpMode 102 was multiplied by the ratio of 3 minutes divided by 18 minutes (the midpoint times of OpMode 101 and 102). The NO_x, CO, and HC soak period ratio results for each vehicle are shown below in Figure 2-41.

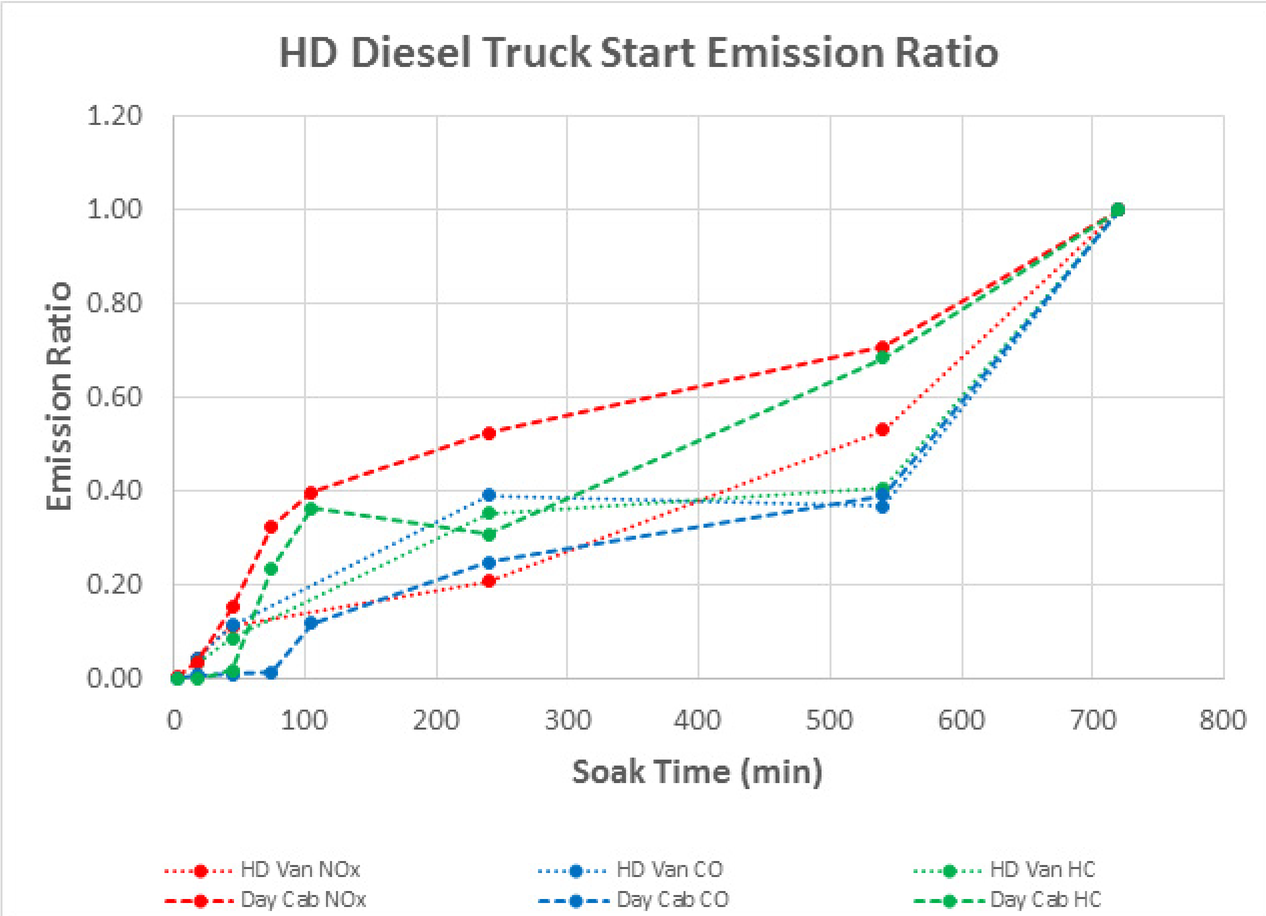


Figure 2-41 Soak Curves from a MY 2015 HD Day-Cab and a MY 2016 HD Van

The 2010 MY and later heavy-duty diesel soak ratios for MOVES_CTI_NPRM were determined based on averaging the results from the two trucks. The resulting soak fractions are shown in Table 2-37. The soak fractions are applied to all heavy-duty diesel regulatory classes because the two trucks tested cover the range of HD diesel regulatory classes.

Table 2-37 HD Diesel Engine Soak Ratios for MY 2010 and Newer

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

The PM start rates by operating mode are given in Table 2-38 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). The PM start rates for MY 2010 and newer vehicles are updated in MOVES_CTI_NPRM using a linear interpolation based on the new cold start data (certification data discussed in Section 2.2.2.2) for Operating Mode 108. This approach is consistent with the approach taken for MY 2009 and older vehicles, as described in Section 2.2.3.1. We did not revise the approach because we obtained PM data for only one of the trucks and it showed mixed soak effect results.

Table 2-38 Particulate Matter Start Emission Rates by Operating Mode (soak fraction) for all MY 2010 and newer HD vehicles (regClassID 41 through 48)

Operating Mode	$PM_{2.5}$ (grams per start) Reg Class 47 and 48	$PM_{2.5}$ (grams per start) Reg Class 46	$PM_{2.5}$ (grams per start) Reg Class 41 and 42
101	0.00000	0.00000	0.00000
102	0.00163	0.00100	0.00100
103	0.00325	0.00200	0.00200
104	0.00488	0.00300	0.00300
105	0.00650	0.00400	0.00400
106	0.00813	0.00500	0.00500
107	0.00975	0.00600	0.00600
108	0.01300	0.00800	0.00800

2.2.3.3 Adjusting Start Rates for Ambient Temperature

The 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. The emission adjustments report discusses the impact of ambient temperature on cold start emission rates (opModeID 108).[56] The ambient temperature effects for starts with warm and hot soaks (opModes 101-107) are documented below.

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 multiply the soak fractions described earlier in Figure 2-31 for pre-2007 trucks by the additive cold temperature effect for the 12-hour cold start (opModeID 108) to obtain cold start temperature adjustments for the warm and hot soaks starts (opModeID 101 through 107). The additive cold start adjustment for HC emission factors are displayed in Table 2-39, along with the soak fractions applied. These additive HC starts are applied to all diesel sources in MOVES, including light-duty diesel (regulatory class 20 and 30). There are currently no diesel temperature effects in MOVES for PM, CO, and NO_x.

Table 2-39 HC Diesel Start Ambient Temperature Adjustment by opModeID

	pre-2010 (Currently used for all model years)		2010+ (planned for use in future version of MOVES)[d]	
opModeID	Start Temp Adjustment	Soak fraction	Start Temp Adjustment	Soak fraction
101	-0.0153×(Temp - 75)	0.38	0×(Temp - 75)	0
102	-0.0152×(Temp - 75)	0.37	-0.0008×(Temp - 75)	0.02
103	-0.0180×(Temp - 75)	0.44	-0.002×(Temp - 75)	0.05
104	-0.0201×(Temp - 75)	0.5	-0.0097×(Temp - 75)	0.24
105	-0.0211×(Temp - 75)	0.52	-0.0146×(Temp - 75)	0.36
106	-0.0254×(Temp - 75)	0.62	-0.0134×(Temp - 75)	0.33
107	-0.0349×(Temp - 75)	0.86	-0.0223×(Temp - 75)	0.55
108	-0.0406×(Temp - 75)	1	-0.0406×(Temp - 75)	1

2.2.4 Start Energy Rates

The MOVES start energy rates for the heavy-duty diesel regulatory classes are shown in Figure 2-42. The energy start rates were developed for MOVES2004[62], and updated in MOVES2010 as documented in the MOVES2010a energy updates report.[49] As shown, there is more detail in the pre-2000 emission rates. The spike in fuel economy at 1984-1985 reflects variability in the data used to derive starts, which was consistent with the more detailed approach used to derive the pre-2000 energy rates in MOVES2004. The only updates to the energy rates post-2000 is the impact of the Phase 1 Heavy-Duty GHG standards, which began phase-in in 2014 and have the same reductions as the running energy rates as presented in Table 2-22 and Table 2-24. It is worth noting that unlike the Phase 1 HD standards, the technologies projected for meeting the Phase 2 HD GHG standards are not expected to have an impact on start energy rates. Therefore, the start energy rates are constant after MY 2018 (the first year of full phase-in of the HD Phase 1 rule).

[d] The values labeled '2010+' are the intended values for 2010+ model years for a future update to MOVES, but they have not yet been incorporated into the model. The current MOVES201X uses the values labeled as 'Pre-2010' for all model years.

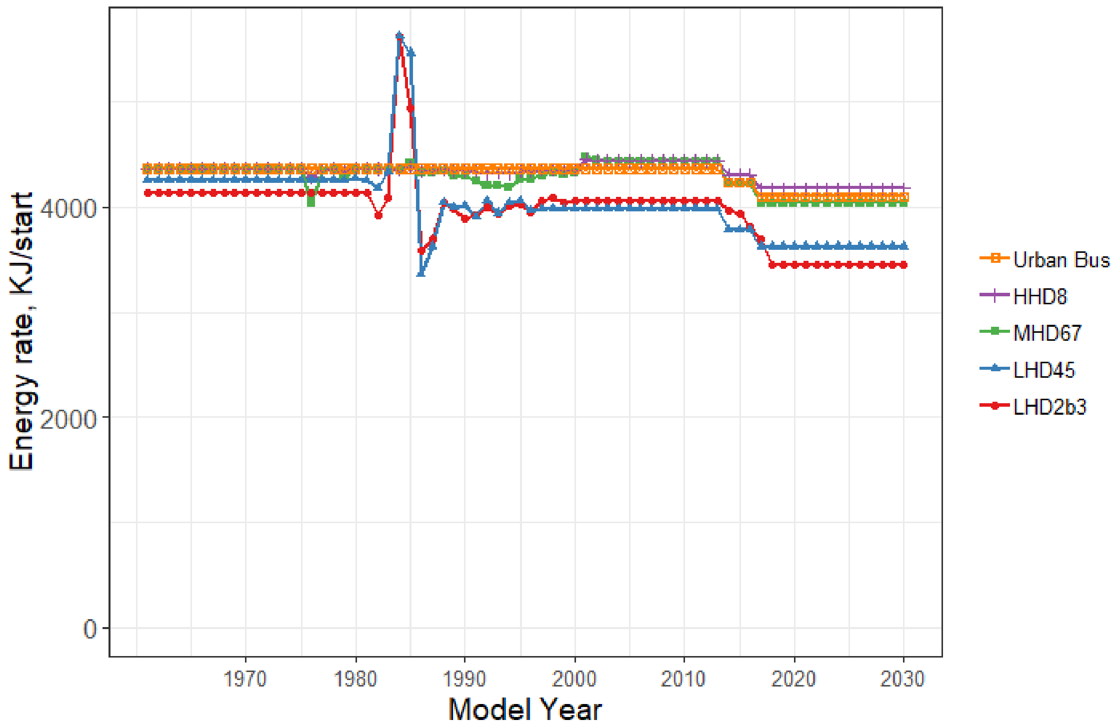


Figure 2-42. Heavy-Duty Energy Cold Start Energy Rates (opMode 108) by Model Year and Regulatory Class

The start energy rates are adjusted in MOVES to account for increased fuel consumption required to start a vehicle at cold ambient temperatures. The temperature effects are documented in the MOVES2004 Energy Report.[62] Additionally, the energy consumption is reduced for starts that occur when the vehicles have soaked for a short period of time. The soak fractions used to reduce the cold start energy consumption emission rates are provided in Table 2-40. These fractions are used for all model years and regulatory classes of diesel vehicles.

Table 2-40. 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 to the energy inventory. Table 2-41 displays the relative contribution of total energy consumption estimated from a national run of MOVES for calendar year 2016, using MOVES_CTI_NPRM. As shown, the estimated energy consumed due to starts is minor in comparison to the energy use of running activity.

Table 2-41. Relative contribution of total energy consumption from each pollutant process by regulatory class for Heavy-Duty diesel vehicles in calendar year 2016

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

2.3 Extended Idling Exhaust Emissions

In the MOVES model, extended idling is idle operation characterized by long duration idle periods (e.g. > 1 hour[e]) , typically overnight, including higher engine speed settings and extensive use of accessories by the vehicle operator. Extended idling most often occurs during long layovers between trips by long-haul trucking operators where the truck is used as a residence (sometimes referred to as "hotelling"). Operators idle to power accessories such as air conditioning systems or heating systems. Heavy-duty engine and truck manufacturers recommend trucks not idle at low engine speeds for extended periods, because it can “create engine wear and carbon soot buildup in the engine and components.”[63]Additionally, idling for extended periods allows the vehicle’s exhaust to cool below the effective temperature required for emission aftertreatment systems in modern trucks such as selective reduction catalysts, and diesel oxidation catalysts. As a result, extended idle is treated as a separate emission process in MOVES which uses a different emission rate than the idling that occurs during the running emission process.

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

In the MOVES model, diesel long-haul combination trucks (sourceTypeID 62) are the only source type assumed to have extended idling activity. These trucks are only associated with diesel MHD (regClassID 46) HHD (regClassID 47) and Glider[f] (regClassID 49) regulatory classes. As an alternative to extended idling, long-haul truck operators can also use auxiliary power units (APUs) to power their cabin and accessories during hotelling. The emission rates for auxiliary power units (APUs) are discussed in Section 2.4

Extended idle rates for HC, CO, NOx and PM were updated in MOVES_CTI_NPRM for all model years. Energy rates were updated for 2007 and later. Separate analyses were conducted using

[e] The default hotelling activity in MOVES_CTI_NPRM is estimated from telematics data assuming all idle events > 1 hr from long-haul combination trucks are extended idling events[11]
[f] Glider extended idle emission rate is documented in Section 3.5

different data sets to derive extended idle emission rates for pre-2007 (Section 2.3.1) and 2007-and-later long-haul combination trucks (Section 2.3.2). For each range of model years, MOVES applies different data and assumptions regarding and the impact of accessory use, frequency of high idle engine speed, and impacts of tampering and mal-maintenance to calculate extended idle emission rates. .

2.3.1 Pre-2007 Extended Idle Emission Rates

The MOVES extended idling emission rates for pre-2007 were derived from data collected in several distinct test programs. The extended idle emission rates are averages of emissions under different types of idle conditions. For MOVES_CTI_NPRM, weightings were adjusted from those in previous versions of MOVES to better account for new information on typical extended idling engine idling speeds and loads. These adjustments are described below.

Note that some of the idle tests used to derive the pre-2007 extended idle rates are of short duration. We believe this is reasonable to include short-duration tests, because the pre-2007 trucks are not equipped with exhaust aftertreatment technology that would reduce the emission control effectiveness at cooler temperatures that occur during long duration idle.

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

- Testing was conducted on 12 heavy-duty diesel trucks and 12 transit buses in Colorado by McCormick et al.[64]. Ten of the trucks were Class 8 heavy-duty semi-tractors, one was a Class 7 truck, and one of the vehicles was a school bus. The model year ranged from 1990 through 1998. A typical Denver area wintertime diesel fuel was used in all tests. Idle measurements were collected during a 20-minute time period. All testing was done at 1,609 meters above sea level (high altitude).
- Testing was conducted by EPA on five trucks in May 2002 (Lim et al.).[65] 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.
- 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.)[66]. Not all trucks were tested under all conditions. Only results from the testing in Tennessee and New York are described in the IdleAire report (Irick et al.)[66]. The California test data was collected on 42 diesel trucks in parallel with roadside smoke opacity testing (Lambert)[67]. All tests were conducted by the California Air Resources Board (CARB) at a rest area near Tulare, California in April 2002 are described in the Lambert[67] Clean Air Study. All analytical equipment for all testing at all locations was operated by Clean Air Technologies.
- Fourteen trucks were tested as part of the E-55/59 Coordinating Research Council (CRC) study of heavy-duty diesel trucks with idling times either 900 or 1,800 seconds long.[68]

- The National Cooperative Highway Research Program (NCHRP)[69] 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.)[70]. The model years ranged from 1984 through 1999. One hundred seconds of idling were added at the end of the WVU five-mile transient test driving cycle.
- A Class 8 Freightliner Century with a 1999 engine was tested using EPA's onroad emissions testing trailer based in Research Triangle Park, North Carolina (Brodrick)[71]. Both short (10 minute) and longer (five hour) measurements were made during idling. Some testing was also done on three older trucks.
- Five heavy-duty trucks were tested for particulate and NO_x emissions under a variety of conditions at Oak Ridge Laboratories (Storey et al.)[72]. 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)[57].

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

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

The use of accessories (e.g., air conditioners, heaters, televisions, etc.) provides recreation and comfort to the operator and increases load on the engine. There is also a tendency to increase idle speed during long idle periods for engine durability. The emission rates estimated for the extended idle pollutant processes in MOVES assume both accessory use and engine idle speeds set higher than used for "curb" (non-discretionary) idling. We classified the extended idling that did not employ high speed idle, and additional auxiliary loads as “curb idle.”

Data from these studies were obtained from one of three idle conditions. The first condition, which has a low engine speed (<1,000 rpm) and no air conditioning is representative of curb idle. The second condition is representative of extended idle with higher engine speed (>1,000 rpm) and no air conditioning. The third represents an extended idle condition with higher engine speed (>1,000 rpm) and air conditioning. For the purpose of this analysis, the load placed on the engine due to air conditioning is assumed to represent all forms of accessory load that may be used during hotelling.

The curb 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. To estimate the elevated NO_x emission rates characteristic of higher engine speed and accessory loading of extended idle, data from the 1991-2006 trucks were used.

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

As mentioned above, an NREL review of owner's manuals found that several heavy-duty engine manufacturers recommend use of fast idle (> 1000 rpm) if the engine needs to idle for extended periods.[73] In a 2004 UC-Davis survey (Lutsey et al. 2004), respondents' average engine idle speed was 866 rpm, with small peaks around 650 and 1000 rpm.[74] Only about one-third of the respondents indicated they changed their idle speed from its usual setting, which is consistent with the distribution of the responses where about one-third of the idle engine speeds reported were 1000 rpm or faster.

A 2015 study by Hoekzema (2015) suggested that even fewer trucks operated in a high idle condition. Drivers surveyed for this study reported high idle operation (> 1000 rpm) just 18 percent of the time during idling periods of an hour or more.[75] Additionally, Hoekzema cited similar studies representing 764 trucks that averaged engine speeds of 886 rpm during extended idle.

While many engine manufacturers recommend using high idle when idling for long periods, Hoekzema (2015) and Lutsey et al. (2004) reported few drivers in their studies followed those recommendations. Previously, MOVES emission rates were calculated assuming all extended idling occurred at a high idle condition. Furthermore, extended idling measurements have large variability due to low engine loads. For MOVES_CTI_NPRM, the amount of high idle was reduced from 100 percent to 33 percent to better match the references noted above. Using the data summarized in Appendix E, an adjusted emission rate was calculated for each pollutant by weighting the overall "high speed idle, A/C on" results by 0.33 and the "low speed idle, A/C off" (i.e., curb idle) results by 0.67.

The NO_x, HC, CO, and PM emission rates from this data analysis are representative of diesel HHD trucks (regClassID 47). In MOVES2014, we calculated the MHD (regClassID 46) extended idle emission rates as half of the corresponding HHD emission rates. However, a study by Khan et al. (2009)[76] found that MHD and HHD trucks had similar emission rates during extended idle. Consequently, MOVES_CTI_NPRM applies the same extended idle emissions rates to regClassID 46 and regClassID 47, as shown in Table 2-42.

MOVES stores PM emission rates according to elemental carbon (EC) and NonECPM, but the data sources used to calculate extended idle emission rates reported total PM. As mentioned in Section 2.1.2.2.8, an EC/PM fraction of 46.4 percent is applied for idle operating mode (opModeID 1), and we also apply it to extended idle. The resulting EC and NonECPM rates are also shown in Table 2-42.

Table 2-42. Pre-2007 Extended idle emission rates (g/hour) in MOVES by pollutant for regClassID 46 and regClassID 47 (g/hour)

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

2.3.2 2007+ Extended Idle Emission Rates

The extended idle emission rates for model year 2007 and later heavy-duty tractor trailers (sourceTypeID 62, regClassID 46 and 47) in MOVES_CTI_NPRM were updated based on two test programs measuring extended idle emissions. The Texas Transportation Institute (TTI) tested extended idle emission from 15 heavy-duty diesel tractors ranging from model year 2005[g] to 2012.[77] Another study conducted by California Air Resources Board (ARB)[78] tested five tractors (engine model years 2007 and 2010).

The study (TTI or ARB), engine model year, engine manufacturer, odometer, the NO_x certification level, California Clean Idle certification, and engine aftertreatment are listed for each of the trucks in Table 2-43. The last three columns in Table 2-43 are taken from the California Executive Order certification database.[79] NO_x certification level (g/bhp-hr) is the standard to which the engine was certified. Some 2010 and later engines were certified above the 0.2 g/bhp-hr NO_x 2010 federal standard due to the emissions averaging, banking and trading (ABT) program, and EPA allowance of nonconformance penalty (NCP) engines in 2012.[80] In these cases, the family emission limit for which the vehicle was certified is reported in Table 2-43. California Clean Idle Certification was implemented in 2008 and allows engines that are certified to a 30 g/hr idle NO_x standard to idle beyond the 5-minute idle limit initiated in 2008 in California. The aftertreatment column in Table 2-43 indicates if the engine was certified with an oxidation catalyst (OC), diesel particulate filter or periodic trap oxidizer (DPF), and/or selective catalytic reduction (SCR) system.

[g] Although, 2005-2006 model year engine data was used in the 2007+ analysis, it was not used to update the pre-2007 emission rates because it was outside the scope of the analysis.

Table 2-43. Information for the Heavy-Duty Diesel Tractors Used to Update the Extended Idle Emission Rates

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

The 15 trucks from the TTI program were tested in an environmental chamber under hot and cold conditions to represent summer conditions in Houston, TX and winter conditions in the Dallas-Fort Worth area. Several tests and idling conditions were measured by TTI, including idling after different soak lengths and 'commanded high idle' for engines capable of idling with an engine speed approximately 400 rpm higher than their standard idle speed. The test data we used in this analysis were the measurements taken after a twelve-hour soak, where the vehicle had idled for at least one hour, and the vehicle had reached a 'stabilized' idling condition. The vehicles were tested at the engine load required to run the heater or air conditioning under the cold winter or hot summer conditions (see Table 2-44) but were not commanded to be in the high idle state. We decided not to use the 'commanded high idle' emission rates for several reasons:

1) Six of the fifteen TTI trucks were not able to be commanded into high idle.
2) The 'stabilized' idling emission tests did contain some high idle that appears representative of automatic engine control strategies for 2007 and later trucks. Two of the trucks included high idle during the winter stabilized tests due to automatic engine control strategies. We assume that for 2007 and later technology trucks, operators and manufacturers rely on automatic engine control strategies rather than the vehicle operators to employ high idle conditions[h]. Because most of the engines did not use high engine speeds to power the

[h]We assume manufacturers rely on vehicle operators commanding the vehicle to be in a high idle state to protect engine component for pre-2007 trucks as discussed earlier.

heater/air conditioner during the winter/summer conditions, we assume this engine operation of MY 2007 and later trucks is also representative of in-use operation.

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

For these reasons, the summer and winter stabilized conditions were deemed to be our best estimate of real-world extended idle emissions. The 'stabilized' idle emission rates (g/hr) for the winter and summer conditions, are reported in Figure 2-43 through Figure 2-47.

Table 2-44. Ambient Test Conditions for the TTI Extended Idle Tests

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

ARB tested five trucks on a chassis dynamometer on the ARB HHDDT 4-mode cycle, reporting the g/hr results from the 10-minute 'Idle' mode. Before testing the 'Idle' mode, the vehicle was first warmed on a pre-conditioning cycle, and then soaked for 10-20 minutes.[81] Additional test conditions were not reported by ARB, but we assumed that the ARB vehicles were tested at moderate temperatures, with no auxiliary loading. Thus, we treated the ARB data as more representative of an extended idling truck that did not require significant A/C or heating system auxiliary loading on the engine, where the extended idling occurred shortly after active driving by the main engine.

To develop the revised extended idle emission rates for MOVES_CTI_NPRM, we averaged the emission rate from each of the tests, within model year ranges that represent engine and aftertreatment technology groups that have similar impacts on extended idle emissions. Where possible, we used all 35 tests (15 trucks × 2 conditions = 30 TTI tests, and 5 ARB tests). Because there were more TTI tests, the average within each model year group is weighted significantly towards the TTI tests. We chose to weight each test equally, because we believe the TTI data are more representative of real-world extended idle conditions, because they were tested with auxiliary loads at non-standard 'lab' temperatures.

The individual test results and the average emission rates by model year group are presented in the following figures (Figure 2-43 to Figure 2-47). Within each figure, the tests are distinguished according to the test condition – 'hot' and 'cold' conditions represent the tests from the TTI test program; 'lab' test condition are the tests from the ARB test program. Additionally, we indicate if the test was from a truck equipped with SCR or not, which we found was the most useful aftertreatment classifier to determine engine model year groups. For CO_2, CO, and NO_x, we directly used the average of the extended idle emission rates in MOVES, with no increase in emissions to account for deterioration, including tampering, of the engines or emission control systems. We did not observe strong effects of the emission control on the extended idle emission rates for these pollutants – the aftertreatment technology (oxidation catalyst, selective catalytic reduction systems) may not be fully functional during the extended idle conditions, due to lower exhaust temperature occurring at extended idle. On the other hand, for THC and $PM_{2.5}$ emissions, we adjust the model year group emission rates to account for deterioration of the aftertreatment systems, as discussed in more detail below.

Figure 2-43 displays the CO_2 individual test results. No trend with respect to aftertreatment or model year is observed (nor was one expected). The emissions from cold tests tend to be higher than the hot tests, which are both higher than the ARB laboratory tests. Two of the cold tests have extended idle emission rates > 10,000 g/hr which is likely due to higher engine rpm for these engines during the cold tests. TTI observed that some engines have an engine control strategy, termed "cold ambient protection", which increases the idle engine speed at cold temperature to warm the coolant temperature, and protect against engine wear. We calculated an average CO_2 extended idle emission rate for all 2007 and later trucks, by using all the data, and treating each test equally across all model years.

The CO_2 extended idle emission rate is used to derive the energy and fuel consumption extended idle rate of 97,084 kJ/hr and 0.71 gallons-diesel/hr, respectively. We used the conversion factor of 0.0736 g CO_2/kJ and 10,045 g CO_2/gallon from B5 (5 percent biodiesel blend) highway diesel reported from the MOVES GHG and Energy Report.[82]

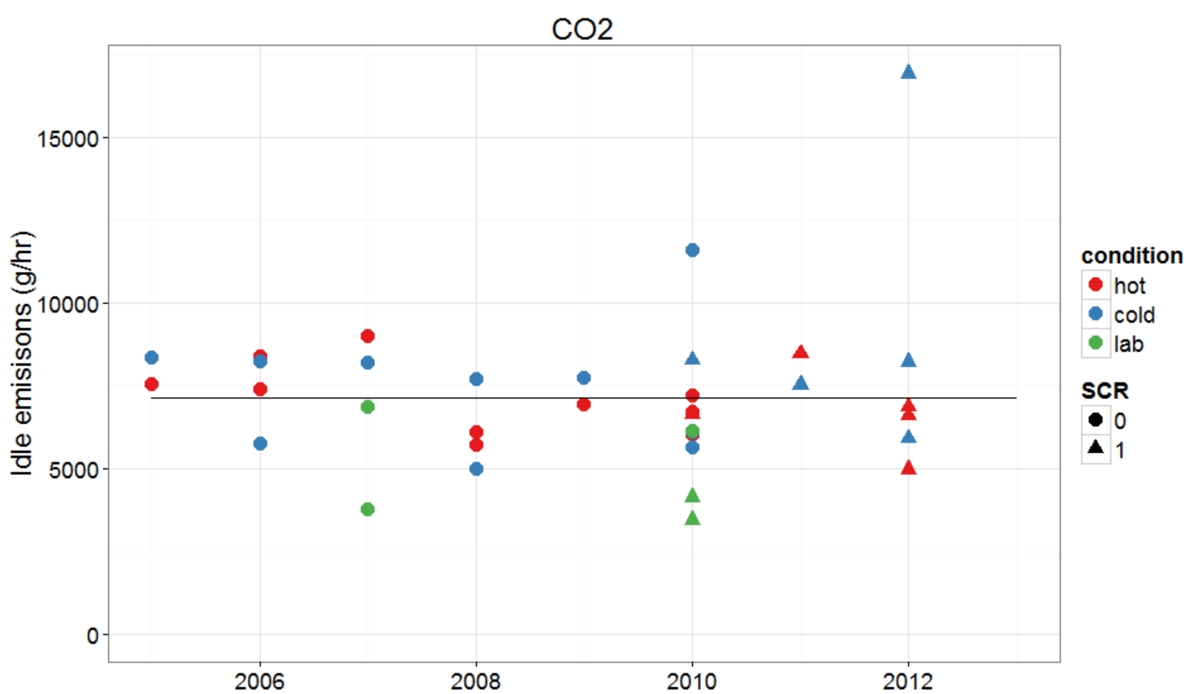


Figure 2-43. CO_2 Emission Rates from the TTI and ARB Programs by Engine Model Year, and Average Emission Rate (line) based on all the data. Within "condition," "hot" refers to the summer conditions from the TTI tests, "cold" refers to the winter conditions from TTI, and "lab" refers to the laboratory tests conducted by ARB. For SCR, 0 means the truck does not have a selective catalytic reduction system (SCR), and 1 means the truck has SCR.

Figure 2-44 displays the CO individual test results. No trend is observed with respect to model year or use of aftertreatment. The laboratory ARB tests are lower than the TTI tests, which could be due to the lower fuel consumption of the tests. The CO emission rate is slightly lower than the

MOVES_CTI_NPRM emission rate for 1990-2006 MY of 55 g/hr. Similar to CO_2, a single average emission rate is calculated for all the tests results.

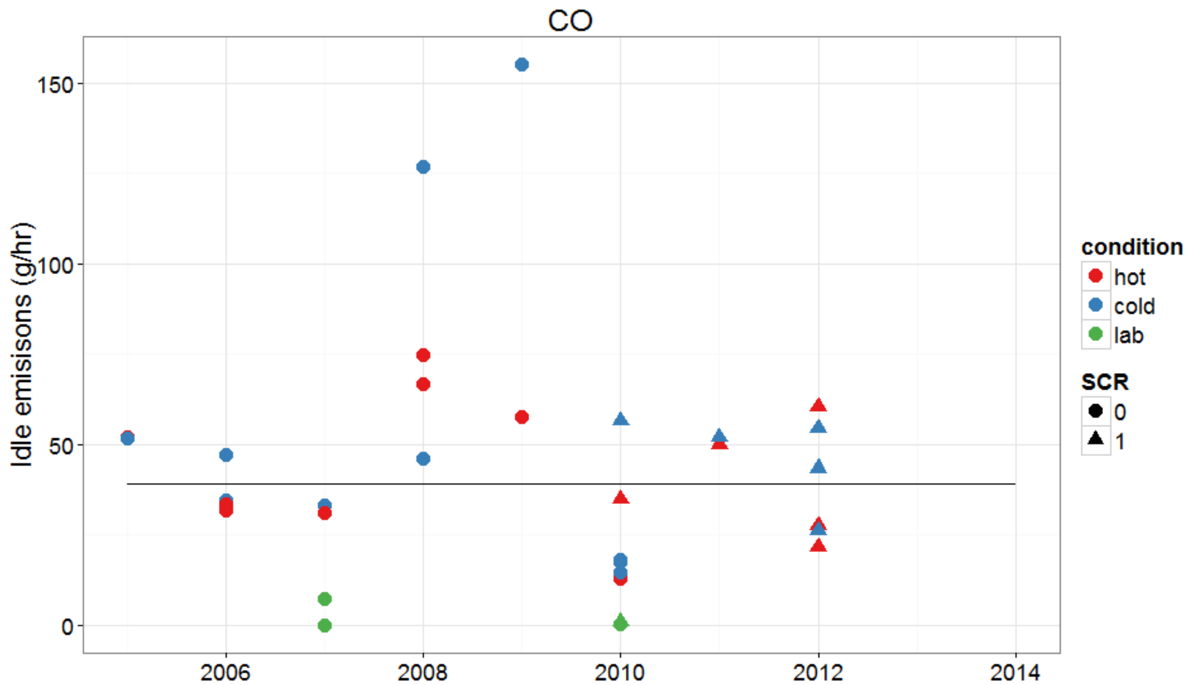


Figure 2-44. CO Emission Rates from the TTI and ARB Programs by Engine Model Year, and Average Emission Rate (line) Based on All the Data

Figure 2-45 displays the NO_x individual test results. We initially expected the data to show a decrease in the extended idle emission rates beginning in MY 2008 to account for the California Clean Idle Certification (all MY 2008 and later trucks were clean-idle certified). However, no reduction was observed. We also expected to observe a decrease in 2012, with the full implementation of SCR, but this was also not the case. Therefore, we calculated average NO_x emission rates for two model year groups (2005-2009) and (2010 and later model years) as represented by a solid line in Figure 2-45. The MY 2005-2009 rates calculated from this analysis compare well to the MOVES_CTI_NPRM rates for MY 2007-2009 of 136 g/hr.

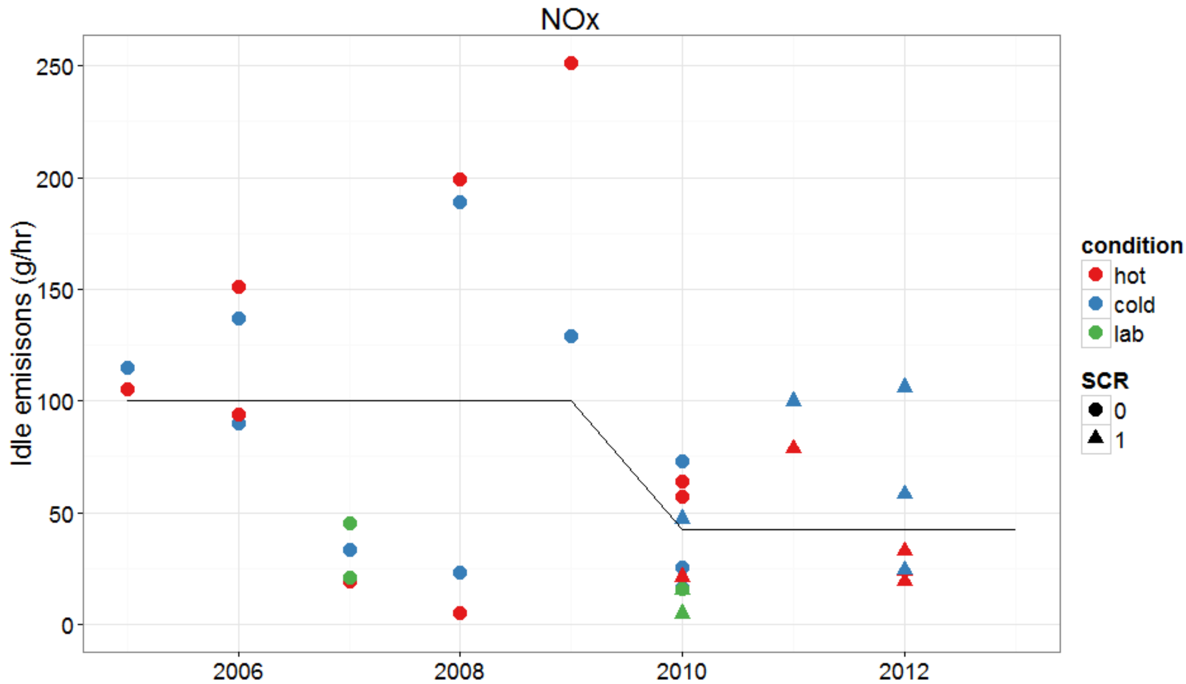


Figure 2-45. NO_x Emission Rates from the TTI and ARB Programs by Engine Model Year, and Average Emission Rates for 2005-2009 and the 2010-2012 Engine Model Years (lines)

Figure 2-46 displays the THC individual test results. The results are displayed with the SCR aftertreatment, rather than according to the use of an oxidation catalyst aftertreatment. The use of SCR corresponded better to THC emissions than the reported use of an oxidation catalyst. We believe the SCR aftertreatment classification is a surrogate for the combined engine control and aftertreatment system used with SCR equipped trucks that have a large impact on THC emissions. For example, with the use of SCR, engines can be calibrated to run leaner, which reduces engine-out THC emissions. Additionally, SCR systems rely on oxidation catalysts, or catalyzed DPFs to convert NO to NO_2, which also reduces the THC tailpipe emissions.

We calculated average emission rates for three model year groups 2005-2009, 2010-2012 and 2013 and later model years. The 2005-2009 model year represents a combination of DPF and non-DPF equipped trucks[i]. The 2010-2012 represents DPF equipped trucks, with some penetration of SCR equipped trucks. The model year group representing 2013 and later model years was developed because starting in 2013, Navistar began certifying a heavy heavy-duty diesel (HHDD) engine equipped with SCR aftertreatment. In 2014 and 2015, Navistar and all other engine manufacturers certified all their HHDD engines equipped with SCR aftertreatment.[83] Therefore, emission rate for the 2013+ model year group was estimated by averaging the rates of all the SCR equipped trucks in the data set, even though the dataset did not include any data on 2013 and later model year engines.

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[i] Note: the 2005-2009 THC rates are ~3 times smaller than the THC MOVES_CTI_NPRM MY 1990-2006 rates derived in the previous section, which may be due to the small sample size (3 MY 2006-2006 trucks) sampled in the TTI study.

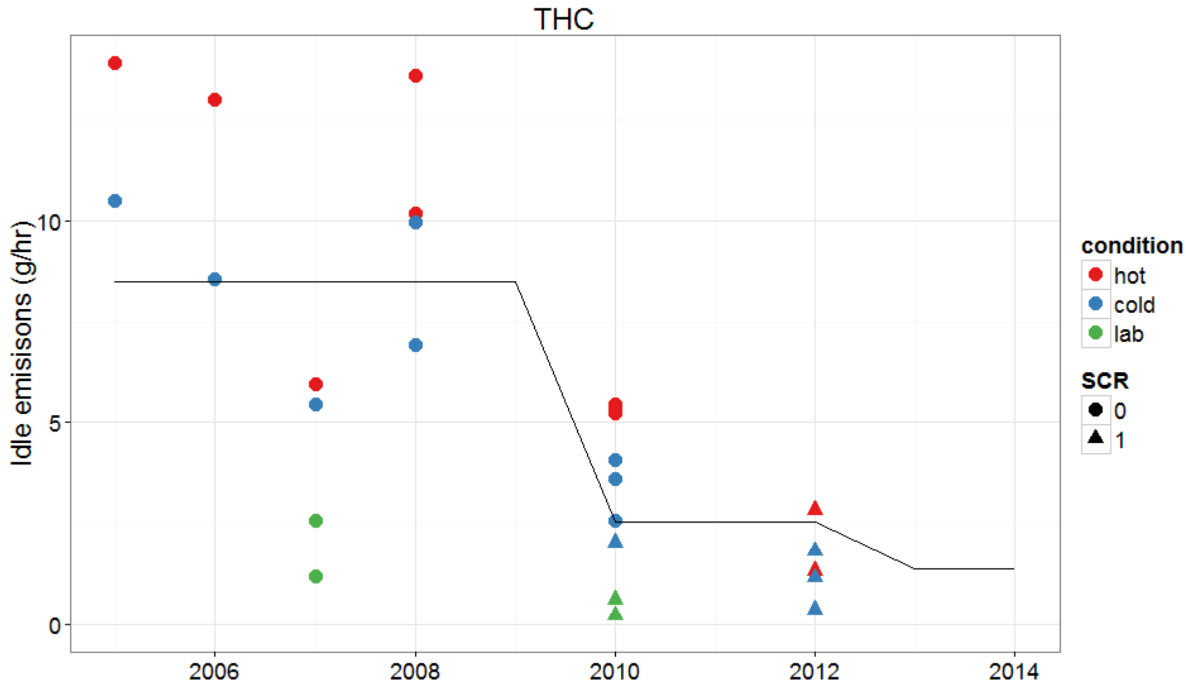

Figure 2-46. THC Emission Rates from the TTI and ARB Programs by Engine Model Year, and Average Emission Rates for 2005-2009, 2010-2012, and 2013 + (SCR only) Engine Model Years (lines)

Figure 2-47 displays the $PM_{2.5}$ individual test results. The ARB tests reported zero emission or "Not Reported due to PM collection failure" for the five ARB tests, and thus, only the TTI data was used to develop the PM extended idle emission rates. Like the THC results, the use of an SCR-equipped engine had a significant impact on the $PM_{2.5}$ emissions. Additionally, and as expected, the implementation of diesel particulate filters starting in 2007 model year had a significant impact on the $PM_{2.5}$ emissions.[j]

We grouped the individual emission tests into four model year groups: 2005-2006 (pre-DPF), 2007-2009 (DPF, pre-SCR), 2010-2012 (DPF and phase-in of SCR) and 2013 and later model years (SCR only). As for THC, we used the results from the 2010 and later SCR equipped trucks to calculate $PM_{2.5}$ emission rate for the 2013 and later model year group.

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[j] Note: The MY 2005-2006 $PM_{2.5}$ emission rates measured from the TTI data are only ~3 times higher than the MY 2007-2009 $PM_{2.5}$ rates, and roughly ~10 times smaller than the MOVES_CTI_NPRM $PM_{2.5}$ rates for MY 1990-2006 (2.5 g/hr), We would expect a larger decrease in $PM_{2.5}$ emission rates with the use of DPF as discussed in Section 3.3.3. We only use the TTI data the to inform the 2007+ $PM_{2.5}$ extended idle emission rates. Using the TTI data on the three MY 2005&2006 vehicles to reconcile and update the pre-2007 $PM_{2.5}$ emission rate was outside the scope of the present analysis.

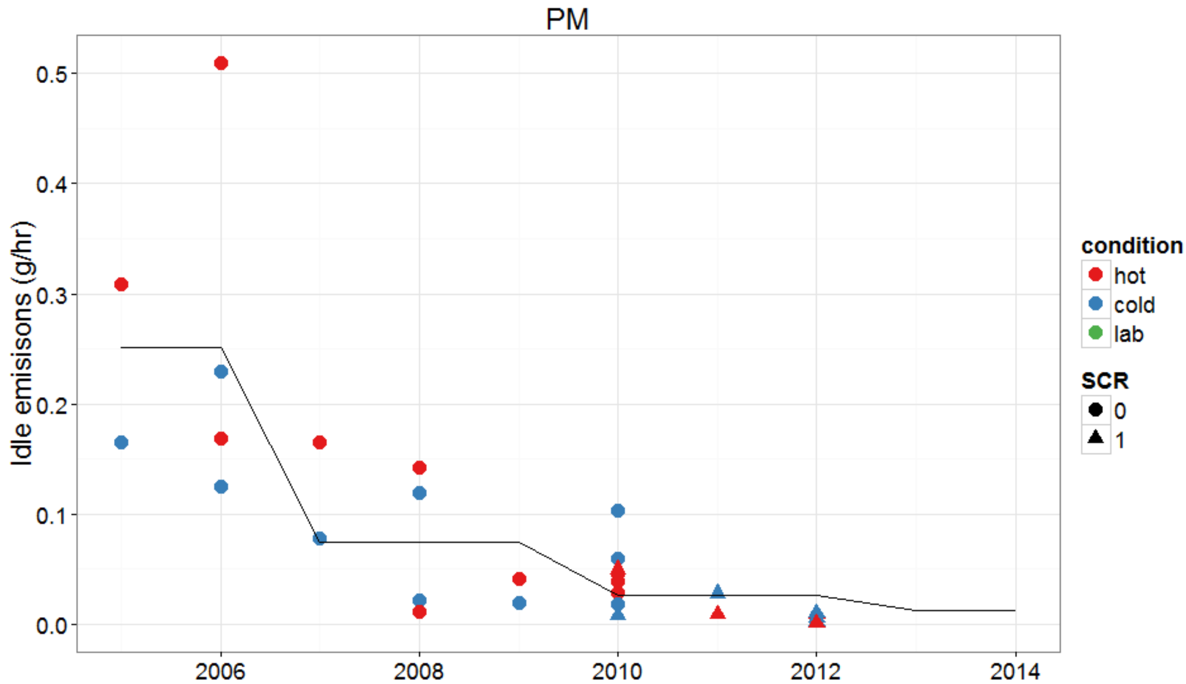

Figure 2-47. $PM_{2.5}$ Emission Rates from the TTI Program by Engine Model Year, and average Emission Rates Using for 2005-2006, 2007-2009, 2010-2012, and 2013 + (SCR only) Engine Model Years (lines)

$PM_{2.5}$ emission rates in MOVES are composed of elemental carbon (EC) and non-elemental carbon PM (nonEC). The TTI study did not include estimate of the EC emission rates. We used the EC/PM fractions from the sources listed in Table 2-45 to estimate the EC and PM emission rates and the results are shown in Table 2-45.

Table 2-45. Baseline elemental carbon to PM2.5 fraction assumed for extended idling

Model Year Group	EC/PM	Source
Pre-2007	0.26	MOVES2014 Extended Idling[85,k]
2007-2009	0.10	ACES Phase I[81]
2010+	0.16	ACES Phase II[84]

As shown in the figures above, the THC and $PM_{2.5}$ emission showed the largest reductions in extended idle emissions with newer model year vehicles. We believe that the reductions are due to the continued effectiveness of the diesel particulate filter even under extended idling conditions. For the MOVES extended idle THC and $PM_{2.5}$ emission rates, we included an estimate of the impact of deterioration and failure of the diesel particulate filters in calculating the 2007-2009, 2010-2012, and 2013+ model year group emission rates. To do so, we made assumptions about the failure rates of DPFs from in-use trucks based on consultation with several references and staff at the California Air Resources Board (CARB) as summarized in Table 2-46. We adopted the

[k] The pre-2007 EC/PM ratio for extended idling has subsequently been updated in MOVES_CTI_NPRM to be 46.4% as discussed in Section 3.3.1, but it was not updated for this analysis.

assumption shared by CARB staff that 10 percent of 2007-2009 DPFs fail in the real-world, and 5 percent of 2010+ DPFs fail in the real-world.

Table 2-46. References Used to Support In-Use DPF Failure Rate Assumption for Extended Idling Emissions

Study	Relevant Information
US EPA (2014)[85]	7% of 2007+ trucks in MOVES are assumed to either have a PM filter leak or have the PM filter disabled.
Preble et al. (2015)[86]	20% of trucks produce 80% of black carbon (BC) emissions from Port of Oakland 2013 truck fleet, where 99% of the trucks are equipped with DPFs
Bishop et al. (2014)[87]	3% of 2007+ trucks at Port of LA PM emissions 3× the standard. 9% of 2008+ trucks at Cottonwood site have PM emissions 3× the standard
CARB (2015)[88]	35% to 4% of trucks submitted warranty claims related to the PM filter between 2007 and 2011
CARB (2015)[88]	8% of trucks were classified as high emitters (emitting over 5% opacity) from a sample of >1,800 trucks test in the snap-idle acceleration test by CARB, about ~1/2 equipped with DPFs
CARB correspondence (2016)	~10% of 2007-2009 DPFs and ~5% of 2010+ DPFs to fail in real-world, based on their observations from warranty claims, snap-idle acceleration opacity tests, and their review of the Bishop et al. (2014)[87] and Preble et al. (2015)[86] studies.

To account for the failure of DPF in the THC and $PM_{2.5}$ emission rates, we used the 2005-2006 average extended idle emission rates to represent the 'failed' DPF emission rates. We then calculated a 'Deteriorated' emission rate that represents a mix of failed and properly operating systems by assigning the 'failed' DPF emission rates a weight of 10 percent in the 2007-2009 model year group, and 5 percent weight in the 2010-2012, and 2013+ model year groups, as shown in Table 2-47. The 'Deteriorated' emission rate represents the presumed emission rate of fully-aged heavy-duty diesel trucks. Unlike the start and running MOVES emission rates, extended idle emission rates in MOVES are not distinguished by age. Thus, these rates are constant with respect to age.

Table 2-47. Baseline and deteriorated THC and PM emission rates to account for failure of diesel particulate filters (DPFs) by model year groups

Engine Model Year	Baseline				Deteriorated				
	THC (g/hr)	$PM_{2.5}$ (g/hr)	EC (g/hr)	nonEC (g/hr)	Failure rate	THC (g/hr)	$PM_{2.5}$ (g/hr)	EC (g/hr)	nonEC (g/hr)
2005-2006	8.49	0.251	0.065	0.187	-	8.49	0.251	0.065	0.187
2007-2009	8.49	0.075	0.007	0.067	10%	8.49	0.092	0.013	0.079
2010-2012	2.53	0.026	0.004	0.022	5%	2.83	0.037	0.007	0.030
2013+	1.38	0.012	0.002	0.010	5%	1.74	0.024	0.005	0.019

We assume that trucks that are under warranty would have substantially fewer aftertreatment failures than older trucks. Because extended idle rates are modelled as constant with age, to estimate the fleet-average emission rates used in MOVES, we used the 'Baseline' emission rates to represent trucks that are within the specified 435,000 miles useful-life of the engine in the US EPA regulations.[89] We use the deteriorated emission rate to represent the years between the regulated "useful life" and the 1,530,000 miles that MOVES models as the mean life-time miles for a long-haul combination trucks. Using the 'deterioration fraction' [(1-.435)/1.53 = 0.72] as the fraction of the vehicle miles traveled during the deterioration phase, we calculated fleet-average emission rates used for MOVES in Table 2-48. As shown, the MOVES EC/PM emission rates for MY 2007+ trucks are slightly higher than the 'Baseline' EC/PM fractions in Table 2-47, because the fleet emissions are assumed to include some contribution of emissions from trucks with failed DPFs, which have a higher EC/PM fraction.

Table 2-48. Emission Rates Calculated from Weighting the 'Baseline' and 'Deteriorated' Emission Rates from Table 2-47 Using the Deteriorated Fraction

Engine Model Year	MOVES					
	Deteriorated Fraction	THC (g/hr)	$PM_{2.5}$ (g/hr)	EC (g/hr)	nonEC (g/hr)	EC/PM
2005-2006	-	8.49	0.251	0.065	0.187	0.26
2007-2009	0.72	8.49	0.087	0.012	0.076	0.13
2010-2012	0.72	2.75	0.034	0.006	0.028	0.18
2013+	0.72	1.64	0.021	0.004	0.017	0.20

Table 2-49 shows the updated MOVES extended idle emission rates in MOVES_CTI_NPRM. Although, 2005-2006 model year engine data was used in this analysis, the update itself is limited to the model year 2007 and later emission rates. In MOVES, extended idling is modeled only for long-haul combination trucks, which consist of heavy heavy-duty (HHD) diesel and medium heavy-duty (MHD) diesel engines. We did not analyze extended idle emission rates from MHD trucks. We populated the MHD extended idle emission rates with the same emission rates derived for HHD emission rates for two reasons. First, for simplicity, since MOVES estimates that only 5 percent of long-haul combination trucks in the US are MHD trucks, they are a minor contributor to the emissions from extended idling trucks. Second, Khan *et al.* 2009[90] evaluated extended idle emission rates of pre-2007 MHD engines and did not observe a pronounced difference in extended idle emission rates between MHD and HHD trucks. Without any extended idling data on 2007 and later model year trucks, we felt it was most defensible to keep the MHD emission rates the same as the HHD emission rates.

Table 2-49. Extended Idle Emission Rates for 2007 and Later Model Year Heavy-Duty Vehicles in MOVES201X

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

2.3.3 Summary of Extended Idle Emission Rates

Extended idle emission rates were updated for all model years, as described in Sections 2.3.1 and 2.3.2. Figure 2-48 through Figure 2-51 illustrate the extended idle emission rates in MOVES_CTI_NPRM for regClassIDs 46 and 47.

As shown, the NOx and the CO extended idle emission rates have a relatively small decrease between the pre-2007 and the 2007+ model years. For HC and $PM_{2.5}$ we observe large decreases in in MY 2007, which is consistent with our understanding of the effect of diesel particulate filters. We observed a decrease by ~29 times in extended idle $PM_{2.5}$ rates between the pre-2007 and post-2007 extended idle rates corresponding to the implementation of the DPFs, which is consistent with the ~27 decrease in $PM_{2.5}$ running exhaust emission rates from $PM_{2.5}$ certification data as discussed in Section 2.1.2.2.6.

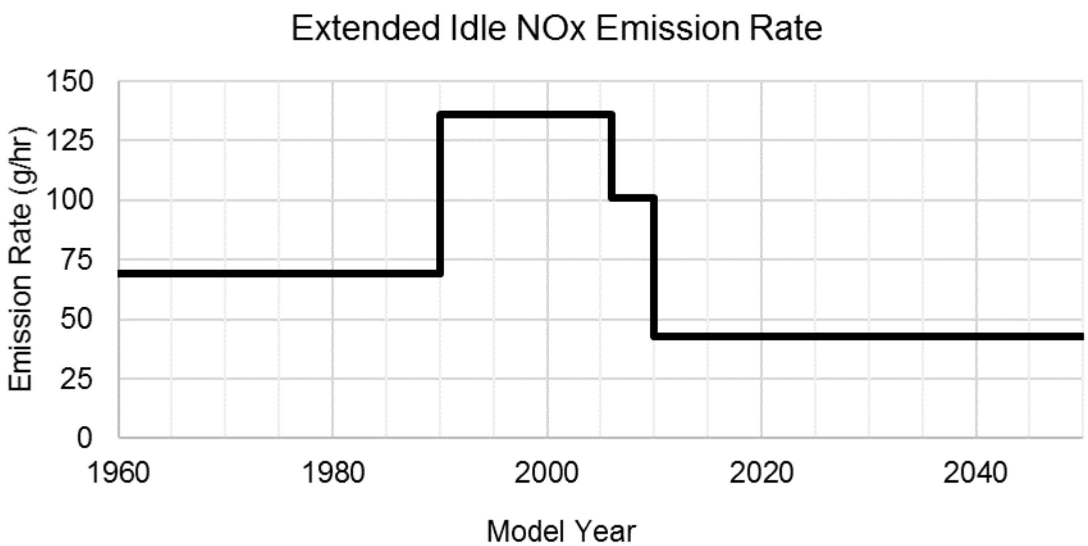

Figure 2-48. Extended Idle NO_x Emission Rates for regClassIDs 46 and 47

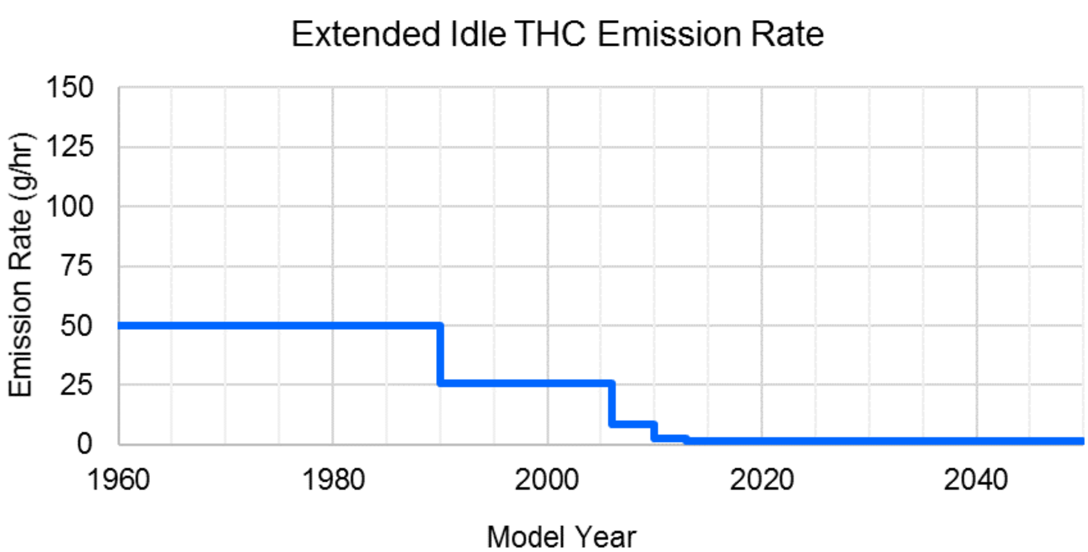

Figure 2-49. Extended Idle THC Emission Rates for regClassIDs 46 and 47

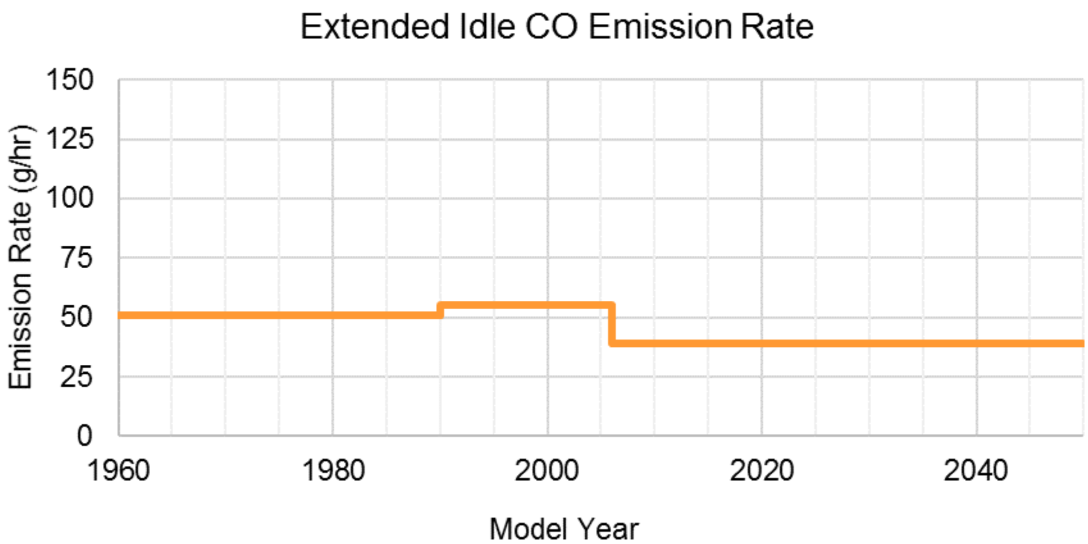

Figure 2-50 Extended Idle CO Emission Rates for regClassIDs 46 and 47

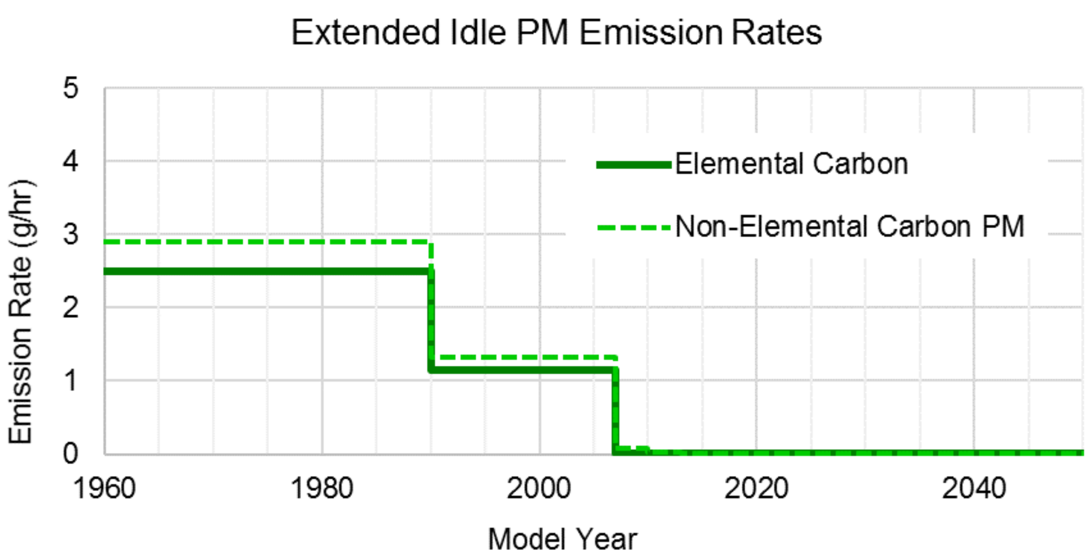

Figure 2-51. Extended Idle PM Emission Rates for regClassIDs 46 and 47

2.3.4 Extended Idle Energy Rates

The pre-2007 extended idle energy emission rates are unchanged from those originally developed for MOVES2004 and are documented in the Energy and Emissions Report[62], and are displayed in Figure 2-52. The extended idle energy consumption rates are the same for both regulatory class MHD and HHD diesel vehicles. The extended idle energy rates for 2007+ trucks were updated in MOVES_CTI_NPRM and estimated using the CO_2 emission rates presented in Table 2-49 and are also plotted in Figure 2-52. The extended idle energy consumption rates are the same for both regulatory class MHD and HHD diesel vehicles.

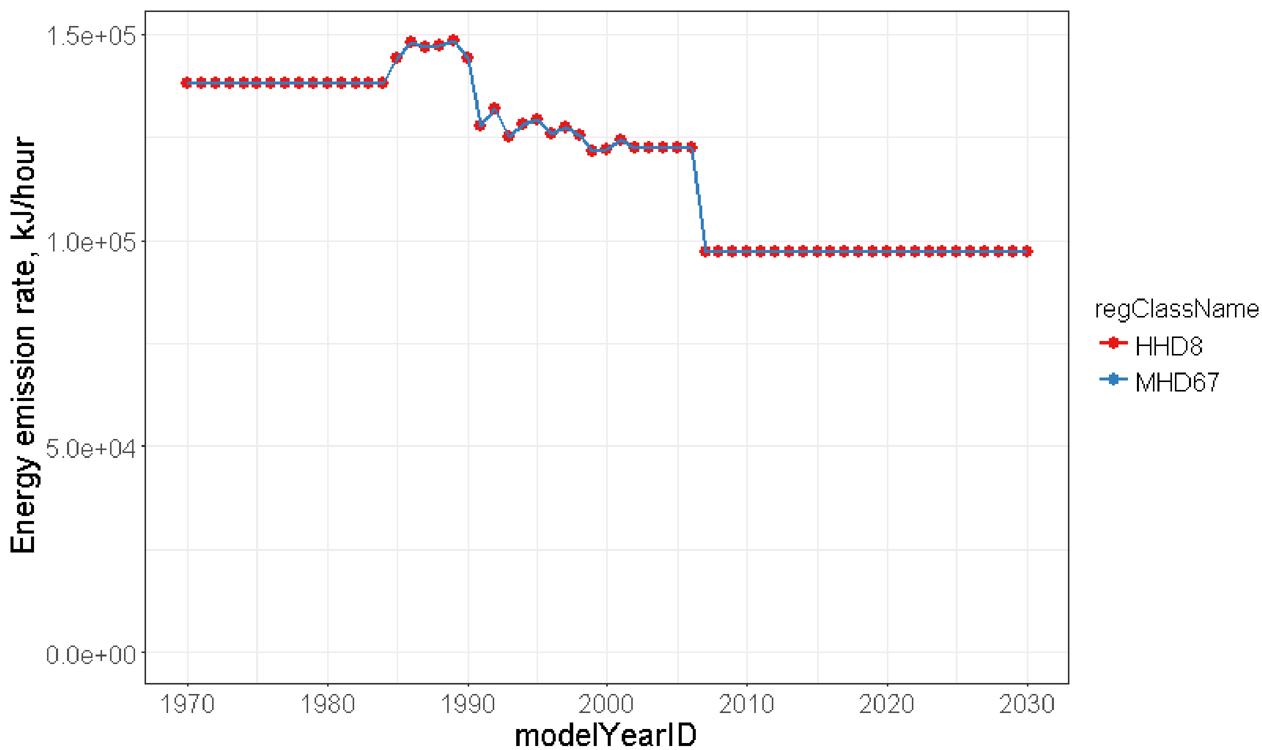

Figure 2-52. Extended Idle Energy Emission Rates for HHD and MHD Diesel Trucks

2.4 Auxiliary Power Unit Exhaust

Auxiliary power unit (APU) exhaust is a separate emission process in MOVES. APU usage only applies to the vehicles with hotelling activity, which are the heavy-duty regulatory classes (MHD, HHD, and Gliders) within the combination long-haul truck source types (sourceTypeID 62). The APU emission rate for MHD, HHD and glider regulatory classes are the same for each model year. The projected use of APUs during hoteling due to the HD GHG Phase 2 program, shown below in Table 2-50, were used to revise the "hotellingactivitydistribution" table in MOVES_CTI_NPRM[52], as is also discussed in the Population and Activity Report.[11] Users can update the fraction of hotelling activity spent in extended idling, APU usage, and engine off activity as discussed in the MOVES2014 User Guide.[91]

Table 2-50: Projected APU Use during Extended Idling for Combination Long-Haul Tractor-Trailers

VEHICLE TYPE	MODEL YEARS	DIESEL APU PENETRATION	BATTERY APU PENETRATION
Combination Long-Haul Trucks	2010-2020	9%	0%
	2021-2023	30%	10%
	2024-2026	40%	10%
	2027+	40%	15%

For MOVES_CTI_NPRM, the APU emission rates have been updated to reflect new standards, data, and analysis. The APU emission rates were updated in MOVES_CTI_NPRM based on two studies that measured in-use APU emission rates. The Texas Transportation Institute (TTI, 2014)[92] tested two diesel APU systems with and without diesel particulate filters at temperatures of 100˚F and 0˚F. The exhaust emission rates (THC, CO, CO_2, and NO_x) and the exhaust flow rates were measured using an ECOSTAR gaseous portable emission measurement system. The PM mass was measured using a BG-3 partial flow dilution and filter sampling system. Limitations of the TTI study are discussed in the HD GHG Phase 2 MOVES documentation.[97,1]

The second study used to update APU emission rates was by Frey and Kuo (2009)[93], who tested two APU systems (APU ID 2 and 3), equipped with 2006 Kubota Z482 engines. The APU systems were tested at a range of electric output loads to obtain the fuel consumption relationship with the electric power demands, and the fuel-based emission rates. The study measured the in-use APU electric loads from a fleet of 20 vehicles (10 trucks equipped with each APU system) for over a year. They then used the relationship between electric power demand and the fuel-based emission rate factors with the average energy use of the APU system to estimate average APU (g/hr) emission rates of CO_2, CO, NO_x, THC, and PM for both a mild temperature (50-68˚F) scenario and a high temperature (100˚F+) scenario. Frey and Kuo 2009 reported a PM emission rate, but the emission rate is 'inferred from the literature' because their PM measurements were semi-qualitative.

An additional two studies were used as a source of data to compare and evaluate emission rates obtained from the previous two studies. TTI 2012[94] conducted testing of two APU systems using their environmental chamber at both 100˚F and 0˚F. The APU systems (APU 4 and 5) manufacturer, engine make and model year were maintained confidential in the report. Storey et al. 2003[95] tested a Pony Pack APU System (APU ID 6), equipped with a Kubota Z482 engine, in an environmental chamber at both 90˚F and 0˚F. This is one of the studies used by Frey and Kuo 2009[93] to determine the PM emission factor for the APU's tested in their study. The engine year, engine displacement, and engine power were not reported in the TTI 2012 and Storey et al. 2003 studies. For this reason, these studies were used as comparative data sets.

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

Table 2-51. APU Engines and Studies Used in This Analysis

APU ID	Engine Model	Engine Year	Displacement (L)	Power (HP/kW)	Tier	Study
1	Kubota Z482	2011	0.48	14.2/11	Tier 4	TTI 2014[92]
2	Kubota Z482	2006	0.48	10.9/8.1	Tier 2	Frey and Kuo 2009[93]
3	Kubota Z482	2006	0.48	10.9/8.1	Tier 2	Frey and Kuo 2009
4	Confidential Information					TTI 2012[94]
5	Confidential Information					TTI 2012
6	Kubota Z482					Storey *et al.* 2003[95]

Table 2-52 contains the in-use emission rates measured from reviewed APU systems. As shown, the emission and fuel rates for the APUs measured in the TTI 2014, and Frey and Kuo 2009 (APU ID 1, 2 and 3) compare well with the APU emission rates reported from TTI 2009 Storey *et al.* 2003 (APU ID 4, 5, and 6). The impact of the DPF is clearly shown on the PM emission rates from APU ID 1, as expected. However, there does not appear to be a substantial impact of the DPF on the gaseous emissions (CO_2, CO, NO_x, and THC). Additionally, no notable emission effects are observed with respect to the nonroad emission standard tier or engine model year.

The impact of ambient temperature can be observed within individual studies. For APU ID 2 and 3, the CO_2, fuel consumption is higher at the hot ambient temperatures compared to the mild conditions, which is expected. However, there is no consistent trend between hot and cold conditions, when the APU is required to either cool or heat the tractor cabin. For APU ID 1 and 4, the cold temperatures had higher CO_2 emissions and fuel use. For APU ID 5 and 6, the hotter temperatures had higher CO_2 emissions and fuel use.

For criteria emissions (CO, NO_x, THC, and PM) there are conflicting trends with respect to ambient temperature. For APU 2 and 3, NO_x and PM emissions are higher at the hot conditions compared to mild conditions, consistent with the higher fuel use. However, CO shows lower emissions at hot conditions, and THC shows a mixed trend. For the other studies, there is no consistent trend in the criteria emissions between the hot and cold conditions.

Table 2-52. In-Use APU Emission Rates

APU ID	CO_2 (g/hr)	CO (g/hr)	NO_x (g/hr)	THC (g/hr)	PM (g/hr)	Fuel (gal/hr)	Ambient condition	Temperature (℉)	DPF present
1	4340	7.3	18.6	1.35	0.96	0.43	Cold	0	No
1	4270	5.1	20.0	0.73	0.02	0.43	Cold	0	Yes
1	2820	6.2	23.5	1.35	0.56	0.29	Hot	100	No
1	2800	5.2	23.7	1.52	0.03	0.28	Hot	100	Yes
2	3000	20.4	6.3	1.4	1	0.3	Mild	60[a]	No
3	2500	7.2	13.4	1.3	0.8	0.25	Mild	60	No
2	3900	13.9	11.5	1.5	1.3	0.38	Hot	100	No
3	3600	6.3	20.2	1	1.2	0.36	Hot	100	No
4	3100	5.8	19	1.3	1.23	0.3	Hot	100	No
5	3600	7.3	24	0.8	0.58	0.35	Hot	100	No
4	4000	3.9	22	1.2	0.75	0.39	Cold	0	No
5	2800	24	14	2.4	0.98	0.28	Cold	0	No
6	2146	25	8.7	7.8	0.48	0.22	Cold	0	No
6	2351	10.8	11.4	4.2	1.00	0.24	Hot	90	No

Note:
[a] Frey and Kuo 2009 report the mild condition for auxiliary loads on the trucks is for ambient temperatures ranging from 10-20℃ (50-68℉)

Because the only notable trend in the APU emissions data was the large decrease in PM emission rates with the use of a DPF, in developing baseline MOVES emission rates, we used the "no DPF" results from TTI, 2014 and Frey and Kuo, 2009 (APU ID 1, 2, and 3). We first averaged the emission rates within the cold, hot, and mild conditions as shown in Table 2-53.

Table 2-53. Average APU Emission Rates from non-DPF APU IDs 1, 2, and 3 according to Cold, Hot, and Mild Ambient Conditions

CO_2 (g/hr)	CO (g/hr)	NO_x (g/hr)	THC (g/hr)	PM (g/hr)	Fuel (gal/hr)	Ambient condition	Temperature (℉)	DPF present
4340	7.27	18.59	1.35	0.96	0.43	Cold	0	No
3440	8.80	18.41	1.28	1.02	0.34	Hot	100	No
2750	13.80	9.85	1.35	0.90	0.28	Mild	60	No

Next, we calculated a fleet-average APU emission rate. Similar to our treatment of the extended idle emission rates, we equally weighted the different ambient conditions. For APUs, we weighted each ambient condition (Cold, Hot, and Mild) equally in developing the fleet-average emission rate shown in Table 2-55.

We estimated elemental carbon (EC) fraction of PM from composition measurements made on APU ID 1 as reported in Appendix J . For each test, we calculated the elemental carbon/total carbon ratio, and then averaged the ratio across all cold and hot tests, separately for the DPF and the non-DPF tests as shown in Table 2-54. We assumed that total carbon (TC) is a reasonable approximation of the total $PM_{2.5}$ emissions from the APU, and we used the EC/TC ratio from the non-DPF tests as the source of the EC/PM fraction to derive the EC and nonEC emission rates in Table 2-55.

Table 2-54. Average Elemental Carbon/Total Carbon Ratio for APU ID 1 without and with a Diesel Particulate Filter

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

Table 2-55. Fleet-Average Non-DPF Equipped APU Emission Rates in MOVES_CTI_NPRM

CO_2 (g/hr)	CO (g/hr)	NO_x (g/hr)	THC (g/hr)	PM (g/hr)	EC (g/hr)	NonEC (g/hr)	EC/PM	Fuel (gal/hr)
3510	10.0	15.6	1.3	0.96	0.13	0.83	0.14	0.35

The HD GHG Phase 2 rule implements a phase-in standard that requires APUs installed in new tractors to meet lower PM standards in 2021 and 2024 (beyond the Tier 4 nonroad standards).[m] The APU PM standards along with the current Tier 2 and Tier 4 nonroad standards for nonroad diesel engines 8≤kW<19 (11≤hp<25) are shown in Table 2-56.[96]

Table 2-56: Nonroad Tier 2, Nonroad (8≤KW<19) Tier 4, and HD GHG Phase 2 Emission Standards

Emission Standard	CO g/kW-hr (g/hp-hr)	NMHC + NO_x g/kW-hr (g/hp-hr)	PM g/kW-hr (g/hp-hr)
Tier 2 2005-2007	6.6 (4.9)	7.5 (5.6)	0.8 (0.6)
Tier 4 2008-2020	6.6 (4.9)	7.5 (5.6)	0.40 (0.30)
APU 2021-2023			0.15 (0.11)
APU 2024+			0.02 (0.01)

We developed the projected APU emission rates due to the new standards by comparing the manufacturer submitted emission levels of two engines commonly used in APU systems based on the engine information and emission levels obtained from the publicly available US EPA nonroad certification database. The development of these rates are described in the HD GHG Phase 2 MOVES documentation and summarized here.[97]

We anticipate that the APU manufacturers will meet the 2021 PM standard by modifying the engine control strategy (such as using leaner air fuel mixture) rather than by using an aftertreatment such as a diesel particulate filter. Such a strategy is likely to lead to increased NO_x emissions, and when we observed a decrease in PM emissions between the 2012 and 2013 certified APU engines, there was an accompanying 25 percent increase in NO_x emissions. Thus, we conservatively estimated a slight NO_x disbenefit in obtaining a lower PM standard. We estimated the in-use APU NO_x emissions for 2021-2023 by multiplying the baseline emissions by 1.25 (15.6 * 1.25 = 19.5 g/hr). We do not anticipate any increases to occur in CO_2, CO, or THC emissions with the 2021 standard, and estimated the emissions will not change in 2021 for these pollutants.

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[m] See 40 CFR 1037.106(g).

To achieve the 2024 APU PM standard, we anticipate APU manufacturers will be required to use DPF aftertreatment. The average PM emission rate from the DPF-equipped APU ID 1 tests was 0.025 g/hr (Table 2-52), which is similar to the extended idle PM emission rate for 2013+ trucks (Table 2-49) of 0.021 g/hr. We do not believe the data are sufficient to determine a difference in PM emission rates between APU and main engine extended idling when both engines are equipped with diesel particulate filters. Thus, we used the extended idle 2013+ extended idle PM emission rate for the APU emission PM emission rate for 2024 and later model years (Table 2-49). We used the EC/PM split measured from the DPF-equipped APU (Table 2-54) to estimate the EC and nonEC emission rates.

From the in-use testing of APU ID 1, we did not observe a meaningful impact on the CO_2, CO, NO_x, and THC emissions with the use of the DPF. Thus, for the model year 2024 and later APUs, we maintained the same emissions rates as were used in the 2010-2020 model year group. The emission standard adjusted APU emission rates by model year group are shown in Table 2-57.

Table 2-57 APU Emission Rates in MOVES_CTI_NPRM with APU PM Controls in the HD GHG Phase 2 Program

Model Year	CO_2 (g/hr)	CO (g/hr)	NO_x (g/hr)	THC (g/hr)	PM (g/hr)	EC (g/hr)	NonEC (g/hr)	EC/PM	Fuel (gal/hr)
2010-2020[1]	3510	10.0	15.6	1.3	0.96	0.13	0.83	0.14	0.35
2021-2023	3510	10.0	19.5	1.3	0.32	0.044	0.28	0.14	0.35
2024-2050	3510	10.0	15.6	1.3	0.021	0.0015	0.019	0.073	0.35

Note:
[1] The default APU allocation in MOVES assigns APU usage beginning in model year 2010. If MOVES users specify APU usage in years previous to 2010, it will use the 2010-2020 APU emission rate.

2.5 Glider Vehicle Emissions

"Glider vehicles" or "Gliders" refer to the vehicles with old powertrain (engine, transmission and/or rear axle) combined with a new chassis and cab assembly. Most of them are Class 8 heavy heavy-duty vehicles and they typically use model year 2001 or older remanufactured engines that do not have to use emissions controls such as DPF or SCR to meet the stringent PM and NO_x standards starting MY 2007+. [98]

Starting with MOVES_CTI_NPRM, we model the emission impacts of the glider vehicles as a separate regulatory class (regClassID 49) because their population became significant starting with model year 2008 as described in the Population and Activity Report.[11]

For modeling purpose, all glider vehicles are presumed to be combination trucks (sourceTypeID 61 and 62) running on diesel fuel. EPA's in-house glider vehicle emission testing data[99] suggest that the glider vehicles' running exhaust emissions for THC, NO_x, PM, and CO_2 (used to estimate energy use rates) are comparable, while CO from glider vehicles is higher, to MOVES emission rates for the model year 2000 heavy heavy-duty (regClassID 47) fleet. See Appendix H for the comparison of glider (based on EPA's in-house testing) versus MOVES2014 rates, that was the basis for selection of MY 2000 rates as representative of glider vehicles. Therefore, in MOVES, the glider vehicles' running, start, and extended idling exhaust rates for all model years are set equal to those of the model year 2000 heavy heavy-duty vehicles, respectively. For example, Figure 2-53 shows a comparison of the running exhaust emission rates (for age 0-3 group) of regClass=47 (heavy heavy-duty) vs. regClass=49 (glider vehicles) for selected pollutants (NO_x, ECPM, NonECPM) and model year groups. It can be seen that the rates for the two regulatory classes are identical for model year 2000. For later model years, however, the emissions rates for regular heavy heavy-duty vehicles are significantly lower due to more stringent emission standards, whereas the rates for glider vehicles stay the same at the model year 2000 levels.

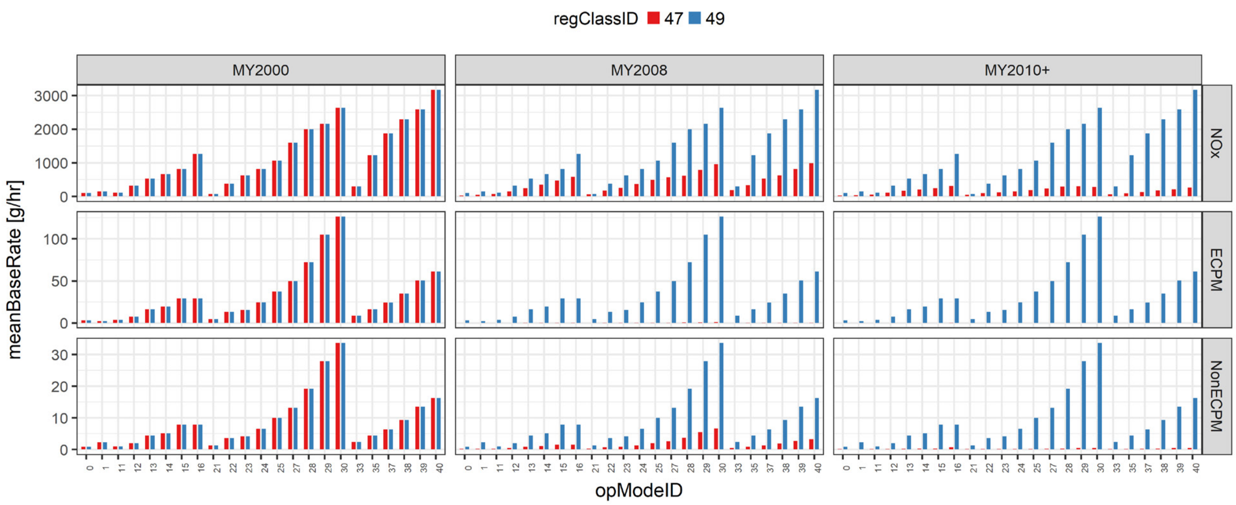

Figure 2-53. Comparison of the running exhaust emission rates (age0-3 group) of regClass=47 (HHD) vs. regClass=49 (glider vehicles) for selected pollutants (NO_x, ECPM, NonECPM) and model year groups

The auxiliary power unit (APU) exhaust emission rates of the glider vehicles, on the other hand, are set equal to those of regular (non-glider) heavy heavy-duty vehicle fleet. This is consistent with our assumption that glider vehicles have the same vehicle characteristics (non-powertrain related ones such as APU, aerodynamics, rolling resistance, brake and tire wear PM rates) as the regular heavy heavy-duty vehicles.

3 Heavy-Duty Gasoline Emissions

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

3.1 Running Exhaust Emissions

3.1.1 HC, CO, and NO_X

3.1.1.1 Data and Analysis for 1960-2007 Model Year Trucks

As gasoline-fueled vehicles are a small percentage of the heavy-duty vehicle fleet, the amount of data available for analysis was small. We relied on four medium heavy-duty gasoline trucks from the CRC E-55 program and historical data from EPA's Mobile Source Observation Database (MSOD)[100], 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 1-4). To supplement the available data, we examined certification data as a guide to developing model year groups for analysis. Figure 3-1 shows averages of certification results by model year.

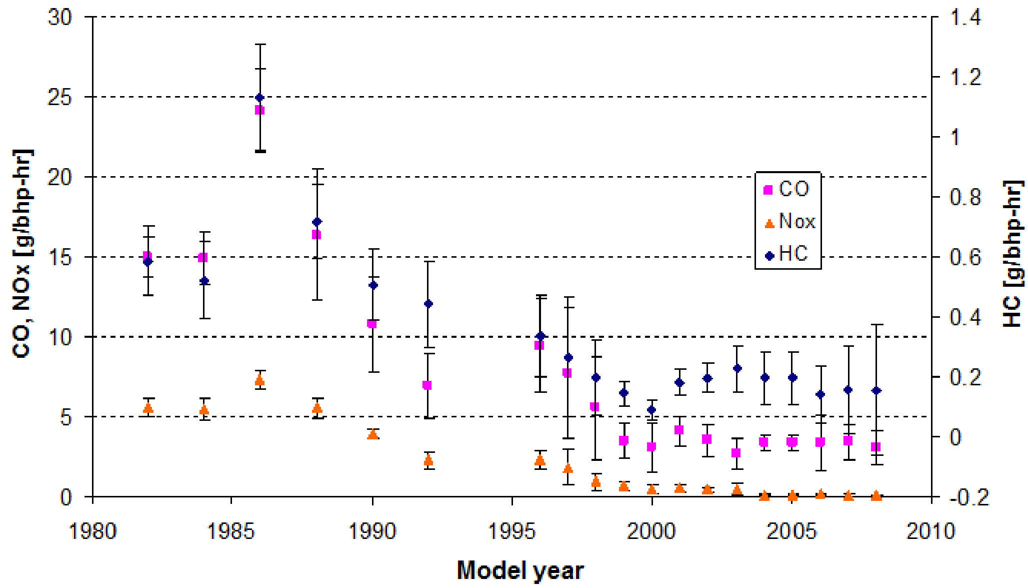

Figure 3-1 Brake-Specific Certification Emission Rates by Model Year for Heavy-Duty Gasoline Engines

Based on these certification results, we decided to classify the data into the coarse model year groups listed below.

- 1960-1989
- 1990-1997
- 1998-2007

Unlike the analysis for HD diesel vehicles, we used the age effects present in the data itself. We did not incorporate external tampering and mal-maintenance assumptions into the HD gasoline rates. Due to sparseness of data, we used only the two age groups listed in Table 3-1. We also did not classify by regulatory class since there was not sufficient data to estimate emission rates by separate regulatory classes. The derivation of the model year 2008 and later emission rates are discussed in Sections 3.1.1.3 and 3.1.1.4.

3.1.1.2 LHD Running Emission Rates for 1960-2007 Model Years

The emission rates for LHD (LHD2b3 and LHD45, regClassID 41 and 42, respectively) were analyzed by binning the emission measurements using the STP with a fixed mass factor of 2.06 (Table 1-4). Figure 3-2 shows all three pollutants vs. operating mode. In general, emissions follow the expected trend with increasing STP, though the trend is most pronounced for NO_x. As expected, NO_x emissions for light heavy-duty gasoline vehicles are much lower than for light heavy-duty diesel vehicles.

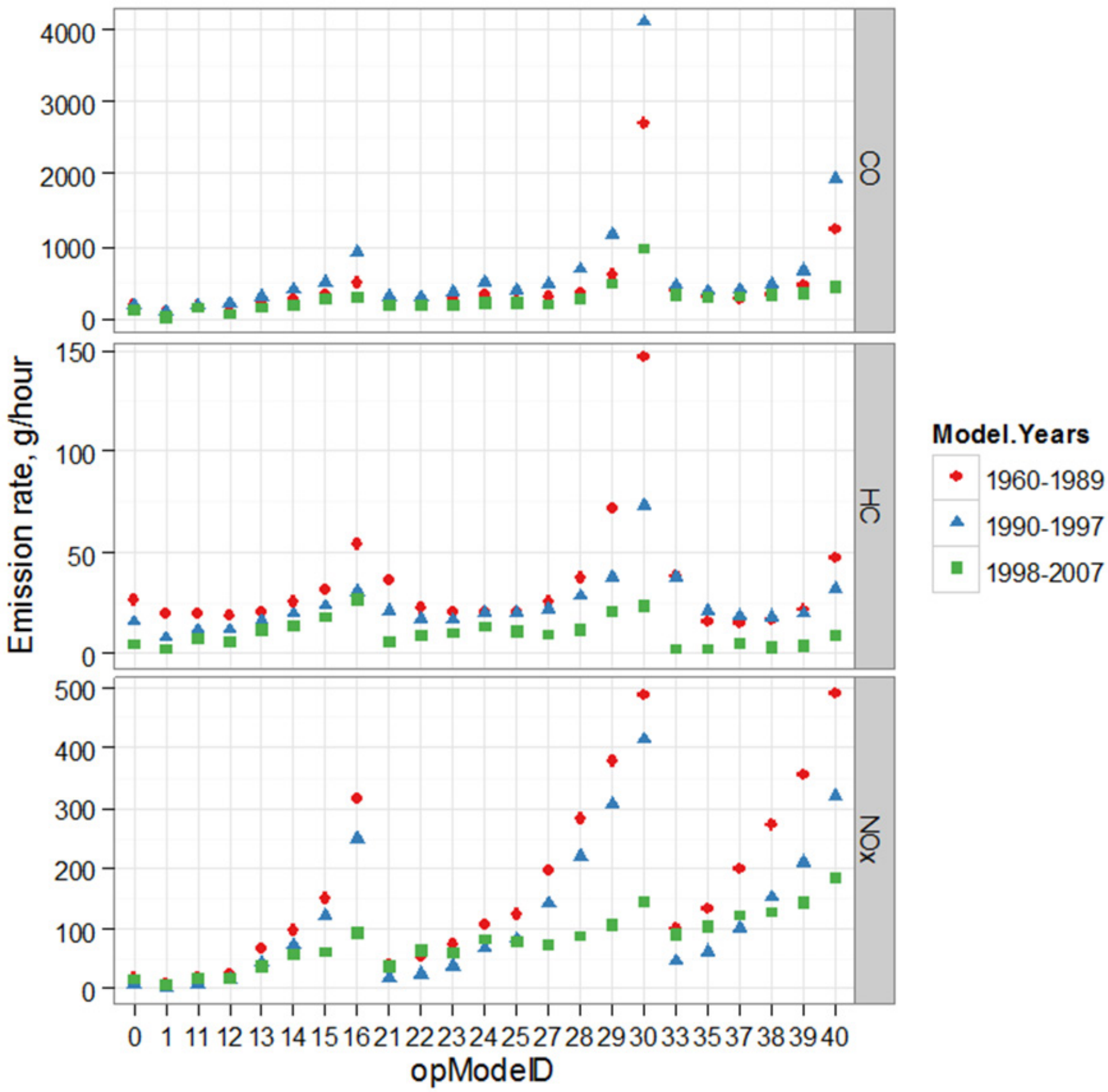

Figure 3-2. Emission Rates by Operating Mode for MY Groups 1960-1989, 1990-1997, and 1998-2007 at Age 0-3 Years for LHD2b3 and LHD45 vehicles

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.

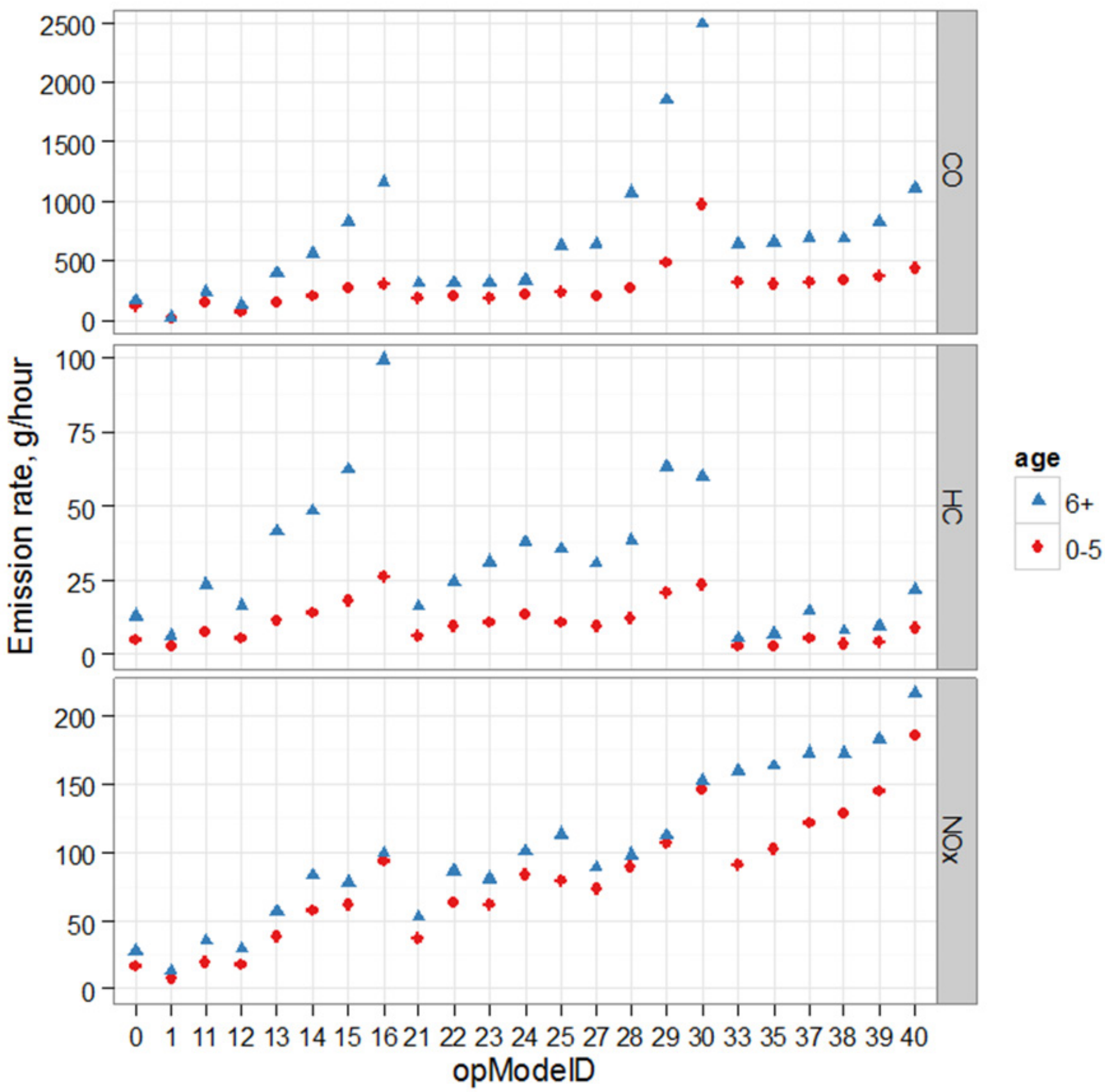

Figure 3-3. Emission Rates by Operating Mode and Age Group for MY 1998-2007 Vehicles in Regulatory Class LHD2b3 and LHD45

Table 3-2 displays the multiplicative age effects by operating mode for LHD gasoline vehicles. The relative age effects are derived from the sample of vehicle tests summarized in Table 3-1. The multiplicative age effects are used to estimate the aged emission rates (ages 6+) years from the base emission rates (ages 0-5) for HC, CO, and NO_x. These multiplicative age effects apply to all model year groups between 1960 and 2007. As discussed earlier, we derived multiplicative age effects from the pooled data across the three model year groups and regulatory classes to develop the multiplicative age effects due to the limited data set.

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

OpModeID	HC	CO	NO_x
0	2.85	1.45	1.67
1	2.43	1.79	1.85
11	3.12	1.66	1.88
12	2.85	2.05	1.69
13	3.55	2.68	1.48
14	3.43	2.84	1.46
15	3.37	3.03	1.26
16	3.76	3.88	1.06
21	2.78	1.67	1.42
22	2.64	1.64	1.36
23	2.96	1.67	1.32
24	2.83	1.62	1.21
25	3.23	2.79	1.43
27	3.21	3.20	1.21
28	3.20	4.04	1.11
29	3.00	3.90	1.05
30	2.55	2.56	1.05
33	1.95	2.00	1.77
35	2.67	2.20	1.59
37	2.80	2.24	1.42
38	2.46	2.06	1.34
39	2.46	2.30	1.27
40	2.47	2.59	1.17

3.1.1.3 LHD for 2008 and 2009 Model Years

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

Gasoline vehicles in 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).[n]

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

Table 3-3 Useful Life FTP Standards from the Tier 2[101] and 2007 Heavy-Duty Highway[102] Rules

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

The relative proportions of the vehicles within the LHD2b3 regulatory class vary each year depending on demand. Consequently, we estimated proportions based on a combination of data for recent model years and engineering judgment. MOBILE6 documentation from 2003 indicates that MDPVs were approximately 16 percent of the gasoline-powered trucks in the 8,500 to 10,000 lb weight class.[103] In MOVES2014, we project that MDPVs are 15 percent of total MOVES LHD2b3 regulatory class. The MOBILE6 document also states that more than 95 percent of class 2B trucks are chassis certified.[103] Thus, we estimate that 5 percent of all vehicles in the LHD2b3 regulatory class are engine certified. Based on analysis from the recent medium and heavy-duty greenhouse-gas rulemaking, we assume that sales of class 2b trucks were triple that of class 3 trucks.[104] This estimate is roughly consistent with recent sales totals. [105] Combining these assumptions, we estimate the sales fractions shown below (Table 3-4).

Table 3-4 Population Percentage of LHD2b3 Trucks

Truck Category	Fraction (%)
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.[p] While the model produces estimates of onroad emissions rather than certification emissions, the weighted certification standard is a useful benchmark for the modeled rates (Table 3-5).[q]

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

Pollutant	Cycle Composite (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),[38]

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

modified to produce Scaled Tractive Power (STP) distributions, was used to generate the operating mode distribution for 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). For this typical vehicle, the modified version of PERE produced the operating mode distribution shown in Table 3-6.

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

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

Combining this operating-mode distribution with emission rates from the MOVES database for the age 0-3 group, we estimated running emissions for the start and hot-running phases of the FTP. In addition, we extracted rates for "cold start" (operating mode 108) and "hot start" (operating mode 102) from the MOVES database, for the age 0-3 group.
Using these components, we constructed a simulated FTP out of four components (running emissions for Bags 1 and 3,[r] running emissions for Bag 2, cold start and hot start). We constructed bag 1 (cold start + bag 1 running) and bag 3 (hot start + bag 3 running) and weighted the resulting components following the formula for the FTP composite.[s]
We then compared the simulated FTP composites for MY 2008 to the aggregate standards calculated above (Table 3-7). MOVES2010a estimates at age 0-3 were two to ten times higher than the standard, indicating that the average HD gasoline-powered vehicle in MOVES2010a is modeled as significantly out of compliance with the relevant emission standards.

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[r] Bag 1 and Bag 3 are considered to have the same emission rate.
[s] FTP = ((Bag 1 + Bag 2)*0.43+ (Bag 3+ Bag 2)*0.57)/ 7.45

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

	MOVES2010 FTP for MY 2008 LHD2b3 Trucks (g/mile)	LHD2b3 Aggregate FTP Standard (g/mile)	Ratio – MOVES to Aggregate Standard
NMOG	0.36	0.18	1.93
CO	14.54	7.49	1.94
NO_x	2.04	0.22	9.28

3.1.1.3.2 Validation against In-Use Verification Program Data

As an additional step, we compared data from the In-Use Verification Program (IUVP) for MY 2004-2008 (estimated test weights of 7,500 pounds to 10,000 pounds) to the MOVES emission rates.[t] We evaluated whether vehicles in these model year groups 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 calculated average ratios of test value to the aggregate standard (Table 3-8) of 0.42 (NMOG) and 0.23 (NO_x). These ratios indicated that vehicles typically comply with the standard, with a substantial compliance margin. The distribution of the data is shown in Figure 3-4.

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

	Average	Average
	Ratio Certification FTP/Aggregate Standard	Compliance margin
NMOG	0.42	0.58
NO_x	0.23	0.77

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

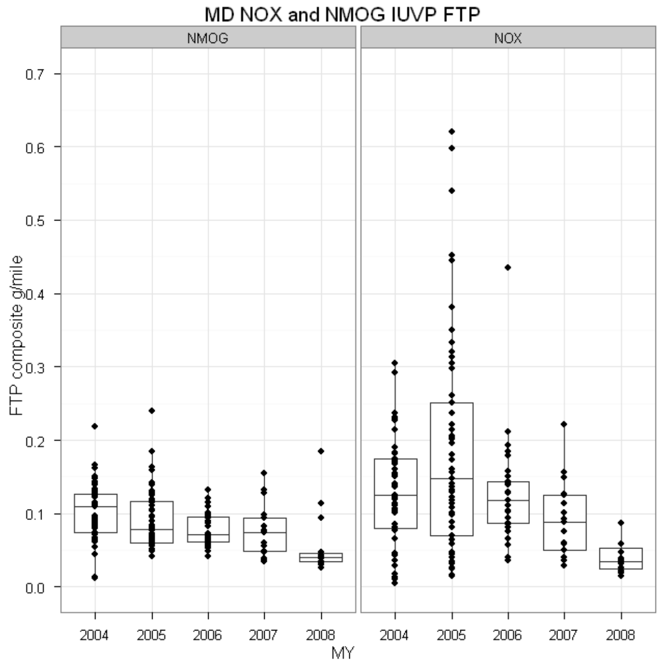

Figure 3-4. Distribution of IUVP FTP Tests for LHD2b3 Trucks

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.[u] However, the emission rates in MOVES2010 are higher than levels expected from vehicles compliant with the standards in place in MY 2008 and later. As a consequence, we made the revisions to the LHD2b3 rates for MY 2008 and 2009 as described in Section 3.1.1.3.3 below.

3.1.1.3.3 LHD2b3 Emission Rates for 2008 and 2009

This section documents the HC/CO/NO_x emission rates for regulatory Class LHD2b3 (regClassID 41) vehicles in model year 2008 and 2009.

In conducting this analysis, we lacked any modal data on regulatory class LHD2b3 (regClassID 41) vehicles. As such, we conducted the analysis using a method that we have used repeatedly for light-duty vehicles, which is ratioing the modal emission profile by the difference in standards.[10] By MY 2008, the LHD2b3 are nearing the emission levels of light-duty vehicles certified to the Tier-2 Bin-8 standard. Consequently, we relied on the analysis of in-use Tier 2 Bin 8 vehicles conducted for the light-duty emission rates.[10] Although the light-duty rates are based on VSP, rather than STP, adapting them for the LHD2b3 rates is reasonable for two reasons: First, we are using a 2.06 f_{scale} which is equivalent to the average source mass of light-commercial trucks. In addition, in the derivation of the light-duty rates, we assume that the individual vehicle mass did not vary substantially from 2.06 metric tons. Second, most LHD2b3 gasoline vehicles are chassis certified to

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

distance-based standards (g/mi). Accordingly, these facts suggest that a VSP-based method is a robust approach for modeling vehicles certified to g/mile rates.

Based on these assumptions, we scaled modal rates for Tier 2 Bin 8 vehicles by the ratio of FTP standards so that the rates would be consistent with the higher emission rates of regulatory class LHD2b3 (regClassID 41), as shown in Table 3-9.

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

	Aggregate LHD2b3 FTP standard	Bin 8 FTP standard	Aggregate/Bin 8
NMOG	0.18	0.1	1.8
CO	7.49	3.4	2.2
NO_x	0.22	0.14	1.6

We took an additional step to "split" these ratios into "running" and "start" components, such that the running rates increased twice as much as the start rates, while maintaining the same simulated value for the FTP composite. This split ratio is consistent with typical emission reduction trends, where running emissions are reduced about twice as much as start emissions.[10] 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 LHD2b3 (regClassID 41) Emission Rates for 2008-2009 MY

	HC	CO	NO_x
Running	2.73	2.73	1.95
Start	1.37	1.37	1.00

We also adopted the light-duty deterioration effects and applied them to the 2009 regulatory class LHD2b3 (regClassID 41) emission rates. The light-duty emission rates have age effects that change with each of the 6 age groups in MOVES, as shown in Table 3-11.

Table 3-11 Multiplicative Age Effect used for Running Emissions for Regulatory Class LHD2b3 (regClassID 41) 2009 Model Year

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

After applying the steps described above (scaling the emission factors by ratio of FTP standards, and applying light-duty deterioration trends), we restricted the scaled data so that the individual emission rates by operating mode were never scaled to be higher than MY 1998-2007 regulatory class LHD2b3 (regClassID 41) rates. This step essentially "capped" the emission rates, such that none of the modal rates for MY 2009 are higher than their counterparts for MY 2007 and earlier. MY 2008 rates are interpolated between MY 2007 and MY 2009 emission rates as discussed later.

This final step "capped" the model-year 2009 emission rates in the highest operating modes, as shown in Figure 3-5. For HC, emission rates in operating modes 28-30 and 38-40 were capped for some or all age groups by the pre-2007 emission rates. For CO, emission rates in 12 of the 23 running operating modes (1, 16, 23-24, 27-30, 35-40) were capped by the pre-2007 rates. None of the NO_x emission rates were impacted by this step. Figure 3-5 shows the regulatory class LHD2b3 (regClassID 41) model year 2008-2009 emission rates for CO, HC, and NO_x. In the figure, rates "capped" by the pre-2007 rates exhibit the uncharacteristic "stairstep" deterioration trends. Even with the "capping" effects, the rates for regulatory class LHD2b3 (regClassID 41) are higher than those for light-duty trucks (regClassID 30), with a few exceptions. The few exceptions are some of the age-dependent HC and or CO emission rates in operating modes 1, 30, 38, 39, and 40. However, the majority of emission rates are considerably higher for the heavy-duty (LHD2b3) than for the light-duty trucks. Similarly, when the FTP is simulated from the resulting rates, estimated composites are substantially higher for LHD2b3 than for light-duty trucks.

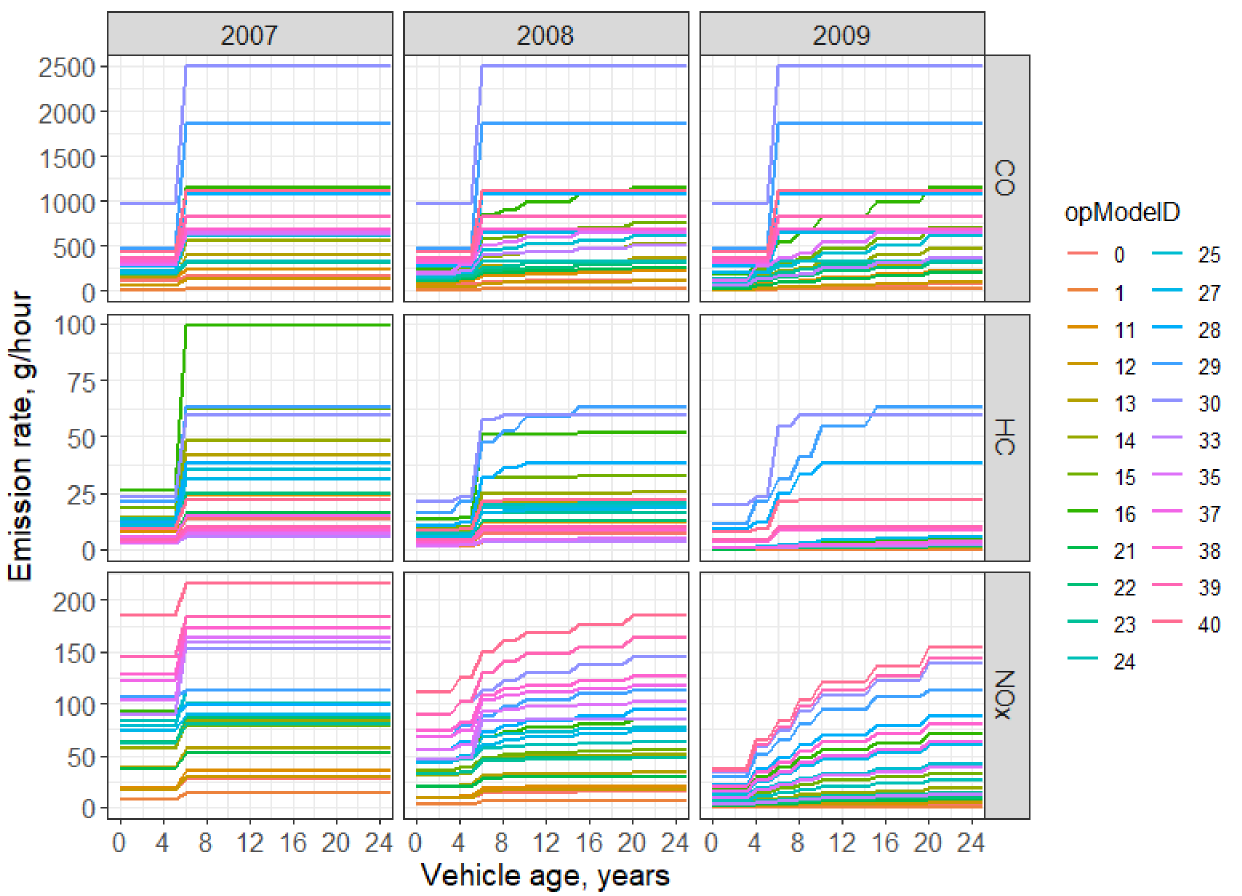

Figure 3-5. Age Effects for CO, HC, and NO_x Emission Rates for Regulatory Class LHD2b3 (regClassID 41) Vehicles in Running Operating Modes for MY 2007, 2008 and 2009

After calculating new regulatory class LHD2b3 (regClassID 41) emission rates, we used the emission rates for age group 0-3 to simulate an FTP cycle, as shown in Table 3-12. We compared these emission rates to the calculated aggregate standard. The calculated headroom for NO_x is less than that shown in the IUVP data, and the calculated headroom for NMOG is greater than that shown in the IUVP data (Table 3-8). For NO_x, this difference is more significant. However, as stated above, the IUVP data is not fully representative of in-use vehicles. By contrast, the Tier 2 Bin 8 rates are based on extensive I/M testing and are considered more representative of the entire fleet.

Table 3-12 Ratio of Final Rates against Standards

	Simulated LHD2b3 regulatory class - 2009 FTP (g/mile)	Aggregate 2010+ LHD2b3 FTP Standard (g/mile)	Simulated FTP emissions/ Aggregate FTP Standard
NMOG	0.06	0.18	33%
CO	3.08	7.49	41%
NO_x	0.18	0.22	84%

In terms of the phase-in of the Light-duty Tier 2 and 2007 Heavy-Duty Highway Rules (Table 3-3), we assumed that the regulatory class LHD2b3 (regClassID 41) rates phase in at a rate of 50 percent in MY2008 and considered fully phased in MY2009. The MY2008 running emission rates are interpolated values between the 2007 and 2009 emission rates by operating mode and age group.

3.1.1.3.4 LHD45 Emission Rates for 2008 and 2009

Due to limited data on LHD45 vehicles, we applied the LHD2b3 emission rates developed in the previous section to the LHD45 emission rates.

3.1.1.4 MHD and HHD for 1960-2007 Model Years

Emission rates are equivalent across all the heavy-duty gasoline regulatory classes: MHD and HHD. Like the LHD rates described above, the heavy-duty gasoline rates are based on emissions data from the mix of LHD2b3 and MHD vehicles outlined in Table 4-1. The same model year groups are used to classify the emission rates: 1960-1989, 1990-1997, and 1998-2007. Also, we use the same relative increase in emission rates for the age effect. The only difference from the analysis of LHD emission rates is that the regulatory class MHD and HHD emission rates were analyzed using STP operating modes with a fixed mass factor of 17.1. Sample emission rates for HC, CO, and NO_x for the 1994 MY Group are presented in Figure 3-6 for these regulatory classes.

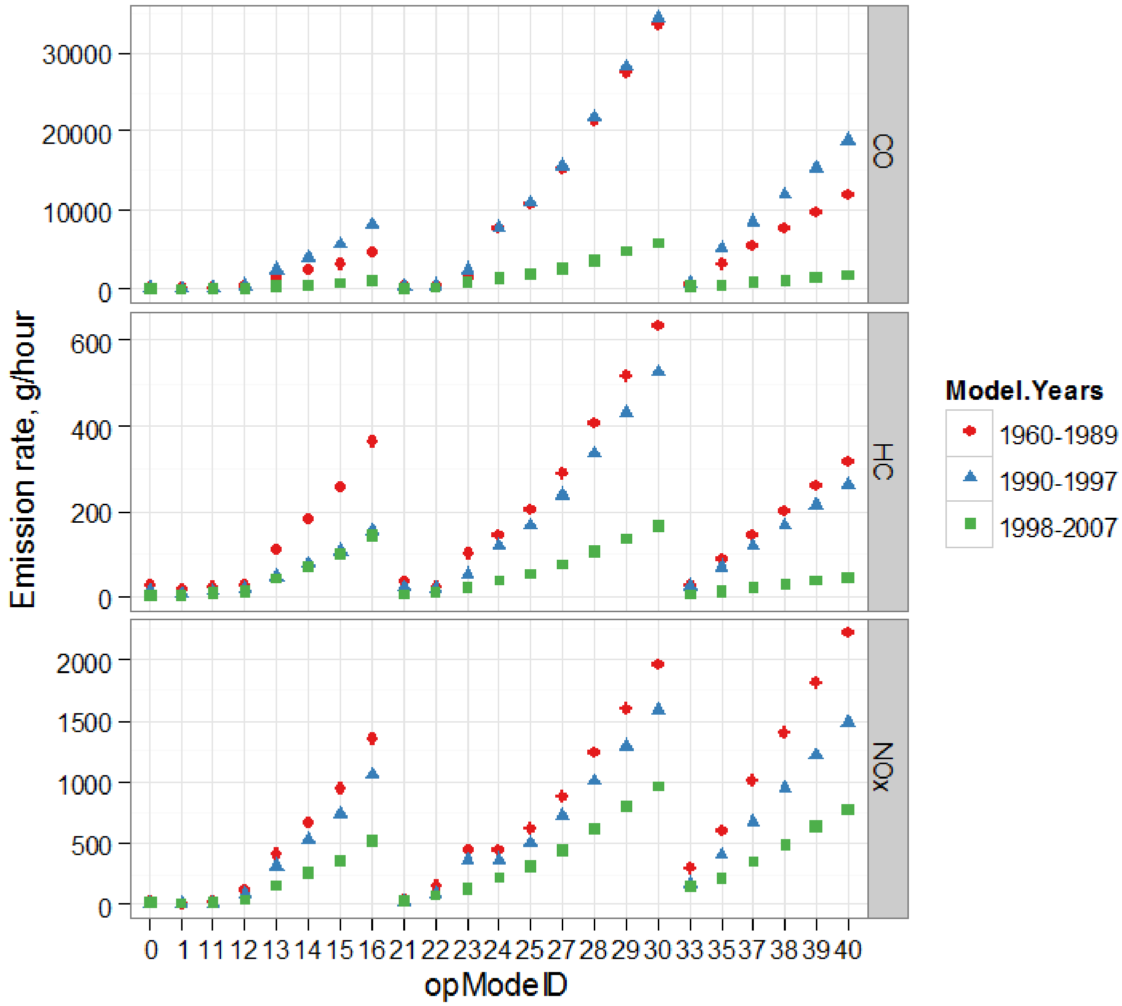

Figure 3-6. Emission Rates by STP Operating Mode for MY 1994 at age 0-3 years for Regulatory Class MHD and HHD

Table 3-13 displays the multiplicative age effects by operating mode for MHD, and HHD gasoline vehicles. While these age effects were derived from the same data as those for the LHD vehicles, these heavy-duty age effects are slightly different 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 age effects. Also, because the vehicles tested were LHD2b3 and MHD vehicles, no data were available in the high STP power modes (typically only a HHD truck would reach these). Thus, the higher operating modes (opModeID 13-16, 24-30, and 35-40 use the same values as the closest operating mode bin with data).

Table 3-13 Relative Age Effect on Emission Rates between Age 6+ and Age 0-5 for MHD and HHD Gasoline Vehicles in All Model Years 1960-2050

OpModeID	HC	CO	NO_x
0	2.85	1.45	1.67
1	2.43	1.79	1.85
11	3.12	1.66	1.88
12	3.36	3.12	1.13
13	3.53	3.16	1.11
14	3.53	3.16	1.11
15	3.53	3.16	1.11
16	3.53	3.16	1.11
21	2.78	1.67	1.42
22	3.08	2.59	1.23
23	2.97	3.31	1.05
24	1.80	1.54	1.03
25	1.80	1.54	1.03
27	1.80	1.54	1.03
28	1.80	1.54	1.03
29	1.80	1.54	1.03
30	1.80	1.54	1.03
33	2.45	2.41	1.33
35	2.16	2.41	1.19
37	2.16	2.41	1.19
38	2.16	2.41	1.19
39	2.16	2.41	1.19
40	2.16	2.41	1.19

Figure 3-7 displays the resulting emission rates by operating mode bin and age group for the LHD45, MHD, and HHD gasoline vehicles, which were calculated by applying the multiplicative age effects in Table 3-13.

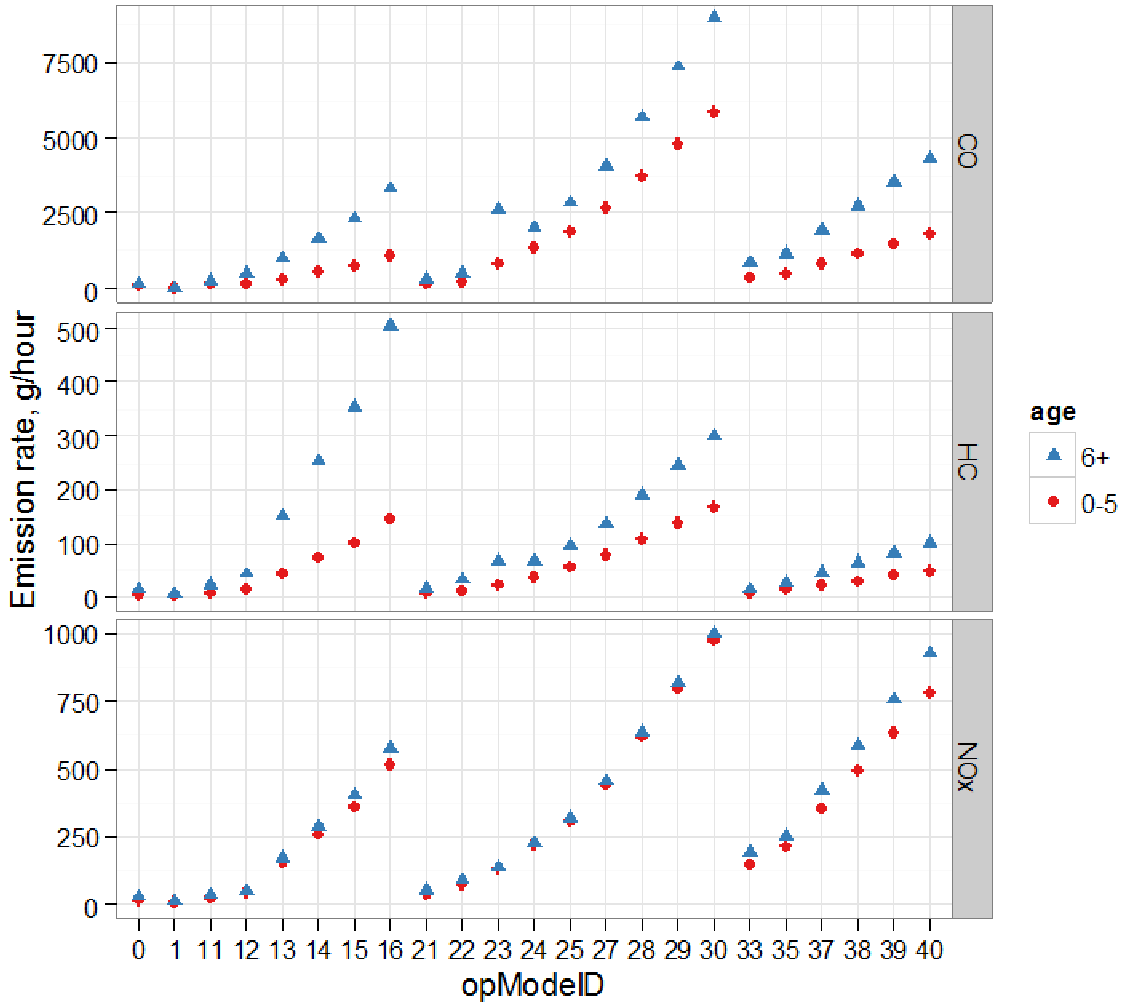

Figure 3-7. Emission Rates by Operating Mode and Age Group for MY 1998-2007 Vehicles in Regulatory Class MHD and HHD Gasoline Vehicles

3.1.1.5 MHD and HHD for 2008 and 2009 Model Years

Of the onroad heavy-duty vehicles GVWR Class 4 and above, a relatively small fraction are powered by gasoline: about 15 percent are gasoline, as opposed to 85 percent diesel.[v] The gasoline percentage decreases as the GVWR class increases. Since these vehicles are a small portion of the fleet, there is relatively little data on these vehicles, and we did not update the 2008 and 2009 model year emission rates from MOVES2010.[106] The 2008 and 2009 model years are modeled with a 70 percent reduction in the running rates starting in MY 2008, which is consistent with the emission standard reduction with the "Heavy-Duty 2007 Rule".[107] The 2008 and 2009 model year emission rates have two age groups (0-5, and 6+) and the same relative multiplicative age effects as the pre-2007 emission rates (Table 3-13).

3.1.1.6 LHD, MHD, and HHD for 2010 and later Model Years

In MOVES_CTI_NPRM, we updated the HC, CO, and NO_x emissions rates for MY 2010+ gasoline vehicles for all heavy-duty regulatory classes (41 – 47). The updated rates are based on analysis of real-world PEMS-based emissions measurement data from two engine-certified and one chassis-certified heavy-duty gasoline vehicles (Table 3-14) with model years between 2015-2017. The testing was conducted by US EPA over various test cycles in the Ann Arbor, Michigan area. The test matrix covered a range of vehicle operation that included:

1. Two idling tests of 15- or 30-minutes duration
2. Seven on-road driving routes that cover the full range of power demand by including transient low- and medium-speed urban driving to steady-state high-speed highway driving
3. Soak times ranging from zero minutes (hot start) to 720 minutes (cold start)
4. Vehicle weight at low or high (Table 3-14)
5. Air conditioning on or off
6. Cabin windows down or up

A total of 202 tests across vehicles and operation modes was available for data analysis. These tests covered about 412,000 seconds of post-QA operation. We removed the effect of warm and cold starts from the operation since the running emissions are expected to be just the hot running operation (section 3.1.1.6.1). After removal of vehicle operation related to start emissions, the final data set used for just the hot running emissions rates update was about 390,000 seconds.

Operating modes (Table 1-3) were assigned to the 1 hz data using the STP equation (Equation 1-4) with road-load coefficients for sourceType 52 (single-unit short-haul truck) for MY 2014-2020 period as defined in the *sourceusetypephysics* table in MOVES_CTI_NPRM database. The values for sourceType 52 are the same for regClasses 41-47. The road-load coefficient values used are:

rollingTermA = 0.596526 [kW.sec/m]
rotatingTermB = 0 [kW.sec^2/m^2]
dragTermC = 0.00160302 [kW.sec^3/m^3]

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

For vehicle mass, we used the actual test weight (Table 3-14). Road-grade was not available, so it was set to zero. The entire data set was analyzed with the new f_{scale} values (Table 1-4) of 5 (LHD2b3 and LHD45), 7 (MHD), and 10 (HHD). The selection of these new f_{scale} values was based on the diesel HDIUT dataset and is described in Appendix G.

Steps to calculate the OpMode-based emission rates for each of LHD, MHD, and HHD:

1. Assign OpModes as per the method described above and calculate the average rate per OpMode per test per vehicle
2. Calculate the average OpMode-based rate per vehicle (using only vehicle specific tests)
3. Calculate the final OpMode-based emission rate as the sales weighted average of the three test vehicles. Note that these three vehicles are using the most popular engine configurations for recent model year heavy-duty gasoline vehicles and thus, together, they represent a large fraction of the total heavy-duty gasoline fleet.

Each of the HD gasoline vehicles has three-way catalyst (TWC) technology to control HC, CO, and NO_x emissions. However, one key difference compared to light-duty gasoline vehicle TWC configuration is that the HD gasoline engine-certified vehicles do not use a close-coupled TWC. There might also be differences in catalyst precious metal loading and in-cylinder combustion control for maximum TWC efficacy. The reason for these differences is that engine-certified and chassis-certified gasoline spark-ignited vehicles have to meet different standards. Thus, ideally, the emission rates from these engine-certified HD gasoline vehicles would be used to update only the LHD45, MHD, and HHD regClasses since they are made up of almost exclusively engine-certified vehicles. However, we also applied the rates calculated for the LHD45 regClass to LHD2b3 because the existing MY 2010+ rates for LHD2b3 are based on mostly pre-1998 vehicles (Table 3-1). Thus, the base emission rates for MY 2010+ LHD2b3 and LHD45 are identical. However, the LHD2b3 rates are further modified by applying the Tier 3 reductions phased-in from MY 2018 to 2022 (section 3.1.1.7).

Table 3-14 Summary of MY 2010+ Heavy-Duty Gasoline Vehicles with Real-World PEMS-based Emissions Measurement Data

Vehicle						Engine		Test Weight (lbs)	
Make	Model	MY	Odometer (miles)	GVWR (lbs)	GCWR (lbs)	Family	Displ (L)	Low	High
Isuzu	NPR	2015	48,000	14,500	20,500	FGMXE06.0584	6.0	8,620	12,940
Ford	E450	2016	31,000	14,500	-	GFMXE06.8BWZ	6.8	9,320	13,080
RAM	3500	2017	32,000	13,300	19,900	HCRXD06.45W0	6.4	14,557	18,020

Age Effects: We applied the MHD/HHD age effects shown in Table 3-13 to all regClasses (41 – 47). We did not use the LHD2b3/LHD45 specific age effects shown in Table 3-2. Both of these age effects tables are based on the same data set (Table 3-1) with the difference being only the f_{scale} used while assigning the data to OpModes. Since we are using the HD gasoline data to update the rates for all regClasses, we chose to also apply the HD specific age effects. Applying the LHD or LD (Table 3-11) age effects to rates developed using HD data and different f_{scale} ranges could over- or under-estimate the increases in emissions from aging. Ideally, LHD2b3 emission rates and age effects would be derived from chassis-certified heavy-duty gasoline vehicles.

3.1.1.6.1 Removal of Start Emissions from Real-World PEMS Data in Developing Running Exhaust Emissions

The running exhaust emissions rates update is meant to include emissions from only the hot-running condition. Thus, ideally, emissions assigned to start effects should be removed before estimating OpMode-based average rates per test and per vehicle. This is less of a concern if each test is a full-day of operation since the incremental start emissions might then be a small fraction of total emissions. However, on-road tests of the three HD gasoline involved drive cycles that range from 10 to 90 minutes in duration. Also, the idle tests, of 15 or 30 minute duration, need to have start effects removed to ensure their contribution to OpMode 1 (idle mode) rate is unaffected by start emissions. Note that the effect of start emissions is modeled as a separate process in MOVES and by removing them from the running emissions, we are minimizing double-counting.

Start emissions in the Federal Test Procedure are calculated as Bag 1 minus Bag 3 of the FTP cycle, where Bag 1 is driving after a cold start and Bag 3 is the same cycle as Bag 1 but under hot-stabilized conditions. This method is not possible in real-world testing because it is not possible to replicate the exact drive cycle due to varying traffic conditions. Thus, we decided to define start emissions as the incremental emissions that occur before the TWC reaches the light-off condition where it achieves optimal emissions reduction efficacy. We define light-off condition as the point when the TWC first reaches 421 °C (790 °F). TWC light-off temperatures are based on design specifics but are generally in the range of 400 °C. The selection of 421 °C as the criteria is somewhat arbitrary at the very precise level – there is not a good reason why 421 °C is more appropriate than say 410 °C or 430 °C. We picked 421 °C based on visual comparison of a handful of the on-road tests for each of the three gasoline vehicles to find out at what point the TWC temperature starts to stabilize. The effect of soak time on time to reach 421 °C catalyst temperature and grams of emissions assigned to the start effect, thus removed from running exhaust emissions, are shown in Table 3-15. Figure 3-8 shows the data for NO_x. Interestingly, the trend for NO_x from on-road testing is comparable to the trends from previous lab-based testing, shown in Figure 3-16. For the on-road data, grams of NO_x from starts emissions for 105-minute soak is 1.15 times the 720-minute soak. For the same conditions, the ratios in Figure 3-16 are approximately 1.17 and 1.37 for the data series labeled as “MOVES” and “New Data”, respectively. The trends for HC and CO are also similar between the two figures.

Table 3-15 Time and Pollutant Mass for Driving Assigned to Start Emissions

Soak Time (min)	Number of Tests	Avg. time[1] for TWC to reach 421 °C (sec)	Avg. grams of pollutant removed			
			NO_x	CO_2	CO	HC
0	109	78	0.2	356	3	0.4
3	6	42	0.02	213	1	0.03
18	6	63	0.1	265	3	0.3
30	6	91	0.8	427	9	0.8
45	8	114	1.9	493	14	1.6
75	5	122	1.8	470	16	1.8
105	7	102	2.3	463	19	1.9
180	4	107	3.0	531	22	2.7
240	2	94	1.1	424	18	1.9
360	1	1	0.00	0	0	0.00
720	48	125	2.0	662	25	3.3

Note:
[1] Of the total 202 tests listed here, in three tests the catalyst never reached 421 °C, so they are not included in the average time calculation, however, the grams of pollutant removed columns include these three tests.

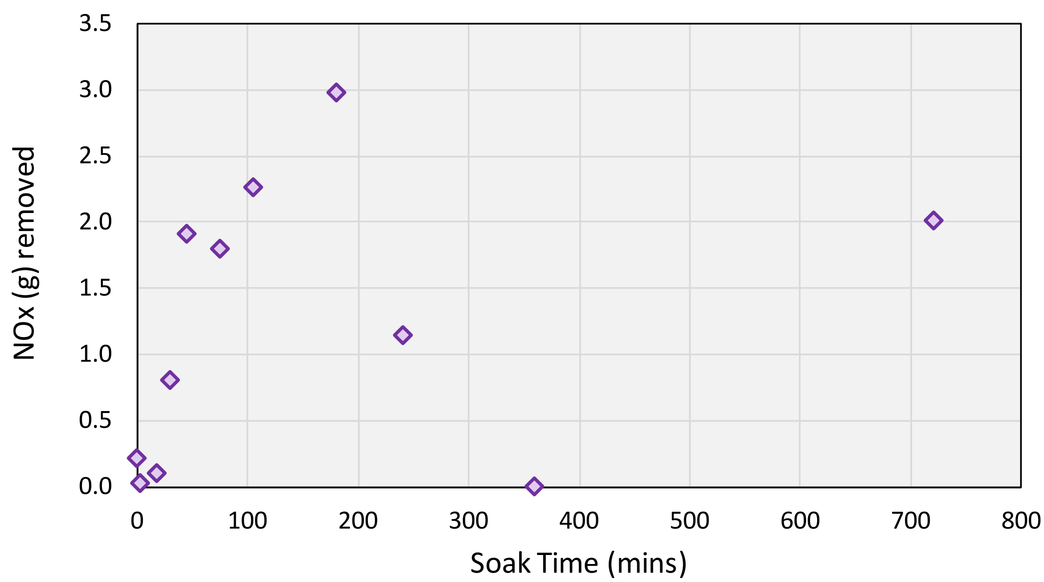

Figure 3-8. Grams of NO_x from Start Emissions versus Soak Time

3.1.1.7 Tier 3 Effects for LHD2b3 for 2018 and later Model Years

In MOVES_CTI_NPRM, we updated the emission rates for LHD2b3 for MY 2010-2015 based on data from the HDIUT program. However, vehicles in this MOVES regulatory class are subject to the Tier 3 light-duty standards starting in MY 2018. To calculate emission rates for MY 2018 and later, we applied reductions representing the Tier-3 phase-in for MY 2018-2022 for LHD2b3 vehicles (as shown in Table 3-16) to the emission rates representing MY 2017 estimated from the HDIUT program, as discussed in Section 3.1.1.6. The reductions for each model year during the phase-in were estimated by extracting the corresponding rates for MY 2007-2022 from the MOVES2014 database, and calculating the fractions relative to MY 2017. The basis and rationale for the rates developed for the Tier-3 rulemaking and retained in MOVES2014 are presented in Appendix I.

The LHD2b3 MY 2018+ rates contain the same heavy-duty gasoline age effects as were applied to the MY 2010-2017 rates (Table 3-13). Resulting emission rates for HC, CO and NO_x are shown in Figure 3-9.

Table 3-16 Tier 3 Reductions by Model Year for LHD2b3 Calculated from MOVES2014 (Appendix I)

Model Year	HC	CO	NOx
2018	35%	38%	41%
2019	44%	48%	52%
2020	53%	59%	63%
2021	62%	68%	74%
2022-2060	71%	78%	85%

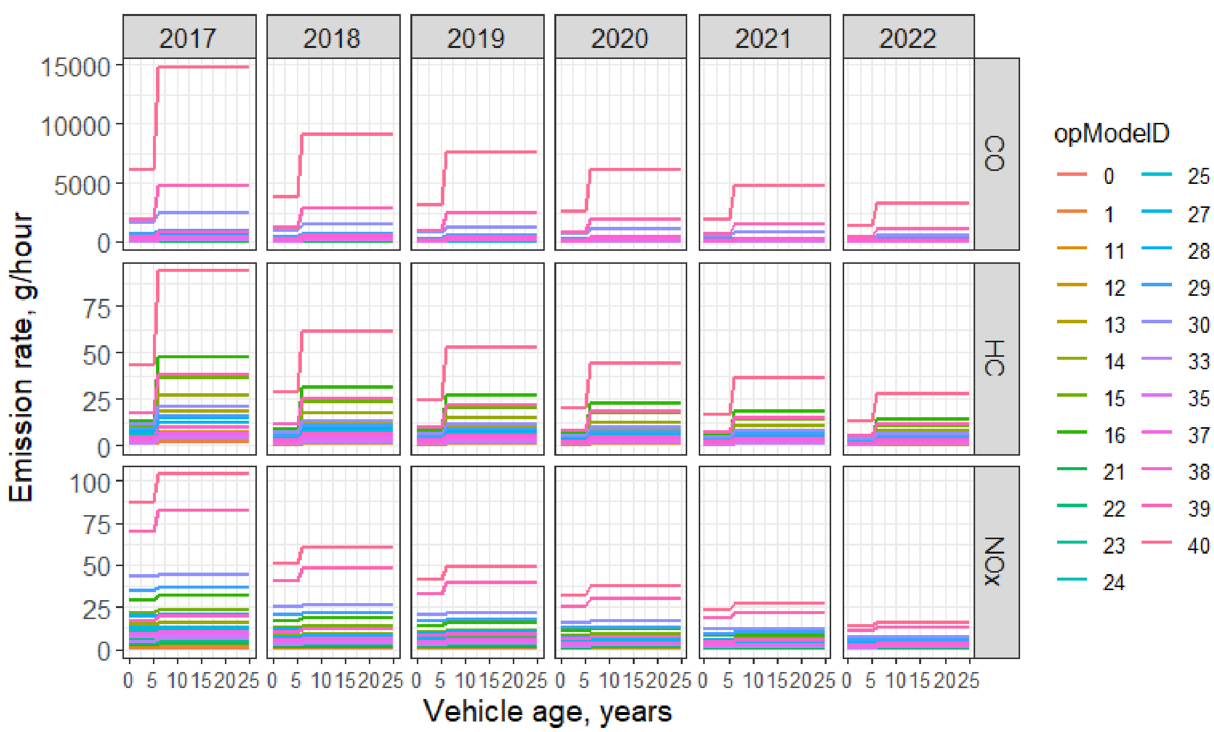

Figure 3-9. Running-Exhaust Emission Rates for Vehicles in the LHD2b3 Regulatory Class (regClassID 41), during the Tier-3 Phase-in. The emission rates remain constant for MY 2022 and beyond.

3.1.2 Particulate Matter

3.1.2.1 Pre-2010 Particulate Matter Emission Rates

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

In MOVES, the heavy-duty gas $PM_{2.5}$ emission rates are calculated by multiplying the MOVES2010 light-duty gasoline truck $PM_{2.5}$ emission rates by a factor of 1.40, as explained below. Since the MOVES light-duty gasoline $PM_{2.5}$ emission rates comprise a complete set of factors classified by particulate sub-type (EC and nonECPM), operating mode, model year and regulatory class, the heavy-duty $PM_{2.5}$ emission factors are also a complete set. No change to the PM emission rates is made beyond 2003, because the HD 2007 Rule PM standards are not expected to change in-use emissions for medium and heavy-duty gasoline vehicles, and the Tier 3 program is not expected to impact the PM emissions of heavy-duty gasoline vehicles. As presented in the next section, the MOVES PM rates for 2008+ vehicles is based on UDDS results of 2.7 mg/mile, while the standard for 2008+ spark-ignition vehicles is 20 mg/mile[107].

3.1.2.1.1 Data Sources

The factor of 1.4 used to convert light-duty gasoline PM rates to heavy-duty rates was developed based on $PM_{2.5}$ emission test results from the four 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 3-17.

Table 3-17 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

3.1.2.1.2 Pre-2010 Model Years for LHD

To compare these rates with rates from light-duty gasoline vehicles, we simulated UDDS cycle emission rates based on MOVES2010b light-duty gas $PM_{2.5}$ emission rates (with normal deterioration assumptions) for light-duty gasoline trucks (regulatory class LDT). The UDDS cycle represents standardized operation for the heavy-duty vehicles.

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 <u>older</u> light-duty gas truck group using MOVES2010b are 38.84 mg/mi (Ignoring sulfate emissions which are on the order of 1×10^{-4} mg/mile for low sulfur fuels). This value leads to the computation of the ratio: $\frac{65.22\,\frac{\text{mg}}{\text{mile}}}{38.84\,\frac{\text{mg}}{\text{mile}}} = 1.679$.

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

The newer model year group produces a ratio which is less than one and implied that large trucks produce less $PM_{2.5}$ emissions than smaller trucks. This result was intuitively inconsistent and is the likely result of a very small sample and a large natural variability in emission results.

Thus, all four data points were retained and averaged together by giving the older model year group a 75 percent weighting and the newer model year group (MY 2001) a 25 percent weighting. This is consistent with the underlying data sample. It produces a final ratio of:

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

Equation 3-1

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 is similar to how the LHD HC, CO, and NO_x emissions were estimated by using the light-duty gasoline truck emissions as the basis.

As documented in the light-duty report[10], the PM emission rates for light-duty vehicles were revised in MOVES2014 and MOVES_CTI_NPRM. These revisions include accounting for the Tier 3 light-duty program and incorporating newer data from port-fueled injection vehicles and gasoline direct injection vehicles (GDI). This analysis used the light-duty truck PM emission rates from MOVES2010b PM emission rates to derive the 1.4 ratio, and the subsequent heavy-duty gasoline PM emission rates. We have not updated the heavy-duty PM emission rates due to limited data regarding heavy-duty PM rates and uncertainty regarding the expected penetration of gasoline direct injection technology in heavy-duty gasoline vehicles. Additionally, the Tier 3 standards are not anticipated to cause reductions in heavy-duty gasoline PM.

3.1.2.1.3 Pre-2010 Model Years for MHD and HHD

For the larger heavy-duty gasoline emission rates, the emission rates are based on a f_{scale} of 17.1. The LHD emission rates are based on the light-duty truck rates, with an f_{scale} *of 2.06.*

We used an indirect approach to derive PM emission rates from the LHD emission rates. We assume that the relationship of total hydrocarbon (THC) between emission rates based on an f_{scale} of 2.06 and 17.1 is a reasonable surrogate to map PM emission rates from an f_{scale} of 2.06 and 17.1. To do so, we first calculated the emission rate ratio for THC emissions for each operating mode between regulatory class MHD (regClassID 46) and LHD2b3 (regClassID 41). We then multiplied this ratio to the PM emission rates in regulatory class LHD2b3 (regClassID 41) to obtain PM emission rates based on the 17.1 f_{scale} used in the heavier regulatory classes (RegClassID 46 and 47). An example of the regulatory class LHD2b3 PM emission rates, 17.1/2.06 f_{scale} THC ratios, and the calculated 17.1 f_{scale} based $PM_{2.5}$ emission rates are displayed in Table 3-18. No reductions are made between 2003 and 2009, because the 2007 HD rule is not anticipated to cause reductions in heavy-duty gasoline PM emissions.

Table 3-18. Derivation of MHD and HHD PM Emission Rates from LHD2b3 Rates using f_{scale} 17.1/2.06 THC emission ratios. Using Model Year 2001 as an Example

opModeID	LHD2b3 EC emission rates (mg/hr)	f_{scale} 17.1/2.06 THC emission ratios	MHD and HHD EC emission rates (mg/hr)
0	0.59	1.000	0.59
1	0.54	1.000	0.54
11	0.60	1.000	0.60
12	0.79	2.263	1.78
13	1.38	3.677	5.08
14	2.62	5.095	13.37
15	5.55	5.443	30.22
16	64.52	5.427	350.13
21	8.38	1.000	8.38
22	2.92	1.154	3.37
23	2.08	2.173	4.52
24	2.92	2.825	8.24
25	10.94	4.842	52.95
27	20.50	7.906	162.10
28	126.42	8.796	1,112.05
29	523.16	6.471	3,385.32
30	2,366.75	7.102	16,809.50
33	26.59	2.121	56.40
35	10.76	4.780	51.42
37	13.29	4.010	53.28
38	43.61	8.979	391.56
39	75.73	9.522	721.06
40	74.96	5.300	397.26

3.1.2.2 Model Year 2010+ Particulate Matter Emission Rates

The real-world PEMS-based emissions measurement data from two engine-certified and one chassis-certified heavy-duty gasoline vehicles used to update the HC, CO, and NOx emission rates (section 3.1.1.6) did not include $PM_{2.5}$. Due to lack of other available data, in MOVES_CTI_NPRM, we copied over the MY 2010+ HD diesel $PM_{2.5}$ rates (section 2.1.2.3) to the MY 2010+ HD gasoline. The diesel LHD2b3 and LHD45 rates were copied to the gasoline LHD2b3 and LHD45, respectively. Since the diesel MHD rates were different than the diesel LHD and HHD rates, we used the diesel HHD rates for gasoline MHD and HHD. The rates were copied at the $PM_{2.5}$ level and the gasoline specific EC (14 percent) and nonEC (86 percent) split was applied to get the gasoline specific EC PM (pollutantID 112) and nonECPM (pollutantID 118) rates. These gasoline specific EC and nonEC PM fractions are based on the Kansas City study of light-duty cars and trucks and the determination is described in the MOVES_CTI_NPRM Speciation Report.[1] The diesel EC (9.98 percent) and nonEC (90.02 percent) split of $PM_{2.5}$ is different than gasoline, so the EC and nonEC rates between diesel and gasoline are different even though the $PM_{2.5}$ rates were the same. The $PM_{2.5}$ rates were copied over with the age effects, thus the resulting gasoline rates are based on the diesel PM age effects described in Appendix B.8.

Gravimetric filter-based PM emissions measured from the three HD gasoline vehicles (described in Section 3.1.1.6) over various chassis-dynamometer tests are shown in Table 3-19.. The average PM rate over all vehicles and test cycles is 1.35 mg/mi. The PM rate for MY 2035 (same rates as MY2013+), age 0-3, diesel HHD (regClass 47) in a MOVES national run was 2.27 mg/mile. Since those numbers are comparable, and there is no modal gasoline HD PM data available, we decided to use the diesel HD PM rates for gasoline HD.

Table 3-19. PM2.5 Emissions for Lab-Based Cycles for HD Gasoline Vehicles[1]

	PM Emissions (mg/mi)				
Vehicle	FTP	HWFET	LA92	Supercycle	Average
2015 ISUZU NPR	1.74	0.75	1.69	2.73	1.64
2016 Ford E450	0.53	0.55	1.55	2.51	1.17
2017 RAM 3500	1.68	0.40	1.43	1.35	1.34
Average	1.36	0.57	1.53	2.24	**1.35**

Note:
[1] The vehicles are described in section 3.1.1.6

3.1.3 Energy Consumption

3.1.3.1 LHD Energy Rates for Model Years 1960-2009

The energy rates for LHD (LHD2b3 and LHD45 regulatory classes) gasoline pre-2009 energy rates are unchanged from MOVES2010a. In MOVES2010a, the energy rates for LHD2b3 and LHD45, along with the light-duty regulatory classes, were consolidated across weight classes, engine size and engine technologies, as discussed in the MOVES2010a energy updates report[49].

3.1.3.2 Energy Rates for MHD and HHD Model Years 1960-2009

The data used to develop energy rates for heavy-duty gasoline vehicles, within MHD, and HHD regulatory classes, is the same data set we used to develop the HC, CO, and NO_x exhaust emission rates. Similar to the diesel running exhaust energy rates, we made no distinction in rates by model year, age, or regulatory class. To calculate energy rates (kJ/hour) from CO_2 emissions, we used a heating value (HV) of 122,893 kJ/gallon and CO_2 fuel-specific emission factor (f_{CO2}) of 8,788 g/gallon for gasoline (see Equation 3-20). STP was calculated using Equation 1-4. Figure 3-10 summarizes the gasoline running exhaust energy rates in MOVES for these regulatory classes.

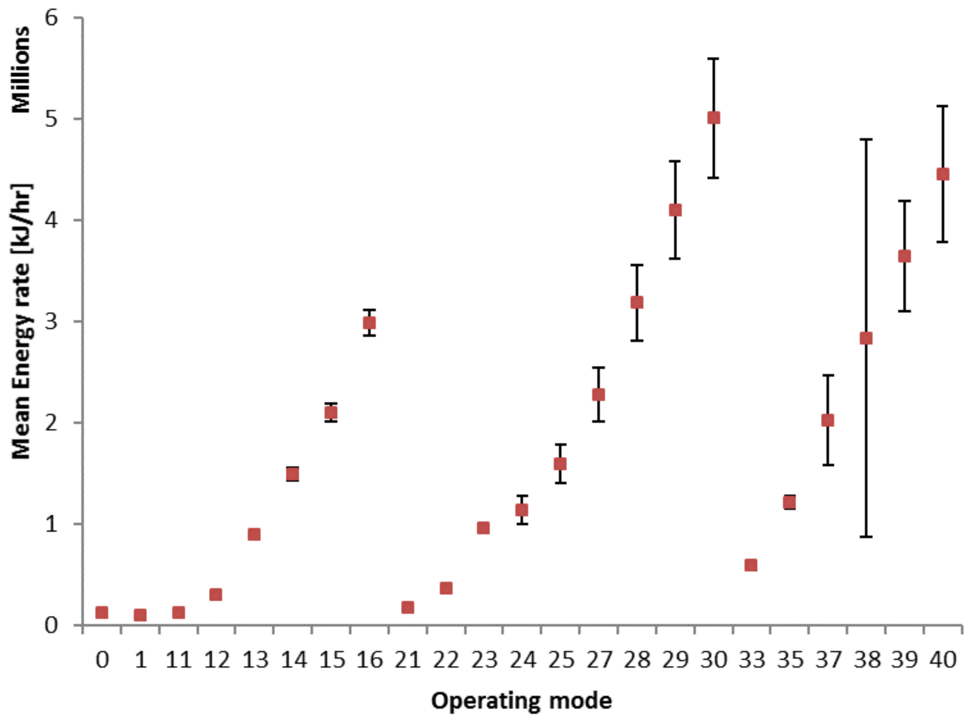

Figure 3-10. Gasoline Running Exhaust Energy Rates for MHD (1960-2009) and HHD (1960-2009)

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

3.1.3.3 Energy Rates for LHD2b3 MY 2010-2013 and LHD45, MHD, and HHD MY 2010-2015

The real-world PEMS-based emissions measurement data from two engine-certified and one chassis-certified heavy-duty gasoline vehicles used to update the HC, CO, and NOx emission rates (section 3.1.1.6) included CO_2 emissions data which was used to update the energy rates. The energy rates are derived using the measured CO_2 values and the conventional gasoline specific values for carbon content (0.0196 g/KJ) and oxidation fraction (1.0) and the molecular mass of CO_2 (44), and atomic mass of Carbon (12). These values are described in the MOVES GHG and Energy Ratesreport.[7]

When calculating the OpMode-based CO_2 rates, we used the hole-filling method described in section 2.1.1.4.1.

For LHD2b3, the energy rates are identical for MY 2010-2013. For LHD45, MHD, and HHD, the energy rates are identical for MY 2010-2015.

3.1.3.4 Energy Rates for LHD2b3 for 2014-2060

The LHD2b3 gasoline energy rates are reduced to incorporate the impacts of the Phase 1 and Phase 2 Heavy-duty Greenhouse Gas rules. The LHD2b3 gasoline rates are adjusted from the 2010-2013 model year rates using the gasoline reductions documented in Table 2-24 (Phase 1) and Table 2-25 (Phase 2) in Section 2.1.4.4.

Unlike GHG Phase 1 reductions, the GHG Phase 2 reductions to energy rates are not pre-applied to the energy rates, for the affected model years, in the *emissionRate* table in the MOVES database. The adjustments for GHG Phase 2 are applied at run-time using the values in the *emissionRateAdjustment* table in the MOVES database.

3.1.3.5 Energy Rates for LHD45, MHD, and HHD 2016-2060

Updates to the energy rates were made to the heavy-duty gasoline energy rates for model years 2016-2020 based on the Phase 1 Medium and Heavy-Duty Greenhouse Gas Rule[51] as discussed in Section 2.1.4.4 and shown in Table 3-20. The energy rates for 2021 model year and beyond were updated in MOVES_CTI_NPRM to reflect the CO_2 emission reductions expected from the Heavy-Duty GHG Phase 2 rule, as shown in Table 3-21, which have separate reductions for vocational and combination trucks.

Unlike GHG Phase 1 reductions, the GHG Phase 2 reductions to energy rates are not pre-applied to the energy rates, for the affected model years, in the *emissionRate* table in the MOVES database. The adjustments for GHG Phase 2 are applied at run-time using the values in the *emissionRateAdjustment* table in the MOVES database.

Table 3-20 Heavy-Duty Gasoline Reductions due to the Heavy-Duty GHG Phase 1 Rule[108]

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

Table 3-21 Heavy-Duty Gasoline Reductions due to the Heavy-Duty GHG Phase 2 Rule[109]

Vehicle Type	Fuel	Model Years	CO_2 Reduction from 2017 Baseline
LHD45	Gasoline	2021-2023	6.9%
		2024-2026	9.8%
		2027+	13.3%
Vocational MHD and HHD	Gasoline	2021-2023	6.9%
		2024-2026	9.8%
		2027+	13.3%
Short-haul Tractor-Trailers MHD and HHD	Gasoline	2018-2020	0.6%
		2021-2023	7.4%
		2024-2026	11.9%
		2027+	15.0%

3.2 Start Emissions

The MOVES heavy-duty gasoline emission rates are developed with reference to the engine emission standards. For LHD2b3 gasoline vehicles, manufacturers comply with chassis (g/mile) emission standards. For the larger regulatory classes, only the engine emission standards apply. We used the engine emission standards to estimate differences in emissions between the LHD2b3 regulatory classes and the heavier regulatory classes.

The heavy-duty spark ignition engine emissions standards[110] for the Federal Test Procedure (FTP) are shown in Table 3-22 FTP Standards for two weight ranges: GVWR ≤ 14,000 lbs (regulatory class LHD2b3) and GVWR > 14,000 lbs (LHD45, MHD, and HHD regulatory classes for heavy-duty gasoline). Note that the standards for model years 1990 through 2004 for CO and THC vary by weight class, but not by model year, whereas those for NO_x vary by model year, but not by weight class. Note that for model years 2005-2007, a single standard is applied for NMHC+NO_x, but that by 2008, separate but lower standards are again in effect. Note also that by model year 2008, the standards for the different weight classes are uniform for the three gaseous pollutants.

Table 3-22 FTP Standards (g/hp-hr) for Heavy-Duty Gasoline Engines for Model Years 1990-2008+[110]

Model-Year Group	GVWR ≤ 14,000 lb (LHD2b3)			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+	14.4	0.14	0.20	14.4	0.14	0.20

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

The heavy-duty gasoline vehicle start emissions for MOVES regulatory class LHD2b3 and LHD45 vehicles are discussed in Section 3.2.1.1. Section 3.2.1.2 discusses the development of the rates for MOVES regulatory class MHD and HHD gasoline vehicles.

3.2.1 HC, CO, and NO_X

Two sets of start emissions are derived for HC, CO, and NO_x for heavy-duty gasoline vehicles. First, we discuss the derivation of LHD2b3 in Section 3.2.1.1. Second, we discuss the emission rates for MHD and HHD in Section 3.2.1.2. In Section 3.2.1.3, we summarize and compare the two sets of start emission rates.

3.2.1.1 LHD2b3

For LHD2b3, the gaseous emission rates for MY 1960-2004 are based on data analysis of test data, and the MY 2005+ emission rates are based on ratioing the pre-2004 rates based on the emission standards.

3.2.1.1.1 1960-2004 model year emission rates

To develop start emission rates for MY 1960-2004 heavy-duty gasoline-fueled vehicles, we extracted data available in EPA's Mobile-Source Observation Database (MSOD).[100] These data represent aggregate test results for heavy-duty spark-ignition (gasoline powered) engines measured on the Federal Test Procedure (FTP) cycle. The GVWR for all trucks was between 8,500 and 14,000 lbs., placing all trucks in the LHD2b3 regulatory class. In MOVES_CTI_NPRM, LHD2b3 have identical start rates that are unchanged (except for the implementation of the Tier 3 rule) from LHD2b3 start emission rates in MOVES2010b.

Table 3-23 shows the model-year by age classification for the data. The model year groups in the table were designed based on the progression in NO_x standards between MY 1990 and 2004. Standards for CO and HC are stable over this period, until MY 2004, when a combined NMHC+ NO_x standard was introduced. However, no measurements for gasoline HD trucks were available for MY2004 and later.

Start emissions are not dependent on power, and therefore, the emission rates do not need to be calculated differently to distinguish VSP/STP or different scaling as was done for running exhaust rates. As discussed later, start emission rates are separated by regulatory classes to account for differences in the emission standards and/or available test data.

Table 3-23 Availability of Emissions Start Data by Model-Year Group and Age Group for Vehicles with GVWR < 14,000 Lbs.

Model-year Group	Age Group (Years)					Total
	0-3	4-5	6-7	8-9	10-14	
1960-1989				19	22	41
1990			1	29		30
1991-1997	73	59	32	4		168
1998-2004	8					8
Total	81	59	33	52	22	247

3.2.1.1.2 Estimation of Mean Rates

As with light-duty vehicles, we estimated the "cold-start" as the mass from the cold-start phase of the FTP (bag 1) less the "hot-start" phase (Bag 3). As a preliminary exploration of the data, we averaged by model year group and age group and produced the graphs shown in Appendix F. Sample sizes were small overall and very small in some cases (e.g., 1990, age 6-7) and the behavior of the averages was somewhat erratic. In contrast to light-duty vehicle emissions, strong model-year effects were not apparent. This may not be surprising for CO or HC, given the uniformity of standards throughout. This result was more surprising for NO_x, but model year trends are no more evident for NO_x than for the other two. Broadly speaking, it appeared that an age trend may be evident.

If we assume that the underlying population distributions are approximately log-normal, we can visualize the data in ways that illustrate underlying relationships. As a first step, we calculated geometric mean emissions, for purposes of comparison to the arithmetic means calculated by simply averaging the data. Based on the assumption of log-normality, the geometric mean (x_g) was calculated in terms of the logarithmic mean (x_l) as shown in Equation 3-2.

$$\bar{x}_g = e^{\ln \bar{x}_l} \qquad \textbf{Equation 3-2}$$

This measure was not appropriate for use as an emission rate, but was useful in that it represents the "center" of the skewed parent distribution. As such, it was less strongly influenced by unusually high or outlying measurements than the arithmetic means. In general, the small differences between geometric means and arithmetic means suggest that the distributions represented by the data do not show strong skew in most cases. Because evidence from light-duty vehicles suggested that emissions distributions should be strongly skewed, this result implied that these data are not representative of "real-world" emissions for these vehicles. This conclusion appeared to be reinforced by the values in Figure E-3 which represent the "logarithmic standard deviation" calculated by model-year and age groups. This measure (s_l), is the standard deviation of natural logarithm of emissions (x_l). The values of s_l were highly variable, and generally less than 0.8, showing that the degree of skew in the data was also highly variable as well as generally low for emissions data; e.g., corresponding values for light-duty running emissions are generally 1.0 or greater. Overall, review of the geometric means confirmed the impression of age trends in the CO and HC results, and the general lack of an age trend in the NO_x results.

Given the conclusion that the data as such are probably unrepresentative, assuming the log-normal parent distributions allowed us to re-estimate the arithmetic mean after assuming reasonable values for s_l. For this calculation, we assumed values of 0.9 for CO and HC and 1.2 for NO_x. These values approximate the maxima seen in these data and are broadly comparable to rates observed for light-duty vehicles.

The re-estimated arithmetic means were calculated from the geometric means, by adding a term that represents the influence of the "dirtier" or "higher-emitting" vehicles, or the "upper tail of the distribution," as shown in Equation 3-3.

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

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 3-11 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.

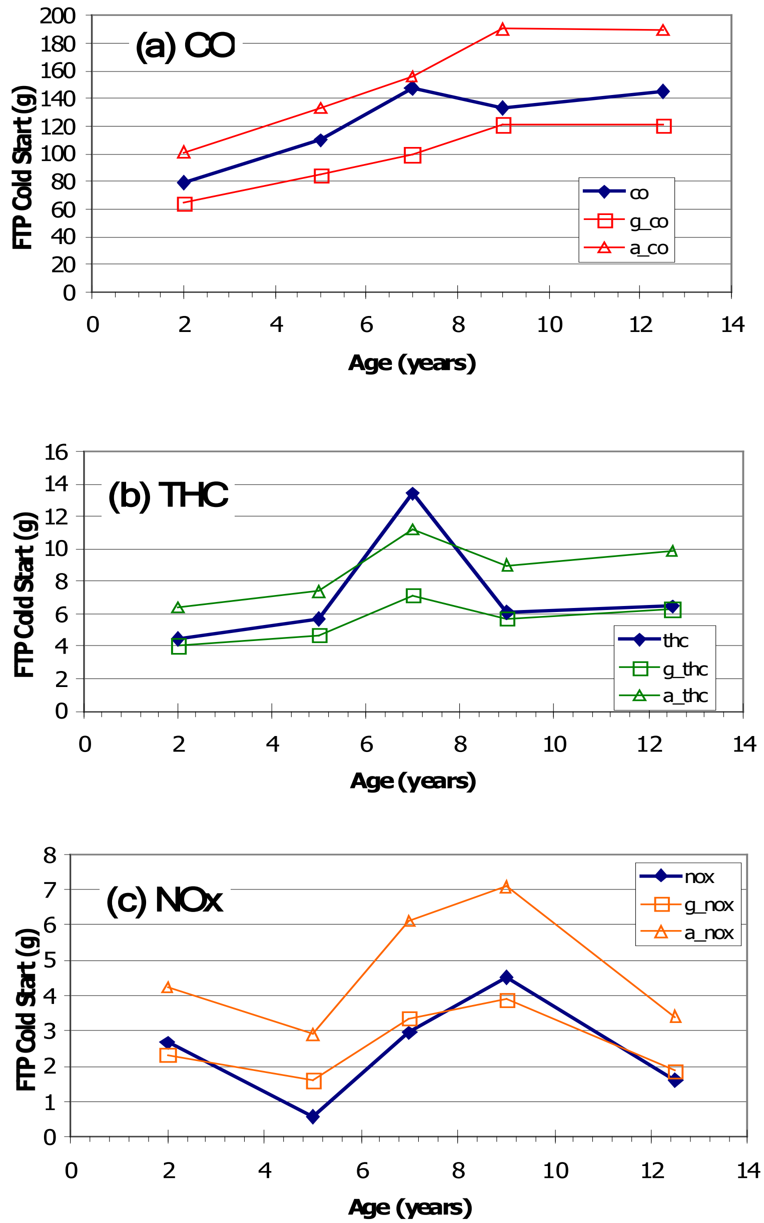

Figure 3-11. Cold-start FTP Emissions for Heavy-Duty Gasoline Trucks, Averaged by Age Group Only (g = Geometric Mean, a= Arithmetic Mean Recalculated from x_l and s_l)

3.2.1.1.3 Estimation of Uncertainty

We calculated standard errors for each mean in a manner consistent with the re-calculation of the arithmetic means. Because the (arithmetic) means were recalculated with assumed values of s_l, it was necessary to re-estimate corresponding standard deviations for the parent distribution s, as shown in Equation 3-4.

$$s = \sqrt{x_g^2 \, e^{s^2} (e^{s^2} - 1)} \qquad \textbf{Equation 3-4}$$

After recalculating the standard deviations, the calculation of corresponding standard errors was simple. Because each vehicle is represented by only one data point, there was no within-vehicle variability to consider, and the standard error could be calculated as $s/\sqrt{n}$. We divided the standard errors by their respective means to obtain CV-of-the-mean or "relative standard error." Means, standard deviations and uncertainties are presented in Table 3-24. and in Figure 3-12. Note that these results represent only "cold-start" rates (opModeID 108).

Table 3-24. Cold-Start Emission Rates (g) for Heavy-Duty Gasoline Trucks, by Age Group (Italicized Values Replicated from Previous Age Groups)

Age Group	*n*	Pollutant		
		CO	THC	NO_X
Means				
0-3	81	101.2	6.39	4.23
4-5	59	133.0	7.40	5.18
6-7	33	155.9	11.21	6.12
8-9	52	190.3	*11.21*	7.08
10-14	22	189.1	*11.21*	*7.08*
Standard Deviations				
0-3		108.1	6.82	8.55
4-5		142.0	7.90	
6-7		166.5	11.98	12.39
8-9		203.2	*11.98*	14.32
10-14		202.0	*11.98*	*14.32*
Standard Errors				
0-3		12.01	0.758	0.951
4-5		18.49	1.03	1.18
6-7		28.98	2.08	2.16
8-9		28.18	*2.08*	1.99
10-14		43.06	*2.08*	*1.99*

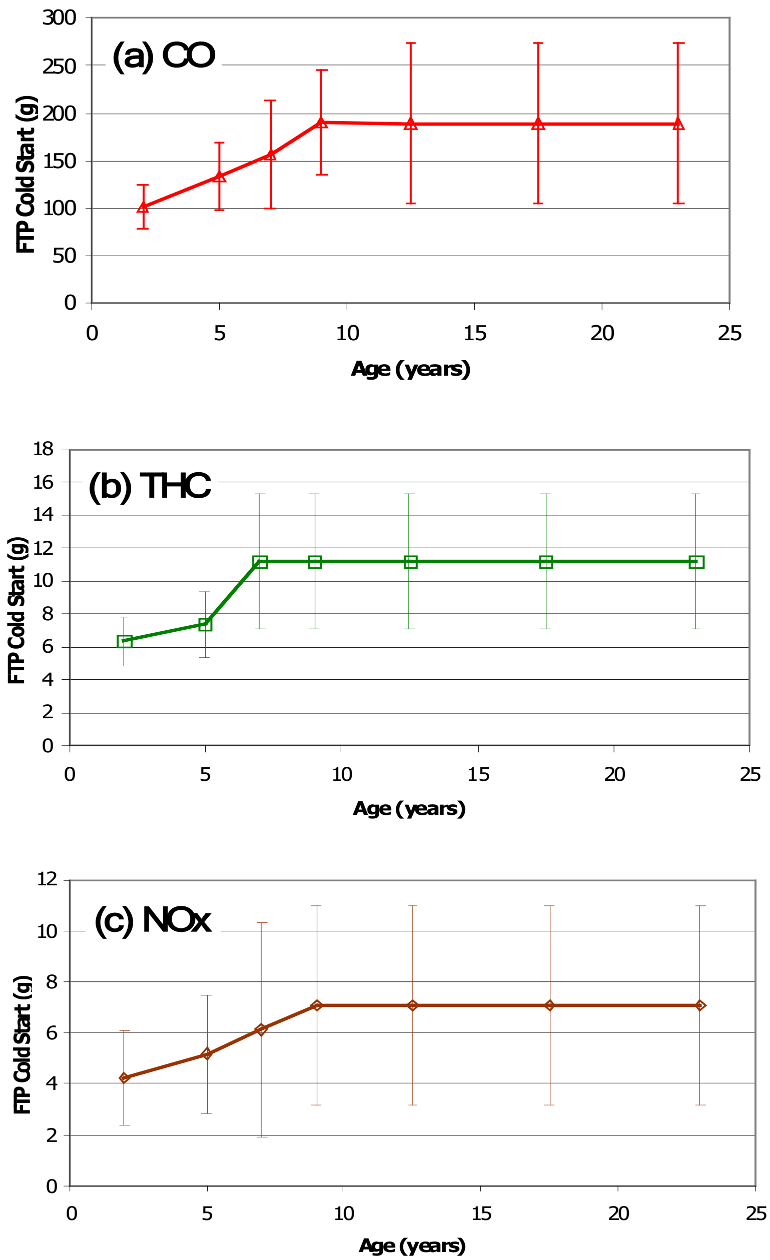

Figure 3-12. Cold-Start Emission Rates for Heavy-Duty Gasoline Trucks, with 95 Percent Confidence Intervals

The steps described so far involved reduction and analysis of the available emissions data. In the next step, we describe approaches used to impute rates for model years not represented in these data. For purposes of analysis, we delineated four model year groups: 1960-2004, 2005-2007, 2008-2017 and 2018 and later. The rates above were used for the 1960-2004 model year group. We describe the derivation of rates for the remaining groups below.

3.2.1.1.4 2005-2007 model year start emission rates

For the 2005-2017 model year emission rates, we estimated reductions in the 1960-2004 emission rates, by comparing the standards between the two model year ranges. For CO, the approach was simple. We applied the age zero values in Table 3-24. to the 2005-2008 model year group. The rationale for this approach is that the CO standards do not change over the full range of model years considered.

For HC and NO_x, we imputed values for the 2005-07 and 2008-2017 model-year groups by multiplying the values in Table 3-24. by ratios expressed in terms of the applicable standards. Starting in 2005, a combined HC+NO_x standard was introduced. It was necessary for modeling purposes to partition the standard into HC and NO_x components. We assumed that the proportions of NMHC and NO_x would be similar to those in the 2008 standards, which separate NMHC and NO_x while reducing both.

We calculated the HC value by multiplying the 1960-2004 value by the fraction f_{HC} as shown in Equation 3-5.

$$f_{HC} = \frac{\left(\frac{0.14\ \text{g/hp-hr}}{(0.14+0.20)\ \text{g/hp-hr}}\right)(1.0\ \text{g/hp-hr})}{1.1\ \text{g/hp-hr}} = 0.37 \qquad \textbf{Equation 3-5}$$

This ratio represents the component of the 2005 combined standard attributed to NMHC. We calculated the corresponding value for NO_x as shown in Equation 3-6.

$$f_{NOx} = \frac{\left(\frac{0.20\ \text{g/hp}-\text{hr}}{(0.14+0.20)\ \text{g/hp}-\text{hr}}\right)1.0\ \text{g/hp-hr}}{4.0\ \text{g/hp-hr}} = 0.147 \qquad \textbf{Equation 3-6}$$

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

3.2.1.1.5 2008-2017 model year start emission rates

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 LHD2b3 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 MOVES2014 light-duty truck start emission rates.[111] The multiplicative age effects for start emission rates for vehicles in model years 2008-2017 are shown in Table 3-25.

Table 3-25 Multiplicative Age Effect Used for Start Emissions for LHD2b3 Vehicles for 2008-2017 Model Years Adopted from the Deterioration Effects for Light-Duty Trucks from the Light-Duty Emission Rate Report[111]

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

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

Emission rates representing the phase-in of Tier-3 standards for the start-exhaust process were developed in MOVES2014 employing the techniques used for running rates, as described in Appendix I. Using this approach, the LHD2b3 Tier 3 start rates are also based on light-duty emission rates scaled to higher emission standards for the LHD2b3 regulatory class.

In addition, the rates during and following the Tier-3 phase-in have relatively lower deterioration than the rates for the model years preceding the onset of the phase-in (MY 2008-2017). The start rates for HC, CO and NO_x during the Tier-3 phase-in model years (2018-2022) are shown below in Figure 3-13.

Note, that in MOVES_CTI_NPRM the age effects for running LHD2b3 emission rates for 2010+ are based on the heavy-duty gasoline data set discussed in Section 3.1.1.1. This results in the MOVES_CTI_NPRM start emission rates having a higher relative deterioration than running emission rates for LHD2b3 vehicles for 2010+ model years. We recognize this is inconsistent with our knowledge of start deterioration.[10] We plan to address this data gap with data collected on LHD2b3 in future versions of MOVES.

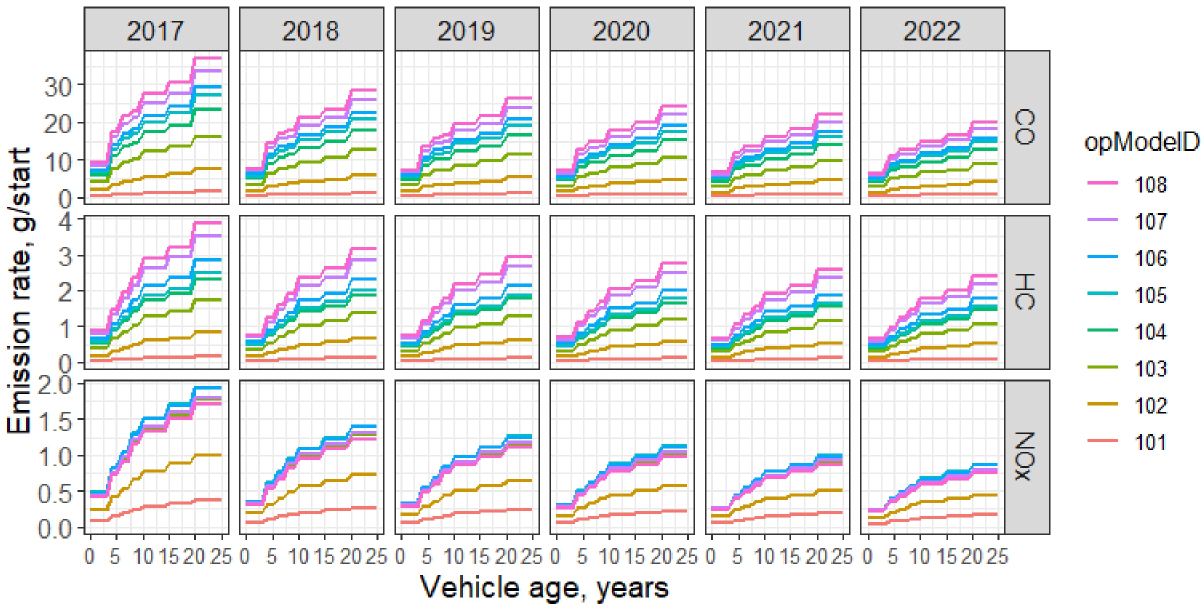

Figure 3-13 HC, CO and NOx Emission Rates for the Cold Start-Exhaust Process for the LHD2b3 (regClassID 41) Regulatory Class by Operating Mode and Age Group during the Tier-3 Phase-In

3.2.1.2 LHD45, MHD, and HHD

The emission rates from LHD45, MHD, and HHD gasoline vehicles were estimated to be different than the cold start emission rates for LHD2b3. The following two subsections document the emission rates for 1960-2007 model years (Section 3.2.1.2.1) and 2008+ model years (Section 3.2.1.2.2).

3.2.1.2.1 1960-2007 model years

Since bag data were lacking for MY 1960-2007 vehicles in classes LHD45 and MHD, we estimated cold start values relative to the LHD2b3 start emission rates.

For CO and HC, we estimated rates for the heavier vehicles by multiplying them by ratios of standards for the heavier class to those for the lighter class. The value of the ratio for CO based on 1990-2004 model year standards is shown in Equation 3-7.

$$f_{\mathrm{CO}} = \frac{37.1\ \mathrm{g/hp\text{-}hr}}{14.4\ \mathrm{g/hp\text{-}hr}} = 2.58 \qquad \textbf{Equation 3-7}$$

The corresponding ratio for HC for 1990-2004 model year vehicles is 1.73, as shown in Equation 3-8.

$$f_{\mathrm{HC}} = \frac{1.9\ \mathrm{g/hp\text{-}hr}}{1.1\ \mathrm{g/hp\text{-}hr}} = 1.73 \qquad \textbf{Equation 3-8}$$

The ratios derived in the previous two equations (2.58 and 1.73) were applied to estimate the start emission rates for 1960-2004 and 2005-2007 model year groups for the LHD45, MHD, and HHD gasoline vehicles (Table 3-28). Note that the ratios for CO and HC do not vary by model year group because the standards do not; See Table 3-21.

For MY 1960-2007, NO_x start emission rates for medium and heavy-duty vehicles are equal to the LHD2b3 start emission rates, because the same standards apply to both classes throughout. The approaches for all three regulatory classes in all model years are summarized in Table 3-28 .

3.2.1.2.2 2008 and later model year

The cold start emissions for 2008 model year and later LHD45, MHD, and HHD spark-ignited (gasoline) engines have been updated for MOVES_CTI_NPRM based on new data. Similar to the approach taken for light-duty vehicles, the cold start emissions are defined as the difference in emissions between a test cycle with a cold start and the same test cycle with a hot start. Heavy-duty gasoline engines are certified using the Heavy-Duty Gasoline Engine Federal Test Procedure (FTP) cycle (40 CFR Part 86, Appendix I.f.1). The test procedure for certification requires that manufacturers run the engine over the FTP cycle with a cold start and then repeat the cycle with a warm start. Starting in model year 2016, EPA began collecting certification data that contained separate cold and hot results for each engine certified. The data that was analyzed for this MOVES_CTI_NPRM update, includes the following engine families from 2016 and 2017 model years shown in Table 3-26.

Table 3-26 Engine Data Analyzed to Revise the Cold Start Emission Rates for HD Gasoline Engines

Category	Number of Engines	Manufacturers
LHD45, MHD, HHD Gasoline	3	Ford, GM, Powertrain Integration

The certification data was used to determine the grams emitted per cold start using Equation 3-9.

$$Grams\ per\ Start = [Cold\ FTP\ Emission\ Results\ (g/(hp-hr)) - Hot\ FTP\ Emission\ Results(g/(hp-hr))] * FTP\ Cycle\ Work\ (hp-hr) \qquad \textbf{Equation 3-9}$$

The amount of work (hp-hr) performed over the FTP cycle is not provided as part of the certification data submitted by the manufacturers to EPA. We only had cycle work data from one 19.3 hp-hr HD gasoline engine. We acknowledge that FTP cycle work is unique to each engine because it is created based on the engine's maximum speed, curb idle speed, and the maximum torque curve, but estimated cycle work for all HD gasoline engines using our one engine data source.

The analysis of cold and hot start FTP emissions data from three HD gasoline engines determined the grams per start for HC, CO, and NO_x. The average and standard deviation of the HC, CO, and NO_x emission levels of the three engines are shown in Table 3-27. The engines included MY2016 and MY 2017, ranged in displacement between 5.4 and 7.2 liters, and ranged in rated power between 297 and 332 HP. The new default cold start emissions values for MOVES_CTI_NPRM are the mean values shown in Table 3-27. The HC and NO_x cold start emissions for HD gasoline engines are increasing with this update, compared to what was in MOVES2014, while the CO emissions are decreasing.

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

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

We applied the same relative age deterioration for the 2008+ model years starts for HC and CO as was used for the previous model year groups (which is based on the gasoline LHD2b3 1960-2004 model years). For NOx, we applied the same relative age deterioration as the updated LDT starts in MOVES_CTI_NPRM.[10] The start rates for this model year group for each age are graphed in Figure 3-15.

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

Table 3-28 summarizes the data and methods used to estimate HC, CO, and NO_x start emission rates from heavy-duty gasoline vehicles as discussed in Sections 3.2.1.1 and 3.2.1.2. Figure 3-14 displays the cold start emission rates across model years for the two different sets of start emission rates for heavy-duty gasoline vehicles. The LHD45 line in Figure 3-14 represents LHD45, MHD, and HHD starts.

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

Regulatory Class	Model-year Group	Method		
		CO	THC	NO_X
LHD2b3	1960-2004	Values from Table 3-24.	Values from Table 3-24.	Values from Table 3-24.
	2005-2007	Values from Table 3-24.	Reduce in proportion to standards from 1960-2004	Reduce in proportion to standards from 1960-2004
	2008 - 2017	Section 3.2.1.1.5 Based on Tier 2 Bin 8 LDT rates and deterioration	Section 3.2.1.1.5 Based on Tier 2 Bin 8 LDT rates and deterioration	Section 3.2.1.1.5. Based on Tier 2 Bin 8 LDT rates and deterioration
	2018 +	Section 3.2.1.1.6. Based on surrogate LDT emission rates	Section 3.2.1.1.6. Based on surrogate LDT emission rates	Section 3.2.1.1.6. Based on surrogate LDT emission rates
LHD45, MHD, HHD	1960-2004	Increase in proportion to standards from LHD2b3	Increase in proportion to standards from LHD2b3	Same values as LHD2b3
	2005-2007	Increase in proportion to standards from LHD2b3	Increase in proportion to standards from LHD2b3	Same values as LHD2b3
	2008 +	Updated based on FTP certification data, deterioration based on the 1960-2004 LHD2b3 data	Updated based on FTP certification data, deterioration based on the 1960-2004 LHD2b3 data	Updated based on FTP certification data, deterioration based on LDT

The outcomes of the methods described in the table are summarized graphically in Figure 3-14 for cold-start emissions. The decline in start emissions with the adoption of more stringent standards is shown over the period between model years 1990 and 2022, at the completion of the phase-in of Tier 3 standards for vehicles with GVWR ≤14,000 lbs. Note that there is a slight increase in THC start emissions in model year 2008, which is the first model year using the new start certification data discussed above in Section 3.2.1.1.5.

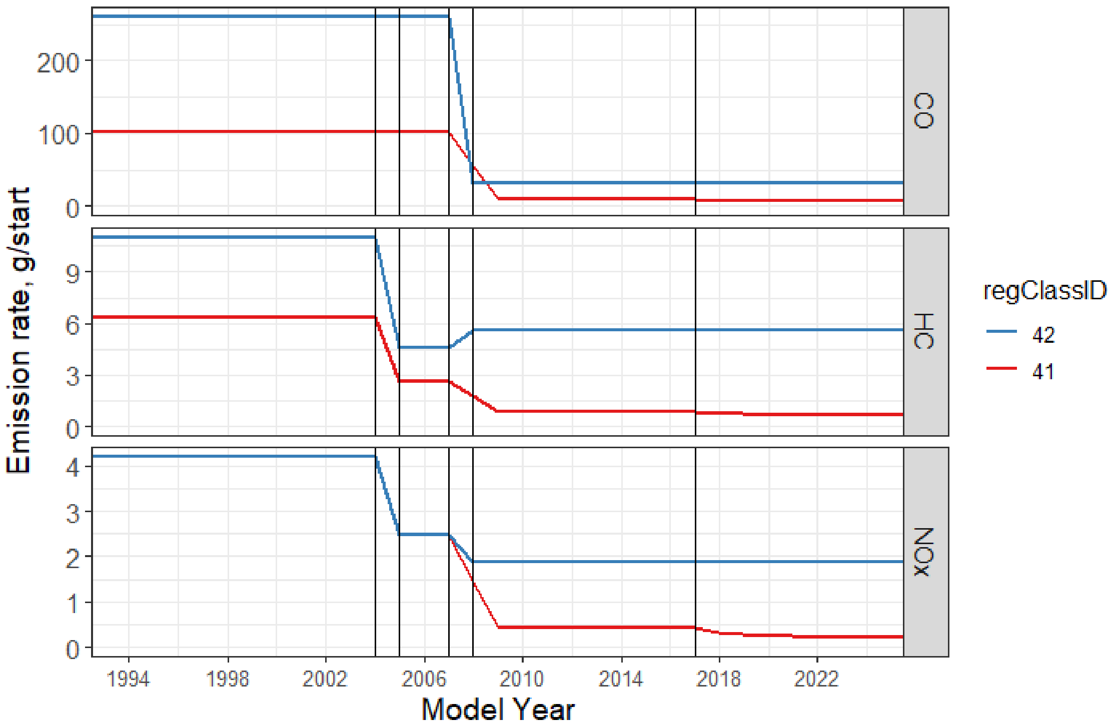

Figure 3-14 Cold-Start Rates (opModeID 108) at Age 0-3 vs. Model Year, by Pollutant, for Heavy-Duty Gasoline Vehicles in Two Regulatory Classes. MHD and HHD are Equivalent to LHD45.

NOTE: The Reference Lines Indicate the Model Years 2004, 2005, 2007, 2008 and 2017, Respectively

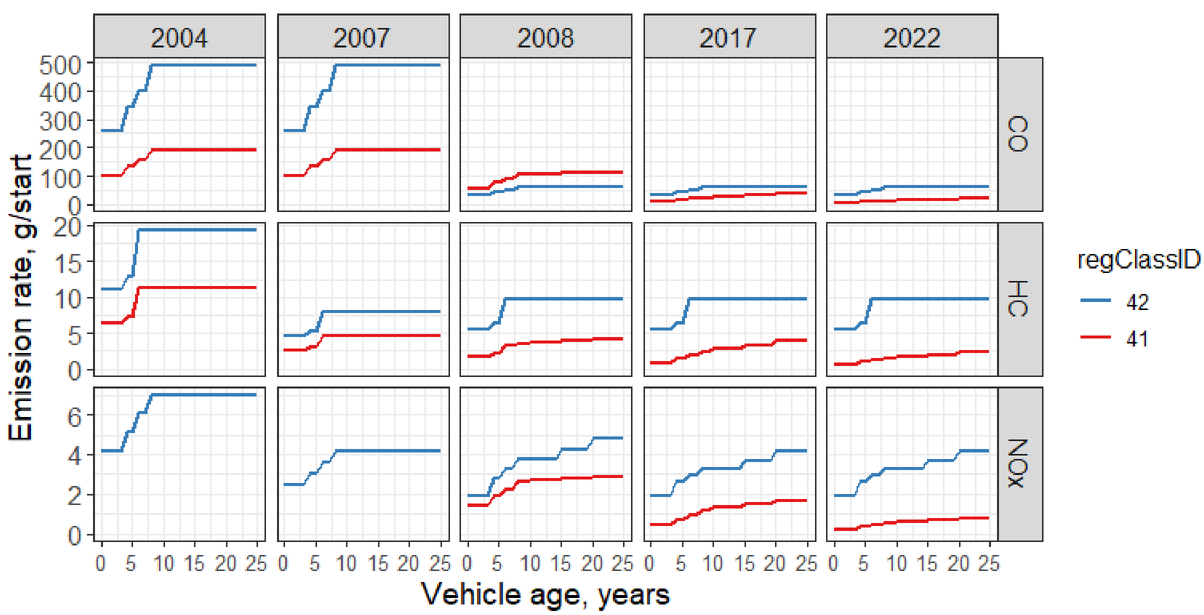

Figure 3-15 Cold-Start Rates (opModeID) vs. Vehicle Age for Select Model Years.

3.2.2 Particulate Matter

Data on PM start emissions from heavy-duty gasoline vehicles were unavailable. As a result, we used the multiplication factor from the running exhaust emissions analysis of 1.40 (derived in

Equation 3-1 in Section 3.1.2.1.2 to scale up start emission rates for light-duty trucks (regClassID 30) for model years 1960-2003. For 2004+ model years, the emission rates are a factor of 1.4 times the model year 2003 light truck (regClassID 30) rates. The light-duty PM rates in 2004-2017 model year increase due to the updated data on emission rates and sales penetration of gasoline direct injection technology. Subsequently, the light-duty PM starts decrease beginning in model year 2018 with the implementation of the Tier-3 Vehicle Emissions and Fuel Standards Program. As discussed in Section 3.1.2, Tier 3 is not expected to impact the PM emissions of heavy-duty gasoline vehicles. Due to limited data regarding heavy-duty PM rates and uncertainty regarding the expected penetration of gasoline direct injection technology in heavy-duty gasoline vehicles, we have decided to project constant start emissions using the 2003 model year emission rates.

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

3.2.3 Soak Time Adjustments

To estimate the start emissions at various soak lengths, we apply the same soak fractions to the cold start emissions that we applied to 1996+ MY light-duty gasoline vehicle as documented in the light-duty emission rate report[10] and shown in Figure 2-31.

For MOVES_CTI_NPRM, we collected new start emission rate data based on soak time from one heavy-duty gasoline truck to verify the rate adjustments. The data was gathered using PEMS using the procedure and methods discussed in Section 2.2.3.2. The vehicle tested was a 2012 MY box truck with a gasoline engine. The results from the testing are shown in Figure 3-16. Because the trend in the soak time effects is similar to the values used in MOVES2014, and because we only had new data from one truck, we retained the start emission fractions from MOVES2014.

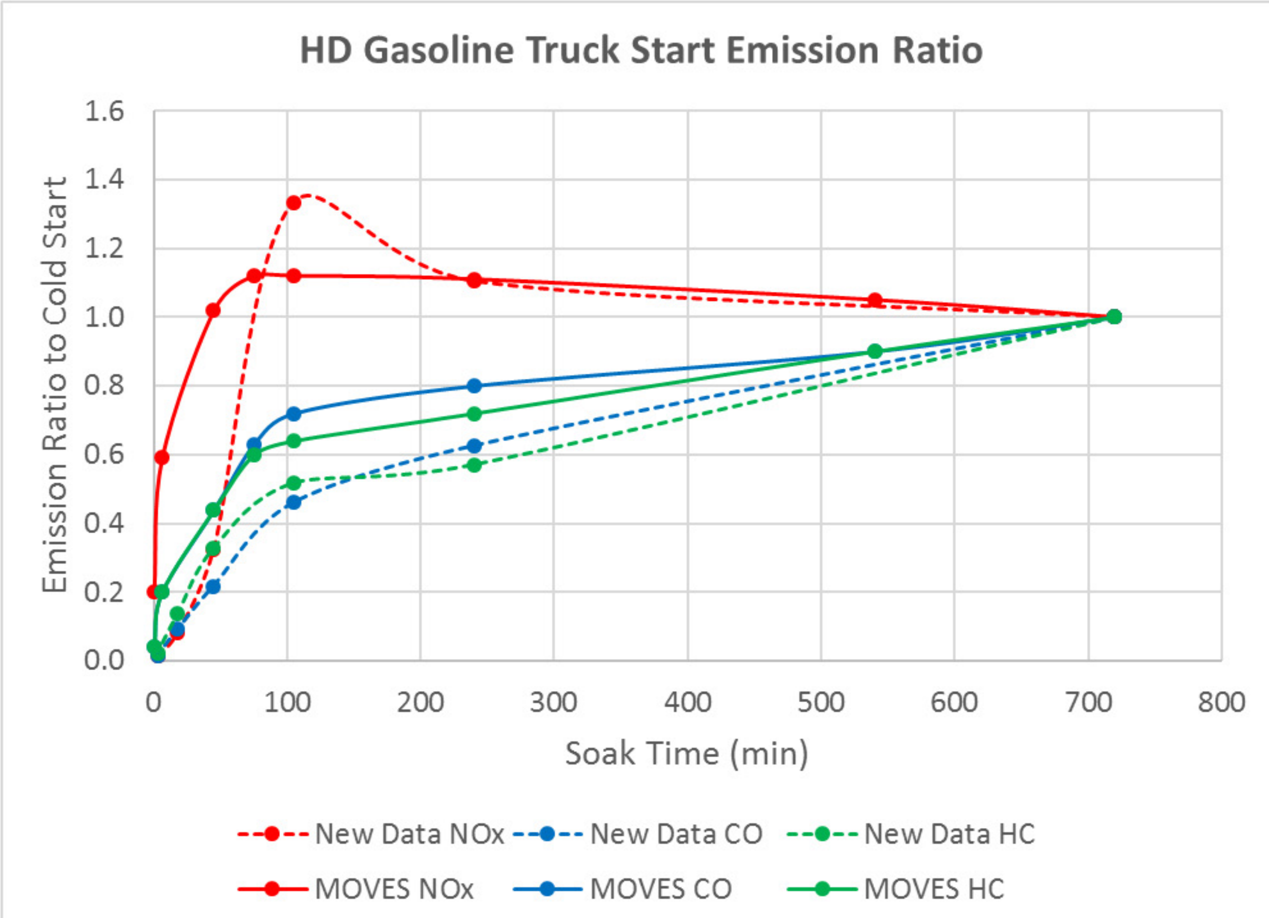

Figure 3-16 HD Gasoline Start Emission Ratio

3.2.4 Start Energy Rates

The MOVES energy rates are displayed in Figure 3-17. The heavy-duty gasoline start energy rates were originally derived in MOVES2004, and updated in MOVES2010a as described in the corresponding reports.[49] As shown, there is substantial variability in the start rates between 1974 and 2000. As discussed in Section 2.1.4.1, the detailed methodology used in MOVES2004 (which modeled different emission rates according to vehicle weights, engine technologies, and engine sizes) introduced variability into the energy rate within the current MOVES regulatory class emission rates.

Table 3-29 displays the relative contribution of running and start operation to total energy consumption from the heavy-duty gasoline regulatory classes from a national MOVES_CTI_NPRM run for calendar year 2016.[w] 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.

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

Table 3-29 Relative Contribution of Total Energy Consumption from Each Pollutant Process by Regulatory Class for Heavy-Duty Gasoline Vehicles in Calendar Year 2016

processID	processName	LHD≤14K	LHD45	MHD	HHD
1	Running Exhaust	97.8%	99.2%	99.0%	99.2%
2	Start Exhaust	2.2%	0.8%	1.0%	0.8%

The start energy rates are reduced for shorter soak times using the same factors for diesel vehicles, as presented in Table 2-40. The energy rates also increase with cold temperatures using the temperature effects documented in the 2004 Energy Report.[62]

The start energy rates include the projected impact of the Phase 1 Heavy-Duty GHG standards, which began phasing-in in 2014 and have the same reductions as the running energy rates, as presented in Table 2-22 and Table 2-24. As discussed in Section 2.2.4, the start energy rates are not projected to change due to the HD GHG Phase 2 standards.

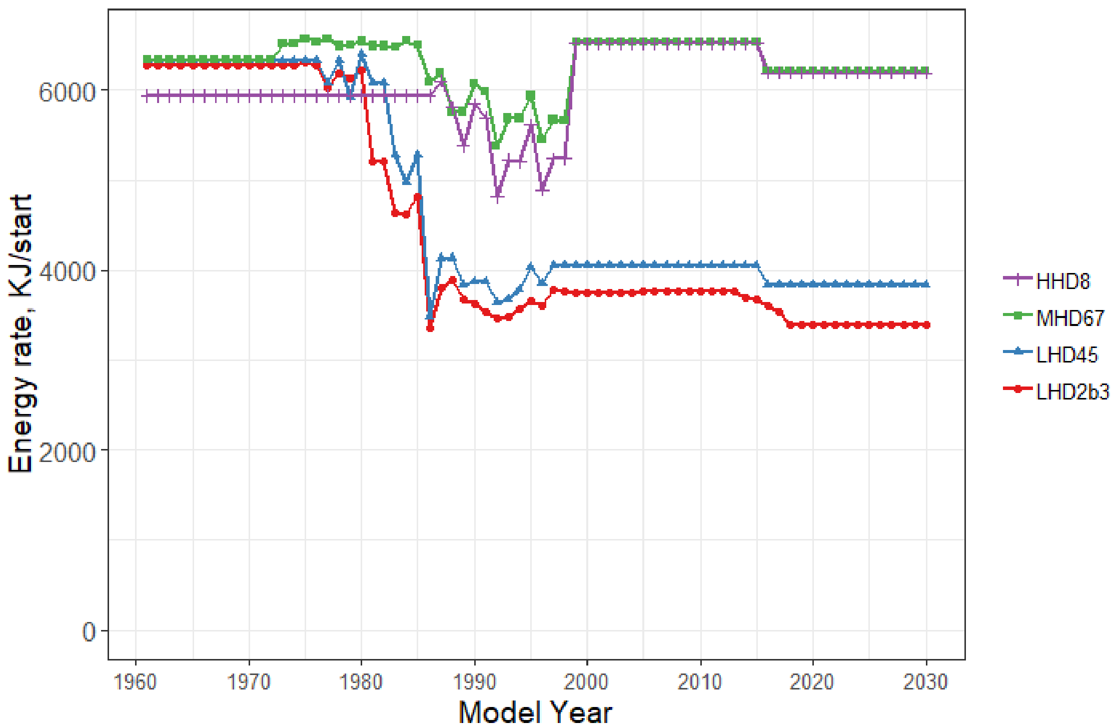


Figure 3-17 Heavy-Duty Gasoline Cold Start Energy Rates (OpmodeID 108) by Model Year and Regulatory Class

4 Heavy-Duty Compressed Natural Gas Emissions

While natural gas lacks the ubiquitous fueling infrastructure of gasoline, compressed natural gas (CNG), propane, and liquefied natural gas have grown as transportation fuels for public transit, government, and corporate fleets. Such fleets typically utilize centralized, privately-owned refueling stations. Fleet vehicles are operated as back-to-base, which means the vehicles return to the same base location each day for refueling. Within this segment, some of the most rapid growth in CNG vehicles over the last 15 years has occurred among city transit bus fleets, as seen in Figure 4-1[112], and in solid waste collection or refuse truck fleets.[113]

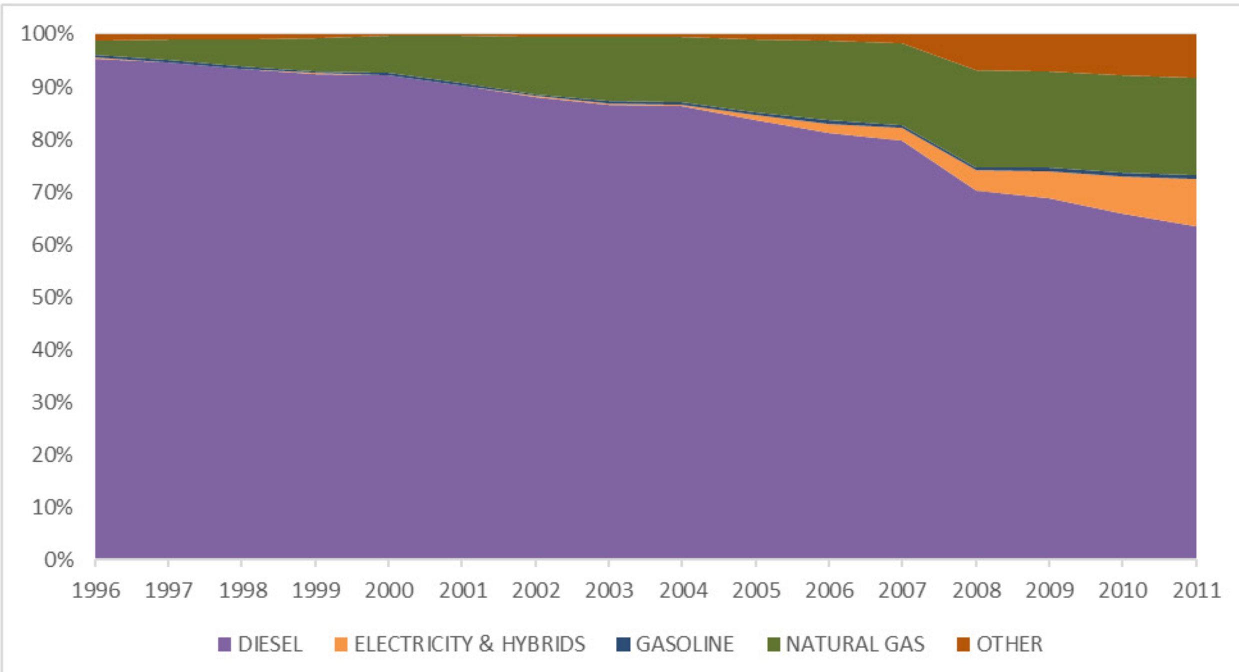


Figure 4-1. US Natural Gas Bus Population by Year and Fuel Type for 1996-2011 (APTA) [114]

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

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

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

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

However, for MOVES_CTI_NPRM, we expanded the modeling capabilities and made improvements to the emissions rates for newer model years, as described below:

1. Allowed modeling of CNG for all heavy-duty source types (41 through 62). Consistent with MOVES2014, transit bus (sourceTypeID 42) is mapped to urban bus (regClassID 48). However, in MOVES_CTI_NPRM, all other heavy-duty source types are mapped to the heavy heavy-duty regulatory class (regClassID 47). Further, the OpMode-based emission rates for the allowed CNG heavy-duty regulatory classes (regClassIDs 47 and 48) are identical. Thus, any differences in CNG emissions between source types is due to differences in population and activity.
2. For MY 2007-2009, the overall method of estimating emission rates is same as MOVES2014, with two differences:
   a. MY 2010+ rates are now a separate group. MOVES2014 had the MY 2007-2012 group.
   b. The MY 2007-2009 group uses all CNG vehicles in the certification database to calculate the adjustment ratio while in MOVES2014 we utilized only the CNG urban bus data.
3. MY 2010+ rates are based on second-by-second data from MY 2010+ compressed natural gas vehicles in the HDIUT data set. Thus, the rates for this group are now based on real-world in-use measurement of vehicles and emission control technologies relevant to the model years.

4.1 Comparison of Simulated Rates and Real-World Measurements

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

For our comparison, we considered two driving cycles:

1. Central Business District (CBD)
2. Washington Metropolitan Area Transit Authority (WMATA)

4.1.1 Heavy-Duty Transit Bus Driving Cycles

The CBD cycle is defined as a driving pattern with constant acceleration from rest to 20 mph, a short cruise period at 20 mph, and constant deceleration back to rest, repeated for 600 seconds (see Figure 4-2).[115] The WMATA cycle was developed using GPS data from city buses in Washington, DC, and has higher speeds and greater periods of acceleration than the CBD cycle (see Figure 4-3).

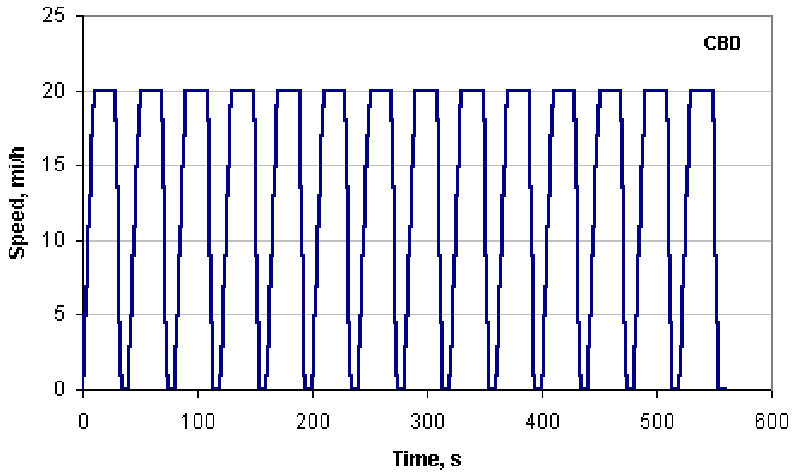


Figure 4-2 Driving Schedule Trace of the Central Business District (CBD) Cycle [116]

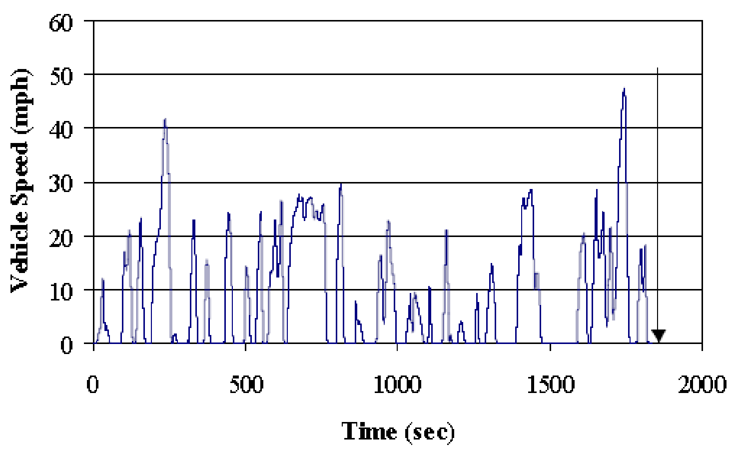


Figure 4-3 Driving Schedule Trace of the Washington Metropolitan Area Transit Authority (WMATA) Cycle[117]

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

The MOVES2010b project level importer was used to input the second-by-second drive cycle. A single link was created, with the test cycle entered as a drive trace. Running MOVES2010b generated the operating mode distribution, which is created by allocating the time spent in each operating mode according to the cycle speed and acceleration, as shown in Figure 4-4 and Figure 4-5. The derivation of scaled tractive power (STP) and operating mode attribution for heavy-duty vehicles are discussed earlier in this report, in Section 1.3. Road grade is set to zero because these are chassis dynamometer runs.

Since STP is dependent on mass (among other factors), the average vehicle inertial test mass for each cycle was inserted into the MOVES2010b sourceUseType table in place of the default transit bus mass to ensure a more accurate simulation. Using the measured vehicle masses across all the test programs reviewed, the CBD cycle had an average test mass of 14.957 metric tons and the WMATA cycle had an average mass of 16.308 metric tons, compared to the MOVES2010b default of 16.556 metric tons. We used the road-load coefficients from MOVES2010b for transit buses, and any changes in the coefficients (*A*, *B*, and *C*) with the tested buses were assumed to be negligible.

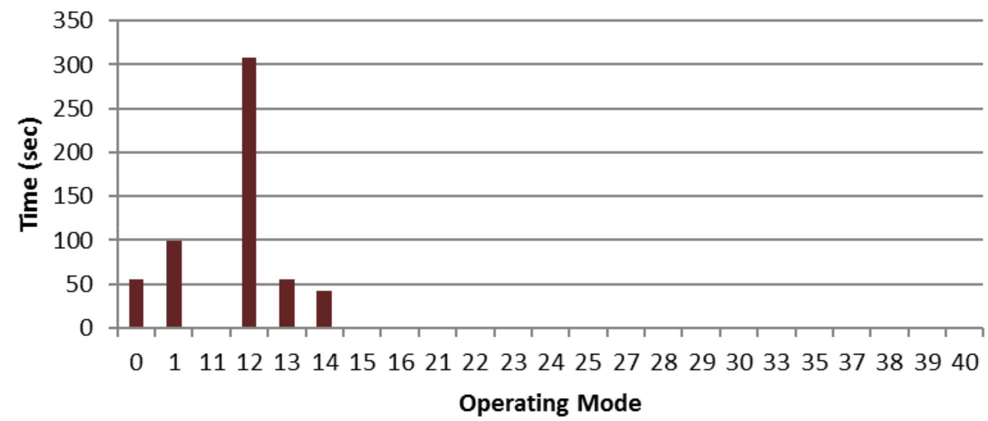


Figure 4-4 Operating Mode Distribution for the CBD Cycle

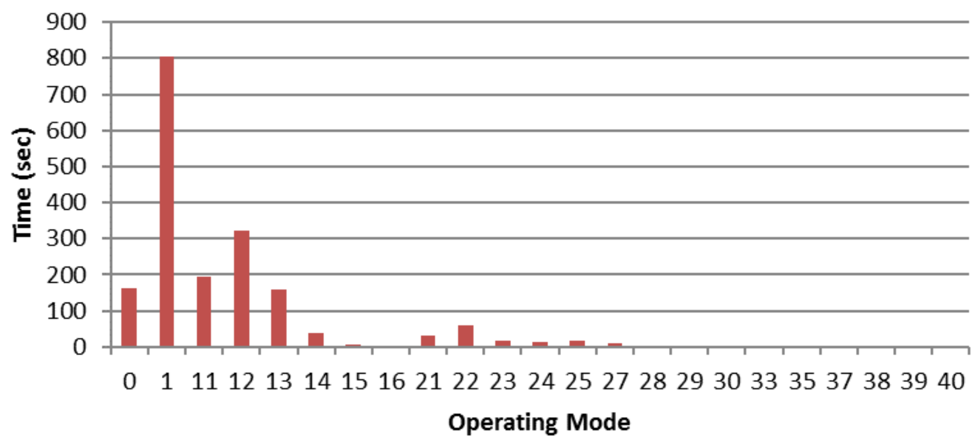


Figure 4-5 Operating Mode Distribution for the WMATA Cycle

4.1.3 Simulating Cycle Average Emission Rates

Having determined the total amount of time spent in each operating mode for a drive cycle, and using the MHD gasoline emission rates in the MOVES2010b database (DB), we were able to simulate the cycle total emissions for each pollutant for each cycle. Which, when divided by the cycle total distance gives us the simulated cycle-average distance-specific rate for that cycle ($E_{simcycle}$, g/mile), as shown in Equation 4-1. Using this method, the simulated cycle emission aggregates were calculated as a function of the following parameters:

- fuel type,

- driving cycle,
- age group,
- regulatory class,
- model year, and
- pollutant and process.

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

Where:

D_{cycle} = distance of the cycle, in miles
$R_{p,OM}$ = emission rate of pollutant p in operating mode OM, in g/hr
$T_{OM,cycle}$ = time spent in operating mode OM for given cycle, in hr

We compared the MOVES2010b simulated MHD gasoline rates with the published chassis dynamometer measurements. We also specified the age group and model year to match individual vehicles in the testing programs from the literature on CNG transit buses.

4.1.4 Published Chassis Dynamometer Measurements

The real-world data was collected from programs that were conducted at several research locations around the country on heavy-duty chassis dynamometer equipment. In our analysis, we collected ~~35~~ 34 unique dynamometer measurements—which consisted of distance-specific running emissions rates for each of the following pollutants and total energy:

1. oxides of nitrogen (NO_x)
2. carbon monoxide (CO)
3. particulate matter (EC + non-EC)
4. total hydrocarbons (THC)
5. methane (CH_4)
6. total energy consumption

Note that in MOVES, methane emissions are not estimated using emission rates, as are the other pollutants listed above. Rather, methane is estimated in relation to THC, using ratios stored in the MethaneTHCratio table. The ratios are categorized by fuel type, pollutant process, source type, model-year group, and age group. MOVES multiplies the THC rate by the corresponding ratio from the "methanethcratio" table to calculate the CH_4 rate.

All criteria emission rates are dependent on vehicle age, and thus are stored in the emissionRateByAge table. Total energy consumption is age independent, and therefore stored in the EmissionRate table. Some of the published studies did not report total energy consumption directly, so it was necessary to compute energy from a stoichiometric equation based on the carbon content in the emitted pollutants or from reported values of miles per gallon equivalent of diesel fuel. In the former case, we used 0.8037 as the carbon fraction coefficient for non-methane hydrocarbons (NMHC) when the bus was equipped with an oxidation catalyst and 0.835 without due to high ethene levels, using speciation profiles from Ayala et al. (2003)[118] discussed later in this section. All other conversion factors to energy were taken from Melendez et al. (2005).

On a similar note, MOVES does not report particulate matter (PM) as a single rate; it reports one rate for PM from elemental carbon (EC) of 2.5 microns or less, and another rate for non-elemental carbon of 2.5 microns or less. These separate rates for PM (EC) and PM (NonEC) from the emissionRateByAge table are added together for a total PM rate used for comparison to the measurements.

Table 4-1. shows a summary of the number of unique CNG bus measurements by driving cycle for each study. Navistar published a similar study of CNG and diesel buses in 2008, and this analysis shares many of the same sources.[119]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)[121] and Ayala et al. (2003).[118] In the Ayala et al. (2002) study the 2000 model year CNG bus was tested and then retested after approximately two months of service,[121] 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[117]	National Renewable Energy Laboratory (NREL)	WMATA	2001 (4), 2004 (3)
Ayala 2003[118]	California Air Resources Board (CARB)	CBD	2000 (4), 2001 (2)
LeTavec 2002[120]	Atlantic Richfield Company (ARCO)	CBD	2001 (1)
Ayala 2002[121]	CARB	CBD	2000 (2)
Lanni 2003[122]	New York Department of Environmental Conservation	CBD	1999 (3)
McKain 2000[123]	West Virginia University (WVU)	CBD	1999 (3)
Clark 1997[124]	WVU	CBD	1996 (10)
McCormick 1999[125]	Colorado School of Mines	CBD	1994 (2)
TOTAL			**(34)**

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

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

4.1.5 Plots of Simulated Aggregates and Published Measurements

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

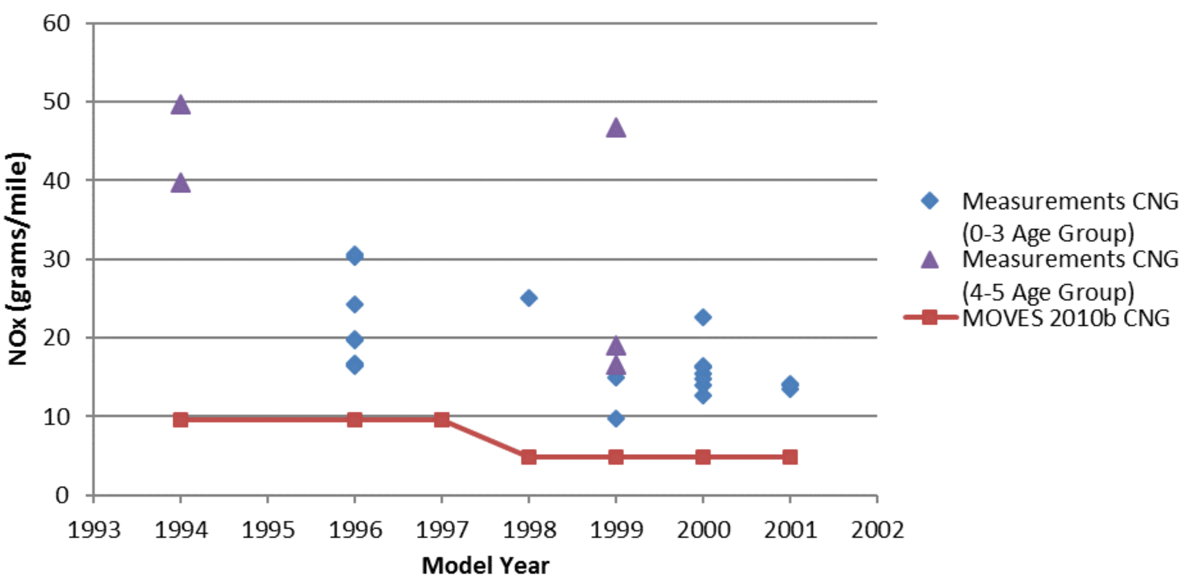


Figure 4-6. NOx Emission Comparisons of CNG Transit Bus Dynamometer Measurements and MOVES2010b Simulated Aggregates on the CBD Cycle

[x] Note that for MY 1994 in Figure 5-6 through Figure 5-10, MOVES2010b MHD gasoline (same as CNG) rates are based on age group 405. All other MOVES2010b rates are based on age group 3.

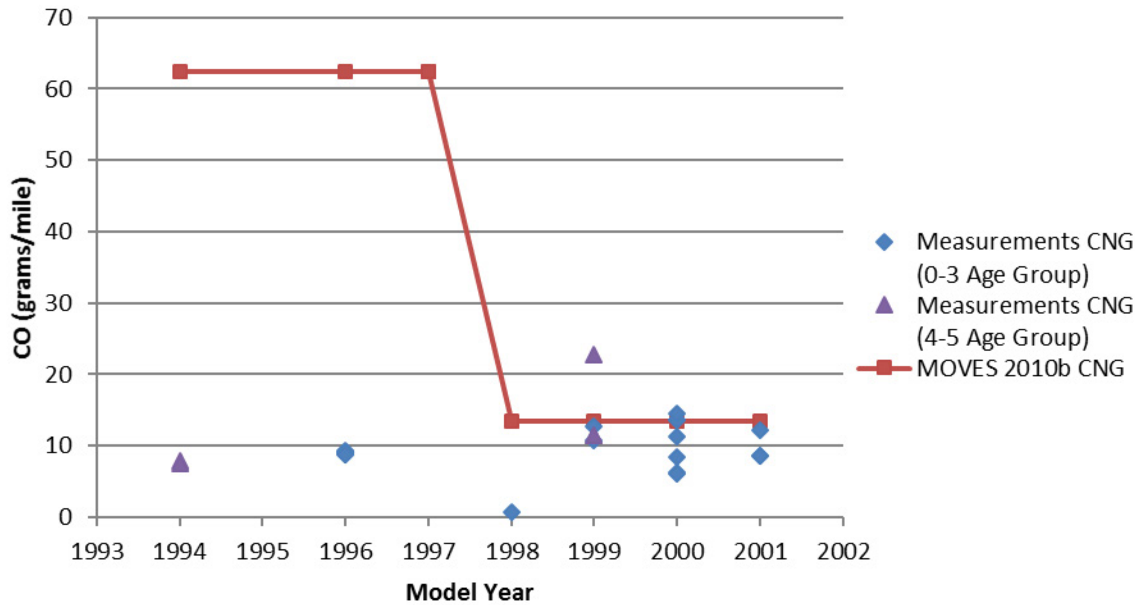


Figure 4-7. CO Emission Comparisons of CNG Transit Bus Dynamometer Measurements and MOVES2010b Simulated Aggregates on the CBD Cycle

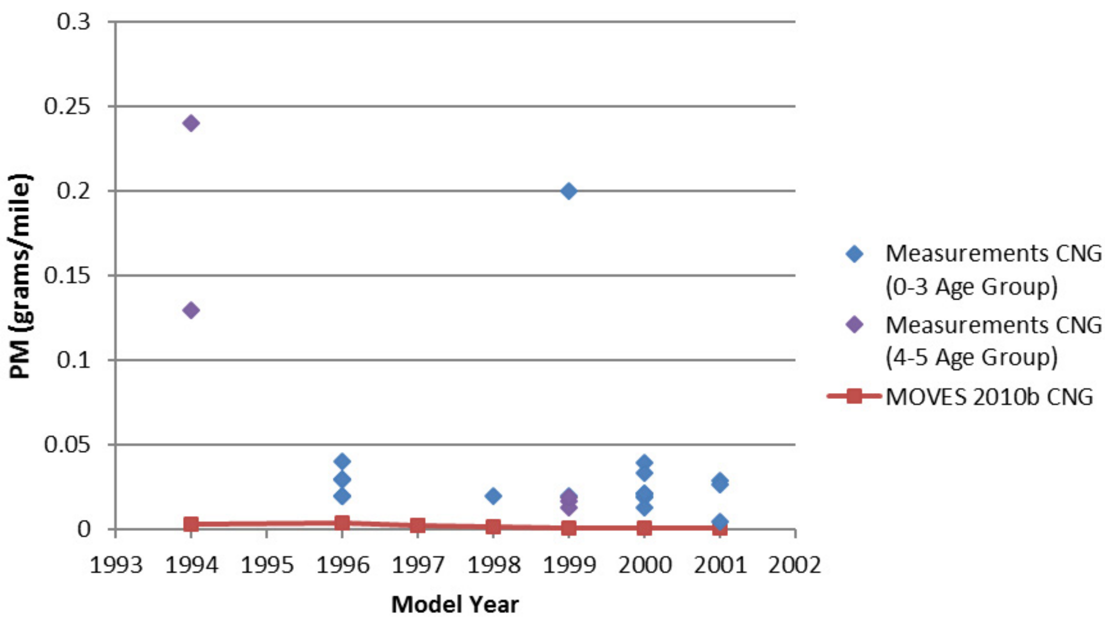


Figure 4-8. PM Emission Comparisons of CNG Transit Bus Dynamometer Measurements and MOVES2010b Simulated Aggregates on the CBD Cycle

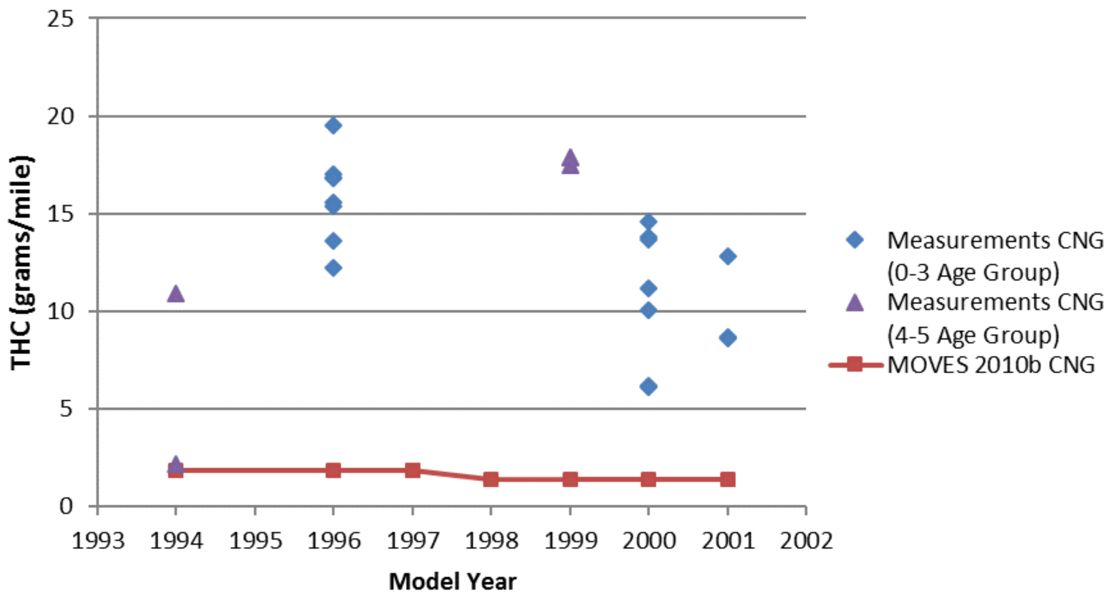


Figure 4-9. THC Emission Comparisons of CNG Transit Bus Dynamometer Measurements and MOVES2010b Simulated Aggregates on the CBD Cycle

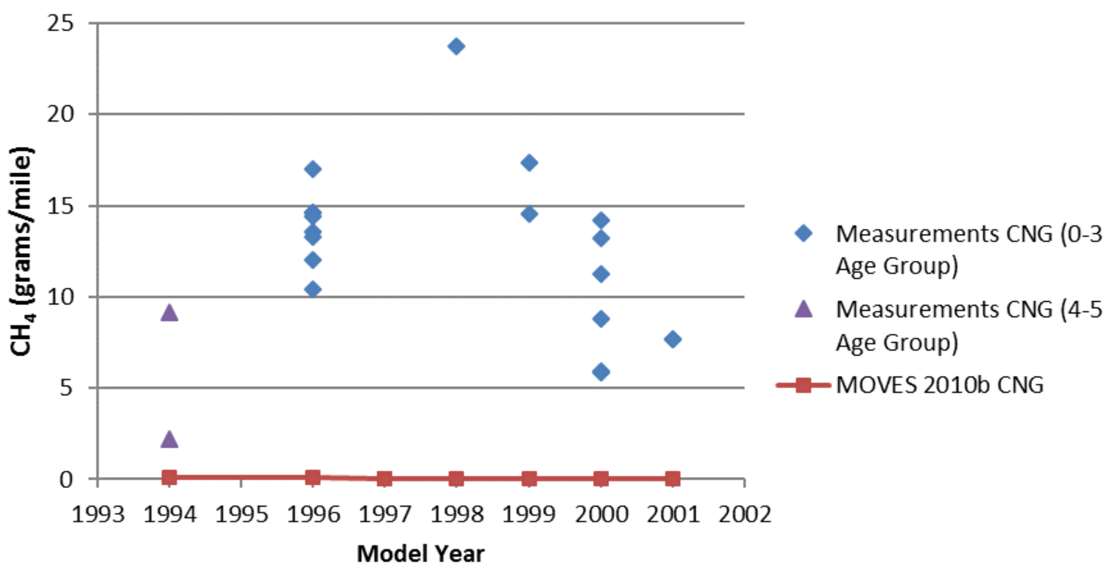


Figure 4-10. CH_4 Emission Comparisons of CNG Transit Bus Dynamometer Measurements and MOVES2010b Simulated Aggregates on the CBD Cycle

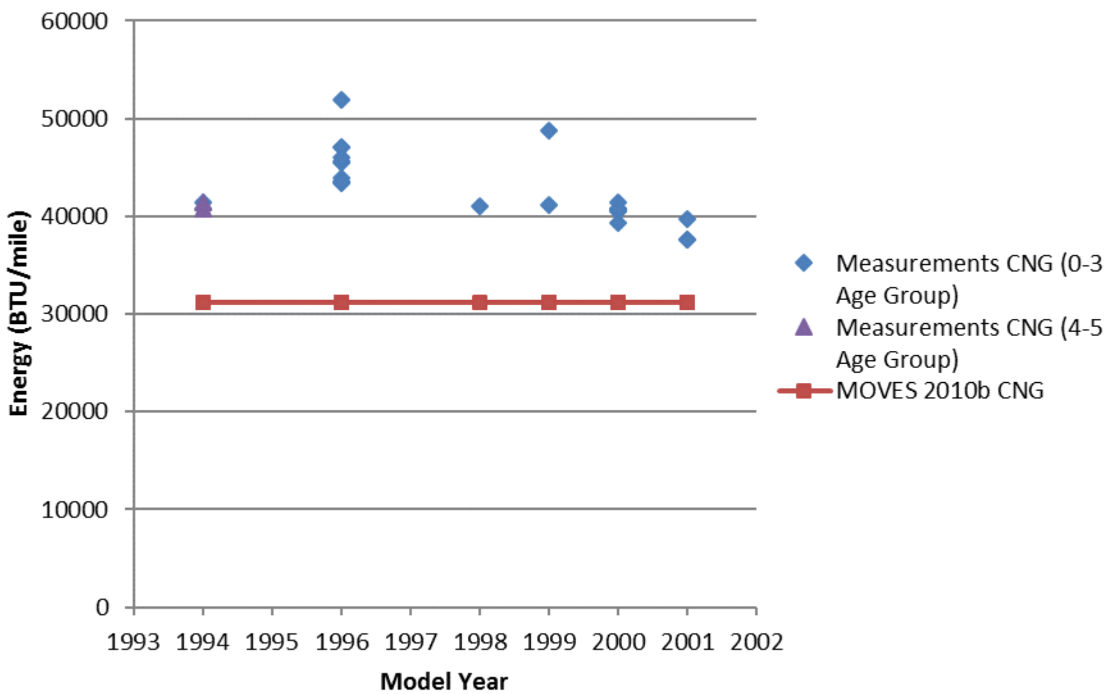


Figure 4-11. Total Energy Consumption Comparisons of CNG Transit Bus Dynamometer Measurements and MOVES2010b Simulated Aggregates on the CBD Cycle

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

4.2 Development of Running Exhaust Emission Rates

Ideally, MOVES emission rates would be developed through analysis of second-by-second data of vehicles of the appropriate regulatory class, model year, and age. Unfortunately, such modal data are not readily available for all model years in this case. However, we substantially improved the CNG bus emission rates in MOVES2014, relative to MOVES2010b, by adjusting the MY emission rates as a group (as opposed to individual adjustments by operating mode). The methods to calculate the adjustment ratios are discussed in detail in subsequent sections.

In MOVES_CTI_NPRM, we further improved the group-based adjustment factor, estimated emissions rates for MY2010+ based on real-world CNG vehicle emissions data, and allowed all HD vehicle types to be modeled with CNG fuel. We improved the rates by:

1. Creating two model year groups, 2007-2009 and 2010+, to replace the 2007-2013 model year group in MOVES2014. This allows for better representation of differences in combustion and aftertreatment technology, such as stoichiometric-combustion with three-way catalysts (TWC) that became more prevalent starting year 2010. The rates for MY 2007-2009 are based on the same methodology as MOVES2014 while the rates for MY 2010+ are based on real-world measurements of MY 2010+ CNG vehicles (and thus different from the MOVES2014 methodology for these model years).
2. Including all HD CNG engine emissions data, within a model year group, in arriving at the certification emission rate for that model year group. In MOVES2014, the certification emission rate was based on only engine families marked as urban bus (since we only allowed HD CNG buses to be modeled).

4.2.1 Determining Model Year Groups

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

4.2.1.1 MY 1994-2001

We evaluated the measured criteria pollutant rates (NO_x, CO, PM, and THC) to establish model year groups. Initially, for MOVES2014, we separated CNG buses with and without aftertreatment (AT), such as oxidation catalysts, to determine if this was a reasonable distinction, and to see if these vehicles' emission rates for criteria pollutants varied by model year and by age. For some model years, both vehicles with and without aftertreatment existed. Criteria emission improvements between the vehicles with aftertreatment versus those without were primarily inconclusive and did not exhibit any clear trends.[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. Note that we decided to exclude one of the studies that had four MY 2001 buses tested on the WMATA cycle from the analysis to develop MY 1994-2001 rates. This was done because inclusion increased the complexity of analysis by having to deal with two driving cycles within a model year group while providing only an incremental increase in sample size.

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

4.2.1.2 MY 2002-2006

Of the surveyed data, only one study had vehicles newer than MY 2001.[z,126] This paper, a joint study between NREL and WMATA, had three MY 2004 vehicles. The MY 2004 vehicles have a visibly different emissions profile than the other vehicles. While these buses were only tested on the WMATA cycle, they were all equipped with oxidation catalysts and had substantially lower emissions, particularly for PM, compared to the 1994-2001 buses tested on the CBD cycle. As a result, we created a second model year group from MY 2002 to MY 2006 based on the MY 2004 buses tested on the WMATA cycle. This MY group ends before MY 2007 when a new series of stringent emission standards went into effect, as described below.[127]

4.2.1.3 MY 2007-2009 and MY 2010+

Certification emission data for natural gas heavy-duty vehicles are publicly available by model year on the EPA's Office of Transportation and Air Quality website.[128] Analysis of these data showed that from MY 2002 to MY 2017, there have been changes in average certification levels for all the pollutants considered in this report. In particular, NO_x and PM levels have dropped dramatically over that decade. This effect is largely attributable to increasingly stringent emission standards, which have affected both diesel and CNG engines.

In MOVES_CTI_NPRM, we split the MY 2007-2012 group into two groups, MY 2007-2009 and MY 2010+ (noted as MY 2010-2017 when comparing certification data). We decided to split the groups in this way because: (1) changes to f_{scale} values starting MY 2010 requires rates to be re-analyzed using 1 hz data; (2) the HDIUT data set has MY 2010+ CNG vehicles; and (3) certification data showed a significant difference between the average emissions rates, for NO_x and CO, between these two model year groups (but note that certification data for is not used in developing the rates for MY2010+). Emission rates from analysis of certification data and number of CNG engine families in the certification data are shown in Table 4-2 below. The current, and historically most stringent, heavy-duty compression-ignition NO_x standard of 0.20 g/bhp-hr was fully phased in by 2010 and MY 2010+ heavy-duty CNG engines are required to meet this standard (even if they are not compression-ignition). Thus, the average NO_x certification value for the MY 2010-2017 group is considerably lower compared to the MY 2007-2009 group. At the same time, and mostly to meet the new NO_x standard, heavy-duty CNG engines transitioned from lean-burn to stoichiometric-combustion with TWC. This technology transition is the likely reason for the increase in CO emissions rates from MY 2007-2009 to MY 2010-2017 and has been observed in more recent testing with stoichiometric-combustion with TWC based CNG buses.[129,130]

[z] Several papers have discussed more recent vehicles. Examples include Clark et al. (2007).[126] 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.

Table 4-2 Model Year Group Based Certification Emission Rate for Heavy-Duty CNG Engine Families

Model Year Group	Number of Engine Families[a,b]	Certification Emission Rate (g/bhp-hr)[c]			
		NO_X	CO	PM	NMHC[d]
2002-2006	22	1.208	1.355	0.0078	0.147
2007-2009	30 (24 for PM)	0.6123	1.940	0.0042	0.063
2010-2017[e]	*159 for NO_X and CO, 153 for HC, and 120 for PM*	*0.1051*	*4.413*	*0.0028*	*0.044*

Notes:
[a] For MY 2002-2006, the number of engine families is based on HD CNG urban bus regulatory class. For MY 2007-2009 and MY 2010-2017, the number of engine families is based on all HD CNG engine families.
[b] Some engine families did not report emission data for HC and/or PM.
[c] MY 2002-2006 group emission rates are projected sales weighted average of HD CNG urban bus certification emission rates. MY 2007-2009 and 2010-2017 group emission rates are simple average of all HD CNG certification emission rates (no weighting for projected sales).
[d] Certification data has measurements of organic material non-methane hydrocarbon equivalent (OMNMHCE). For this analysis they were treated as NMHC values.[131]
[e] Only shown for comparison. Certification data for MY 2010-2017 is not used in developing MY 2010+ rates, which are based on MY 2010+ CNG vehicles in the HDIUT data set.

4.2.2 Emissions Rates by Model Year Group

4.2.2.1 MY 1994-2001 and MY 2002-2006

The OpMode based emissions rates for MHD gasoline vehicles were adjusted by the ratio of cycle-average emissions rates from chassis dynamometer measurements (see Section 4.1.4) to simulated cycle modeling (see Section 4.1.3). For MY 1994-2001 and MY 2002-2006, the adjustment ratios were based on the CBD cycle and WMATA cycle, respectively.

For each model year group, a central model year was selected as the source for the MHD gasoline OpMode based rates. For MY group 1994-2001, we used MHD gasoline rates from MY 1997 because it is one of the median years in the group. Alternatively, we could have used the other median year, MY 1998. Even though the average rate for MY 1998 was significantly lower (44 percent of that of MY 1997), based on Equation 4-2, we expect minimal differences in the final estimated CNG rates (R_{CNG} term) whether we use MY 1997 or MY 1998 as the median year since the lower OpMode rates (R_{MDG} term) will lead to lower simulated cycle-average rate (E_{MDG} term), which in turn will lead to larger adjustment ratio (E_{CNG}/E_{MDG}). For MY group 2002-2006, we used MHD gasoline rates from MY 2004 because that was the model year of the engine in each of the CNG vehicles measured on the chassis dynamometer (the MY 2001 vehicles were not included in this group). See Equation 4-2 and Equation 4-3 for MY groups 1994-2001 and 2002-2006, respectively.

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

Equation 4-2

$$R_{CNG,OM,2002-2006} = R_{MDG,OM,2004} * \frac{E_{CNG,WMATA,2004}}{E_{MDG,simWMATA,2004}}$$ **Equation 4-3**

Where:
$R_{CNG,OM,MYG}$ = OpMode based emissions rate for CNG vehicles for model year group (MYG) 1994-2001 or MY 2002-2006, in g/hr
$R_{MDG,OM,MY}$ = OpMode based emissions rate for MHD gasoline vehicles for model year 1997 or 2004 (corresponding to MYG), in g/hr
$E_{CNG,Cycle,MYG}$ = Chassis dynamometer cycle-average emissions rate for MY 1994-2001 or 2004 CNG buses tested on a CBD or WMATA cycle, respectively, in g/mile. See Table 4-4.
$E_{MDG,simCycle,MY}$ = Simulated cycle-average emissions rate for MY 1997 or 2004 MHD gasoline vehicles for CBD or WMATA cycle, respectively, in g/mile. This cycle-average rate is calculated using the $R_{MDG,OM,MY}$ OpMode rates. See Table 4-4.

4.2.2.2 MY 2007-2009

Due to lack of published data on MY 2007-2009 in-use vehicles, we used certification emissions rates, shown in Table 4-2, to scale the OpMode based emissions rates. Certification emissions rates are reported in grams per brake horsepower-hour (g/bhp-hr) and are not directly used in formulating MOVES emission rates because they do not include real-world effects such as deterioration.[132] These real-world effects were present in the chassis dynamometer measurements that were used in estimating emissions rates for MY 1994-2001 and MY 2002-2006. So, we created scaling factors that we could apply to the MY 2002-2006 emissions rates to estimate rates for MY 2007-2009. This scaling factor is the right-most term in Equation 4-4 shown below.

$$R_{CNG,OM,2007-2009} = R_{MDG,OM,2004} * \frac{E_{CNG,WMATA,2004}}{E_{MDG,simWMATA,2004}} * \frac{C_{CNG,2007-2009}}{C_{CNG,2002-2006}}$$ **Equation 4-4**

Where:
$C_{CNG,newMYG}$ = Average certification emission rate of all heavy-duty CNG engine families of model year MY 2007-2009 or MY 2010-2017, in g/bhp-hr
$C_{CNG,2002-2006}$ = Projected sales weighted average certification emission rate for CNG urban bus engine families in MY 2002-2006, in g/bhp-hr

4.2.2.3 MY 2010+

For developing MY 2010+ emissions rates (for THC, CO, NO_x, and $PM_{2.5}$) and energy consumption rates based on CO2, we used the MY 2010+ CNG vehicles in the HDIUT data set. At the time of analysis, there were five MY 2011 vehicles and six MY 2014 vehicles. These 11 vehicles are all stoichiometric-combustion with TWC and are certified at or below the 0.20 g/bhp-hr standard. The post-QA 1 hz data set included about 310,000 seconds of operation. OpModes (Table 1-3) were assigned to the 1 hz data using the method to calculate STP described in section 2.1.1.2. The analysis used updated f_{scale} values described in section 2.1.1.4.1 and Appendix G and thus, there was no need for hole-filling of missing OpModes. The OpMode-based rates were calculated using f_{scale} = 10. The rates for regClass 47 and 48 are identical. Unlike the analysis method for HD diesel (described in section 2.1.1.3.2), the method for HD CNG did not use the NO_x FEL based grouping since all 11 vehicles are in the same NO_x FEL group. As a result, the zero-mile (age 0) THC, CO, NO_x, and $PM_{2.5}$ rates for CNG are identical for all model years starting 2010 (unlike HD diesel where they change for each model year in 2010-2015 based on production volume differences between the NO_x FEL groups)

Age-based deterioration factors:

THC, CO, and NO_x age-based deterioration factors for MY 2010+ CNG vehicles in MOVES_CTI_NPRM are unchanged from MOVES2014. In MOVES2014, these factors are identical to MY 2010+ HD gasoline vehicles, which in turn are identical to and based on MY 1960-2007 HD gasoline vehicles. There is no deterioration for age groups 0-3 and 4-5 and the deterioration factor (per OpMode) is same across age groups for ages 6+ but varies between OpModes within an age group. These deterioration factors are described in Table 3-13 in Section 3.1.1.4.

For $PM_{2.5}$, in MOVES_CTI_NPRM, ages 0-3 and 4-5 have no deterioration and the MOVES2014 deterioration factor for age 6-7 is applied to all ages 6+, thus making the PM and gaseous pollutant methods more (but not fully) aligned. In MOVES2014, each of the age groups starting age 4+ had a unique deterioration factor. Note that, unlike gaseous pollutants, the PM deterioration factor does not vary between OpModes for a given age group. See Section 3.1.2.1.3 for more details and Table 4-3 for a comparison between MOVES_CTI_NPRM and MOVES2014.

Table 4-3 Age-based Deterioration Factor for PM Emission Rates for HHD and Urban Bus CNG Vehicles in Model Year 2010+

	PM Deterioration Factor	
Age	**MOVES2014**	**MOVES_CTI_NPRM[1]**
0-3 (Baseline)	1.00	1.00
4-5	1.57	1.00
6-7	1.75	1.75
8-9	1.96	1.75
10-14	2.38	1.75
15-19	3.14	1.75
20+	4.15	1.75

Note:
[1] When recreating the deterioration factor, for age 6+, from the age-group based default emissions rates in the MOVES database, the ratios will not be exactly 1.75 because the final rates (with deterioration factors already applied) are rounded to a set precision before submission to the database.

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

The adjustment ratio for energy consumption for MY 2002-2006 (Equation 4-3) is applied to all model years in 2007-2009. For MY 2007+, we did not scale the energy consumption rates like we did for criteria pollutants (Equation 4-4) because even though we have certification data on CO_2 emission rates for 2007-2009 model years, we do not have certification data on CO_2 emission rates for MY 2002-2006. As a result, MY 2007-2009 energy consumption rates are identical to the MY 2002-2006 rates.

Further, for energy consumption in MOVES_CTI_NPRM, we split the MY 2010+ group into MY 2010-2013, MY 2014-2017, and MY 2018+ groups. The MY 2010-2013 energy consumption rates are identical across these model years and based solely on the HDIUT data set analysis. For MY 2014-2017, the CNG energy consumption rates of MY 2013 are reduced by the percentage reduction assigned to HHD vehicles in the Greenhouse Gas Emissions Standards and Fuel Efficiency Standards for Medium and Heavy-Duty Engines and Vehicles — Phase 1 rule[51] (see Table 2-22). Similarly, for MY 2018 and later, using MY 2017 rates as base year, the energy consumption rates of CNG vehicles are further reduced as per the Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium and Heavy-Duty Engines and Vehicles — Phase 2 rule[52] (see Table 2-23). Note that the Phase 1 reduction for CNG vehicles is identical across all allowed source type and regulatory class combinations. However, for the Phase 2, different reductions for CNG vehicles are applied by source type and regulatory class (see Table 2-23). The anticipated improvements in fuel efficiency from the Phase 2 rules are stored in the EmissionRateAdjustment table.

Table 4-4 Ratios Applied to MHD Gasoline Rates to Compute CNG Rates

E_{CNG}, Cycle-Average Chassis Dynamometer Measurement Rates (g/mile)								
MY	**Age Group**	**Cycle**	**NO_X**	**CO**	**PM_NonEC**	**PM_EC**	**THC**	**TOTAL ENERGY (BTU/mi)**
1994-2001	0-3	CBD	20.8	9.97	0.037	0.0038	13.2	42782
2002-2006	0-3	WMATA	9.08	2.17[a]	0.0039	0.0005	11.2	40900
E_{MDG}, Simulated Cycle-Average Medium Heavy-Duty Gasoline Rates (g/mile)								
MY	**Age Group**	**Simulated Cycle**	**NO_X**	**CO**	**PM_NonEC**	**PM_EC**	**THC**	**TOTAL ENERGY (BTU/mi)**
1997	0-3	CBD	9.63	62.4	0.0024	0.0002	1.84	31137
2004	0-3	WMATA	5.45	18.9	0.0035	0.0003	1.43	35489
Ratios Applied to the Medium Heavy-Duty Gasoline Rates to Create CNG Rates								
MY	**Age Group**	**MHD Gasoline MY[b]**	**NO_X**	**CO**	**PM_NonEC**	**PM_EC**	**THC**	**TOTAL ENERGY**
1994-2001[c]	all	1997	2.16	0.160	15.5	21.6	7.17	1.37
2002-2006[c]	all	2004	1.67	0.115	1.09	1.87	7.79	1.15
2007-2009[d]	all	2004	0.842	0.157	0.587	1.01	3.34	1.15
2010+[e]	Age 0- 3 (and 4-5) rates are based on analysis of 1 hz data from MY 2010+ CNG vehicles in the HDIUT data set. Ages 6+ apply deterioration factors to age 0-3 rates as described in main text.							

Notes:
[a] The measured CO rate (0.14 g/mi) was uncharacteristically low and thus determined to be an outlier and not used. Each of the three post-2001 vehicles in this study had the same MY 2004 engine (John Deere 6081H). This engine's CO certification rate was a full order of magnitude lower than certification rate of other MY 2004 engine models, and was not supported by additional test results. We adjusted the WMATA chassis dynamometer CO rate by the ratio between the sales-weighted average CO certification level of all MY 2004 CNG engine models and the CO certification level for the MY 2004 John Deere 6081H engine.
[b] Model year of the medium heavy-duty gasoline OpMode rates to which the pollutant-specific ratios are applied
[c] The ratios are calculated using Equation 4.2 or Equation 4.3 and the E_{CNG} and E_{MDG} values in this table
[d] The ratios are calculated using Equation 4.4, the E_{CNG} and E_{MDG} values in this table, and the C_{CNG} values in Table 4.2
[e] Energy consumption rates for MY 2014-2017 and MY 2018+ are reduced as per heavy-duty GHG Phase 1 and Phase 2 rules, respectively. See main text for details.

4.2.2.4.1 Other Model Years, Age Groups, and Deterioration

We assumed that the MY 1993 and earlier CNG buses have the same emission rates as MY group 1994-2001.

Due to limited data on older vehicles in the literature, the ratios (shown in Table 4-4) developed using vehicles in the 0-3 age group have been applied to all other age groups. In addition, we assumed that CNG vehicles exhibit the same deterioration trend as medium heavy-duty gasoline trucks (Table 3-13 in Section 3.1.1.4 for HC, CO and NO_x, and Section 3.1.2.1.3 for PM).

4.3 Start Exhaust Emission Rates

In the absence of any measured start exhaust emissions from CNG vehicles, their start rates are copied from the MOVES pre-2010 heavy-duty diesel start rates for all pollutants including energy rates. We believe this is an environmentally conservative approach, rather than assuming zero CNG start emissions. MOVES still estimates that the majority of emissions from CNG vehicles are from running emissions, which are based on CNG test programs. We acknowledge that the diesel start rates may not accurately represent CNG start rates.

4.4 Ammonia and Nitrous Oxide emissions

No data were available on ammonia emissions rates from CNG vehicles at the time the rates were developed. We used the ammonia emissions for heavy-duty gasoline vehicles, which are documented in a separate report.[8]

The nitrous oxide emission rates for CNG in MOVES remain unchanged from MOVES2009 and later versions and are documented in the MOVES201X Greenhouse Gas Emissions Report.[7]

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.[133]

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.[134] 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'.[133] 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 [135] [136] [137]. 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.[138] Most manufacturers have adopted open crankcase filtration systems.[133] 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.[133] 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.[139]

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

Table 5-1 Literature Review on the Contribution of Crankcase Emissions to Total Diesel Emissions (Exhaust + Crankcase)

Study	Model Year	Type	# Engines/ Vehicles	HC	CO	NO_X	PM
Hare and Baines, 1977[142]	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[135], Ireson et al. 2011[136]	2000, 2003	Conv. Diesel	2				13.5% - 41.4%
Clark et al. 2006[141], Clark et al. 2006[140]	2006	Conv. Diesel	1	3.6%	1.3%	0.1%	5.9%
Khalek et al. 2009	2007	DPF-equipped	4	95.6%	27.2%	-0.2%	38.2%

5.2 Modeling Crankcase Emissions in MOVES

MOVES calculates THC, CO, NO_x, and $PM_{2.5}$ using a gaseous and a particulate crankcase emission calculator. Within the calculator, crankcase emissions are calculated as a fraction of tailpipe exhaust emissions, including start, running, and extended-idle. As discussed in the background section above, the 2007 heavy-duty diesel emission regulations impacted the technologies used to control exhaust and crankcase emissions. The regulations also expanded the types of emissions data included in certification tests, by including crankcase emissions in the regulatory standards, which previously included only tailpipe emissions. Because heavy-duty diesel engine manufacturers are using open-filtration crankcase systems, the crankcase emissions are included in the emission certification results. In MOVES, the base exhaust rates for 2007 and later diesel engines are based on certification levels.

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

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

5.3 Conventional Heavy-Duty Diesel

Table 5-2 includes the crankcase/tail-pipe emission ratios used for conventional diesel exhaust. For HC, CO, and NO_x, we selected the values measured on the MY2006 diesel engine reported by Clark et al. 2006.[141] These values compare well with the previous HC, CO, NO_x values reported much earlier by Hare and Baines (1977),[142] which represent much older diesel technology. The similarity of the crankcase emission ratios across several decades of diesel engines, suggests that for conventional diesel engines, crankcase emissions can be well represented as a fraction of the exhaust emissions.

For $PM_{2.5}$ emissions, we use a crankcase/tail-pipe ratio of 20 percent. The 20 percent ratio falls within the range of observations from the literature on diesel PM emissions. Zielinska et al. 2008[135] and Ireson et al. 2011[136] reported crankcase contributions to total $PM_{2.5}$ emissions as high as 40 percent. Jääskeläinen (2012)[133] reported that crankcase can contribute as much as 20 percent of the total emissions from a review of six diesel crankcase studies. Similarly, an industry report estimated that crankcase emissions contributed 20 percent of total particulate emissions from 1994-2006 diesel engines.[143]

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

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

As outlined in the MOVES2014 TOG and PM Speciation Report, MOVES does not apply the crankcase/tailpipe emission ratio in Table 5-4 to the total exhaust $PM_{2.5}$ emissions. MOVES applies the crankcase/tailpipe emission ratios to $PM_{2.5}$ subspecies: elemental carbon $PM_{2.5}$, sulfate $PM_{2.5}$, aerosol water $PM_{2.5}$, and the remaining PM (nonECnonSO4PM). This allows MOVES to account for important differences in the PM speciation between tailpipe and crankcase emissions.

The pre-2007 diesel ratios are derived such that the total crankcase $PM_{2.5}$/exhaust $PM_{2.5}$ ratio is 20 percent, and the crankcase emissions EC/PM fraction reflects measurements from in-use crankcase emissions. Zielinska et al. 2008[135] reported that the EC/PM fraction of crankcase emissions from two conventional diesel buses is 1.57 percent. Tailpipe exhaust from conventional diesel engines is dominated by elemental carbon emissions from combustion of the diesel fuel, while crankcase emissions are dominated by organic carbon emissions largely contributed from the lubricating oil.[135,136] The crankcase emission factors shown in Table 5-3. are derived such that the crankcase $PM_{2.5}$ emissions are 20 percent of the $PM_{2.5}$ exhaust measurements, and have an EC/PM split of 1.57 percent.

The PM_{10} emission rates are subsequently estimated from the $PM_{2.5}$ exhaust and crankcase emission rates using PM_{10}/$PM_{2.5}$ emission ratios as documented in the MOVES Speciation Report.[1]

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

Pollutant	Process	Start	Running	Extended Idle
EC	Exhaust	1	1	1
nonECnonSO4PM		1	1	1
SO4		1	1	1
H2O		1	1	1
EC	Crank-case	0.007	0.004	0.007
nonECnonSO4PM		0.367	0.937	0.367
SO4		0.367	0.937	0.367
H2O		0.367	0.937	0.367

5.4 2007+ Heavy-Duty Diesel

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

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

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

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

For $PM_{2.5}$ emissions, we used data from the ACES Phase 1 test program to inform the crankcase and exhaust ratios for the updated $PM_{2.5}$ crankcase emissions calculator. The crankcase emissions measured in the ACES Phase 1 test program contributed 38 percent of the total $PM_{2.5}$ emissions on the hot-FTP driving cycle. Other tests suggest that the crankcase emissions can contribute to over 50 percent of the particulate matter emissions from 2007 and later diesel technologies.[143]

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

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

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

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

As a special case, the crankcase emissions from the glider vehicles are handled in a different way. Like other exhaust emissions rates as described in 2.5, the crankcase emissions for the glider vehicles are set to the rates equal to the model year 2000 regular heavy heavy-duty vehicle rates.

5.5 Heavy-Duty Gasoline and CNG Emissions

The data on heavy-duty gasoline and CNG crankcase emissions are limited. All 1969 and later spark ignition heavy-duty engines are required to control crankcase emissions. All gasoline engines are assumed to use positive crankcase ventilation (PCV) systems, which route the crankcase gases into the intake manifold. For heavy-duty gasoline engines we use the same values of crankcase emission ratios as light-duty gasoline, which are documented in the MOVES light-duty emission rates report.[10] We assume 4 percent of PCV systems fail, resulting in the small crankcase to exhaust emission ratios shown in Table 5-6 for 1969 and later gasoline engines. Due to limited information, we used the gasoline heavy-duty crankcase emission factors for heavy-duty CNG engines because they have low crankcase PM emissions.

Table 5-6 Crankcase to Tailpipe Exhaust Emission Ratio for Heavy-Duty Gasoline and CNG Vehicles for HC, CO, NO_X, and $PM_{2.5}$

Pollutant	pre-1969	1969 and later
HC	0.33	0.013
CO	0.013	0.00052
NO_X	0.001	0.00004
PM (all species)	0.20	0.008

The crankcase and exhaust ratios used by the crankcase calculator for $PM_{2.5}$ emissions from heavy-duty gasoline and compressed natural gas vehicles are provided in Table 5-7. No information is available to estimate separate speciation between exhaust and crankcase, so the factors are the same between the PM subspecies.

Table 5-7 MOVES Exhaust and Crankcase Ratios for Heavy-Duty Gasoline and CNG Vehicles by Pollutant, Process, Model Year Group, and Fuel Type, and Source Type for $PM_{2.5}$ Species

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

6 Nitrogen Oxide Composition

This section discusses the values used to estimate nitric oxide (NO), nitrogen dioxide (NO_2) and nitrous acid (HONO) from nitrogen oxide (NO_x) emissions from heavy-duty vehicles. A similar section on NO_x composition from light-duty emissions is included in the light-duty emissions report. NO_x emissions are reported in mass-equivalent space of NO_2. In other words, the molar mass of NO_2 (46 g/mole) is used to calculate grams of NO_x from the molar concentration of NO_x.

Nitrogen oxides (NO_x) are defined as NO + NO_2.[144,145] NO_x is considered a subset of reactive nitrogen species (NO_y) with a nitrogen oxidation state of +2 or greater which contain other nitrogen containing species (NO_z), thus $NO_y = NO_x + NO_z$.[144] NO_z compounds are formed in the atmosphere as oxidation products of NO_x.[145]

Chemiluminescent analyzers used for exhaust NO_x measurements directly measure NO, as NO is oxidized by ozone to form NO_2 and produces florescent light. Chemiluminescent analyzers measure NO_x (NO + NO_2) by using a catalyst that reduces the NO_2 to NO in the sample air stream before measurement. NO_2 is calculated as the difference between NO_x and NO measurements. The NO_x converter within chemiluminescent analyzers can also reduce other reactive nitrogen species (NO_z), including HONO to NO. If the concentrations of NO_z interfering species in the sample stream are significant relative to NO_2 concentrations, then they can bias the NO_2 measurements high.[146]

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.[8]

MOVES also produces estimates of one important NO_z species, nitrous acid (HONO), from the NO_x values. HONO emissions are estimated as a fraction (0.8 percent) of NO_x emissions from all vehicle types in MOVES, based on HONO and NO_x measurements made at a road tunnel in Europe.[147] 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 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.[148]

6.1 Heavy-Duty Diesel

Table 6-1 shows the NO_x and HONO fractions for heavy-duty diesel vehicles. The conventional diesel (1960-2006 model year) NO_x fractions were estimated as the average reported fraction from three studies of heavy-duty vehicles not equipped with diesel particulate filters.[8] 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[8] were reduced by 0.008 to account for the HONO emissions.

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

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

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

6.2 Heavy-Duty Gasoline

The NO_x fractions for heavy-duty gasoline are based on the MOVES values used for light-duty gasoline measurements. Separate values are used for running and start emission processes. As stated in the Sierra Report,[8] 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[8] were reduced by 0.008 to account for the HONO emissions.

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

Light-Duty gasoline model year groups	Heavy-Duty gasoline model year groups	Running			Start		
		NO	NO_2	HONO	NO	NO_2	HONO
1960-1980	1960-1987	0.975	0.017	0.008	0.975	0.017	0.008
1981-1990	1988-2004	0.932	0.06	0.008	0.932	0.031	0.008
1991-1995	2005-2007	0.954	0.038	0.008	0.987	0.005	0.008
1996-2060	2008-2060	0.836	0.156	0.008	0.951	0.041	0.008

6.3 Compressed Natural Gas

We used the average of three NO_2/ NO_x fraction reported on three CNG transit buses with DDC Series 50 G engines by Lanni et al. (2003)[122] with the 0.008 HONO fraction assumed for other source types, to estimate the NO_x fractions of NO, NO_2, and the HONO fraction. These assumptions yield the NO_x and HONO fractions in Table 6-3, which are used for all model year CNG heavy-duty vehicles.

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

Model Year	NO	NO_2	HONO
1960-2060	0.865	0.127	0.008

7 Appendices

Appendix A Calculation of Accessory Power Requirements

Table A-1. Accessory Load Estimates for HHD Trucks

VSP	Cooling Fan	Air cond	Air comp	Alternator	Engine Accessories	Total Accessory Load (kW)
Low			Off = 0.5 kW			
Power (kw)	19.0	2.3	3.0	1.5	1.5	
% time on	10%	50%	60%	100%	100%	
Total (kW)	1.9	1.2	2.0	1.5	1.5	8.1
Mid			Off = 0.5 kW			
Power (kw)	19.0	2.3	2.3	1.5	1.5	
% time on	20%	50%	20%	100%	100%	
Total (kW)	3.8	1.2	0.9	1.5	1.5	8.8
High			Off = 0.5 kW			
Power (kw)	19.0	2.3	2.3	1.5	1.5	
% time on	30%	50%	10%	100%	100%	
Total (kW)	5.7	1.2	0.7	1.5	1.5	10.5

Table A-2. Accessory Load Estimates for MHD Trucks

VSP	Cooling Fan	Air cond	Air comp	Alternator	Engine Accessories	Total Accessory Load (kW)
Low			Off = 0.5 kW			
Power (kw)	10.0	2.3	2.0	1.5	1.5	
% time on	10%	50%	60%	100%	100%	
Total (kW)	1.0	1.2	1.4	1.5	1.5	6.6
Mid			Off = 0.5 kW			
Power (kw)	10.0	2.3	2.0	1.5	1.5	
% time on	20%	50%	20%	100%	100%	
Total (kW)	2.0	1.2	0.8	1.5	1.5	7.0
High			Off = 0.5 kW			
Power (kw)	10.0	2.3	2.0	1.5	1.5	
% time on	30%	50%	10%	100%	100%	
Total (kW)	3.0	1.2	0.7	1.5	1.5	7.8

Table A-3. Accessory Load Estimates for Buses

VSP	Cooling Fan	Air cond	Air comp	Alternator	Engine Accessories	Total Accessory Load (kW)
Low			Off = 0.5 kW			
Power (kw)	19.0	18.0	4.0	1.5	1.5	
% time on	10%	80%	60%	100%	100%	
Total (kW)	1.9	14.4	2.6	1.5	1.5	21.9
Mid			Off = 0.5 kW			
Power (kw)	19.0	18.0	4.0	1.5	1.5	
% time on	20%	80%	20%	100%	100%	
Total (kW)	3.8	14.4	1.2	1.5	1.5	22.4
High			Off = 0.5 kW			
Power (kw)	19.0	18.0	4.0	1.5	1.5	
% time on	30%	80%	10%	100%	100%	
Total (kW)	5.7	14.4	0.9	1.5	1.5	24.0

Appendix B Tampering and Mal-maintenance

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.

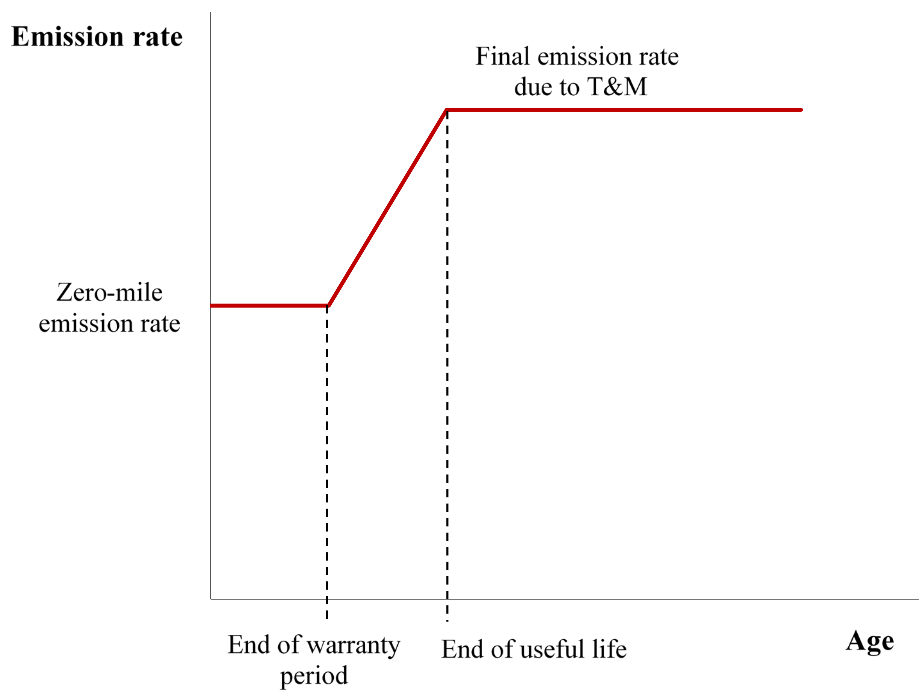


Figure B-1. Qualitative Depiction of the Implementation of Age Effects

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

a. The warranty age and useful life age here are based on typical miles driven by vehicles in the regulatory class. For example, HHD vehicles typically accumulate a large number of miles per year (100,000+/year). Thus, HHD vehicles complete their warranty and useful life requirements based on mileage while the vehicle age is still much below the requirement.

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

Since MOVES deals with age groups and not individual ages, the increase in emissions by age must be calculated by age group. We assumed that there is an even age distribution within each age group (e.g. ages 0, 1, 2, and 3 are equally represented in the 0-3 age group). This is important since, for example, HHD trucks reach their useful life at four years, which means they will increase emissions through the 0-3 age group. As a result, the 0-3 age group emission rate will be higher than the zero-mile emission rate for HHD trucks. Table B-2 shows the multiplicative T&M adjustment factor by age. We determined this factor using the mileage-age data from Table B-1 and the emissions-age relationship that we described in Figure B-1. We multiplied this factor by the emissions increase of each pollutant over the useful life of the engine, which we determined from the analysis in sections B.7 through B.9.

Table B-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 Equation B-1. TM_{pol} represents the estimated emissions rate increase through the useful life for a given pollutant.

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

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[150] (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 NO_x Traps (LNT) for the NO_x control in 2010 and beyond. On the other hand, we also assumed that Selective Catalyst Reduction (SCR) systems will be the primary NO_x aftertreatment system for HHDD. Therefore, the occurrence rates and emission impacts will vary in 2010 and beyond depending on the regulatory class of the vehicles.

B.4 T&M Model Year Groups

EPA developed the model year groups based on regulation and technology changes.

- Pre-1994 represents non-electronic fuel control.
- 1998-2002 represents the time period with consent decree issues.
- 2003 represents early use of EGR.
- 2007 and 2010 contain significant PM and NO_x regulation changes.
- 2010-and later represent heavy-duty trucks with required OBD. This rule began in MY 2010 with complete phase-in by MY 2013. The OBD impacts are discussed in Section B.10.

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[151] so it cannot be ignored.

NO_x Aftertreatment malfunction: EPA developed a NO_x aftertreatment malfunction rate that is dependent on the type of system used. We assumed that HHDD will use primarily SCR systems and LHDD will primarily use LNT systems. We estimated the failure rates of the various components within each system to develop a composite malfunction rate (Table B-3).

The individual failure rates were developed considering the experience in agriculture and stationary industries of NO_x aftertreatment systems and similar component applications. Details are included in the chart below. We assumed that tank heaters had a five percent failure rate but were only required in one third of the country during one fifth of the year. The injector failure rate is lower than fuel injectors, even though they have similar technology, because there is only one required in each system and it is operating in less severe environment of pressure and temperature. We believe the compressed air delivery system is very mature based on a similar use in air brakes. We also believe that manufacturers will initiate engine power de-rate as incentive to keep the urea supply sufficient.

Table B-3. NO_X Aftertreatment Failure Rates

	Occurrence Rate
SCR	
Urea tank	0.5%
Tank heaters	1%
In-exhaust injectors	2%
Compressed air delivery to injector	1%
Urea supply pump	1%
Control system	5%
Exhaust temperature sensor	1%
Urea supply	1%
Overall	**13%**

LNT	
Adsorber	7%
In-exhaust injectors	2%
Control system	5%
Exhaust temperature sensor	1%
Overall	**16%**

NO_x aftertreatment sensor: EPA will assume a 10 percent failure mode for the aftertreatment sensor. We developed the occurrence rate based on the following assumptions:

- Population: HHDD: vast majority of heavy-duty applications will use selective catalytic reduction (SCR) technology with a maximum of one NO_x sensor. NO_x sensors are not required for SCR – manufacturers can use models or run open loop. Several engine manufacturers representing 30 percent of the market plan to delay the use of NO_x aftertreatment devices through the use of improved engine-out emissions and emission credits.
- Durability expectations: SwRI completed 6000 hours of the European Stationary Cycle (ESC) cycling with NO_x sensor. Internal testing supports longer life durability. Discussions with OEMs in 2007 indicate longer life expected by 2010.
- Forward looking assumptions: Manufacturers have a strong incentive to improve the reliability and durability of the sensors because of the high cost associated with frequent replacements.

PM Filter Leak: EPA will use 5 percent PM filter leak and system failure rate. They discounted high failure rates currently seen in the field.

PM Filter Disable: EPA agrees with CARB's 2 percent tamper rate of the PM filter. The filter causes a fuel economy penalty so the drivers have an incentive to remove it.
Oxidation Catalyst Malfunction/Remove: EPA believes most manufacturers will install oxidation catalysts initially in the 2007 model year and agrees with CARB's assessment of 5 percent failure rate. This rate consists of an approximate 2 percent tampering rate and 3 percent malfunction rate. The catalysts are more robust than PM filters, but have the potential to experience degradation when exposed to high temperatures.
Misfuel: EPA estimated that operators will use the wrong type of fuel, such as agricultural diesel fuel with higher sulfur levels, approximately 0.1 percent of the time.

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 NO_X Emission Effects

EPA developed the emission effect from each tampering and mal-maintenance incident from CARB's EMFAC, Radian's dynamometer testing with and without the malfunction present, Engine, Fuel, and Emissions Engineering Inc. (EFEE) results, and internal testing experience. EPA estimated that the lean NO_x traps (LNT) in LHDD are 80 percent efficient and the selective catalyst reduction (SCR) systems in HHDD are 90 percent efficient at reducing NO_x. EPA developed the NO_x emission factors of the NO_x sensors based on SCR systems' ability to run in open-loop mode and still achieve NO_x reductions. The Manufacturers of Emission Controls Association (MECA) has stated that a 75-90 percent NO_x reduction should occur with open loop control and >95 percent reduction should occur with closed loop control.[152] Visteon reports a 60-80 percent NO_x reduction with open loop control.[153]

In testing, the failure of the NO_x aftertreatment system had a different impact on the NO_x emissions depending on the type of aftertreatment. The HHDD vehicles with SCR systems would experience a 1000 percent increase in NO_x during a complete failure, therefore we estimated a 500 percent increase as a midpoint between normal operation and a complete failure. The LHDD vehicles with LNT systems would experience a 500 percent increase in NO_x during a complete failure. We estimated a 300 percent increase as a value between a complete failure and normal system operation.

The values with 0 percent effect in shaded cells represent areas which have no occurrence rate.

Tamper & Malmaintenance
NOX Emission Effect

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

Combining the NO_x emission effects with the frequency results in the initial Tampering & Mal-maintenance (T&M) effects shown in the Table B-4 below. As noted in Section 2.1.1.6, MOVES does not use the estimated NO_x increase from T&M for 2009 and earlier model years, and assumes no NO_x increase. This is incorporated into the 3rd column of Table B-4 labeled with (Remove 2009 and earlier).

Table B-4. Fleet-Average Tampering & Mal-Maintenance (TM) NO_X Emission Increases (Percent) from Zero-Mile Levels Calculated Over the Useful Life.

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

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

Lean NO_x trap (LNT) aftertreatment are assumed to penetrate 25 percent of LHD2b3 trucks starting in 2007, consistent with the assumptions previously made in Section 2.1.1.4.4.

The T&M rates for LHD2b3 in 2007-2009 are calculated by adjusting Equation 3-10 to account for T&M of LNT aftertreatment, as shown in Equation B-2:

$$\frac{2007-2009\ LNT\ NOx\ emissions\ (T\&M)}{2003-2006\ LHD2b3\ NOx\ emissions}$$

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

Equation B-2

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

The ratio of 2007-2009 LHD2b3 (with T&M) over the baseline 2003-2006 NO_x rates is calculated by adjusting Equation 3-11 to account for the T&M effects of LNT, as shown in Equation B-3.

$$\frac{2007-2009\ LHD2b3\ NOx\ emissions\ (T\&M)}{2003-2006\ LHD2b3\ NOx\ emissions}$$

$$= (LNT\ market\ share)\left(\frac{2007-2009\ LNT\ NOx\ emissions\ (T\&M)}{2003-2006\ LHD2b3\ NOx\ emissions}\right) + (non-LNT\ market\ share)\left(\frac{2007-2009\ emission\ standards}{2003-2006\ NOx\ emissions\ standards}\right)$$

Equation B-3

$$=0.25\times0.2548+0.75\times0.5=0.4387$$

Then, the overall T&M effect for 2007-2009 LHD2b3 is calculated in Equation B-4 by dividing Equation B-2 by Equation 3-11.

$$\frac{2007-2009\ LHD2b3\ NOx\ emissions\ (T\&M)}{2007-2009\ LHD2b3\ NOx\ emissions\ (zero\ mile)}$$

Equation B-4

$$= \left(\frac{2007-2009\ LHD2b3\ NOx\ (T\&M)}{2003-2006\ LHD2b3\ NOx\ emissions}\right)\Big/\left(\frac{2007-2009\ LHD2b3\ NOx\ (zero\ mile)}{2003-2006\ LHD2b3\ NOx\ emissions}\right)$$

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

For 2007-2009, LHD45 uses the same emission rates and T&M factors as for the LHD2b3 rates As noted earlier, we assume no NO_x increase for the pre-2007 for the other heavy-duty regulatory classes.

For 2010+, LHD2b3, we assume that both LNT and SCR equipped vehicles will provide the same level of control with a 90 percent reduction from 2003-2006 levels (ignoring the PM regeneration

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

$$\begin{aligned} &2010+\ LHD2b3\ NOx\ emissions\ T\&M \\ &= LNT\ market\ share \times 2010-2012\ \text{LNT T\&M} + non-LNT\ market\ share \times 2013+\text{SCR} \\ &= 0.25\times 0.48 + 0.75\times 0.58 = 56\% \end{aligned}$$

Equation B-5

For the Other HD regulatory classes (42-48) we use the SCR T&M effects from Table B-4. For the other HD, we assume only 33 percent OBD penetration in 2010-2012, and full penetration for 2013+ model years. Note that for 2010+ LHD45, we use the same T&M as the other heavy-duty regulatory classes, that assume no LNT penetration, and a phased-in OBD penetration. The NO_x T&M effects by the MOVES regulatory classes and model year groups are shown in Table B-5.

Table B-5. NO_X T&M Effects (Percent) by MOVES Regulatory Classes and Model Year Groups

Model Year Group	LH2b3 (RegClass 41)	LHD45 (RegClassID	Other HD (RegClassID 46,47,48)	Gliders (RegClass 49)
2007-2009	4%	4%	0%	0%
2010-2012	56%	77%	77%	0%
2013+	58%	58%	58%	0%

B.8 PM Emission Effects

EPA developed the PM emission effects from each tampering and mal-maintenance incident from CARB's EMFAC, Radian's dynamometer testing with and without the malfunction present, EFEE results, and internal testing experience.

EPA estimates that the PM filter has 95 percent effectiveness. Many of the tampering and mal-maintenance items that impact PM also have a fuel efficiency and drivability impact. Therefore, operators will have an incentive to fix these issues.

EPA estimated that excessive oil consumption will have the same level of impact on PM as engine mechanical failure. The failure of the oxidation catalyst is expected to cause a PM increase of 30 percent; however, this value is reduced by 95 percent due to the PM filter effectiveness. We also considered a DOC failure will cause a secondary failure of PM filter regeneration. We accounted for this PM increase within the PM filter disabled and leak categories.

The values with 0 percent effect in shaded cells represent areas which have no occurrence rate. In MOVES2014, we increased the PM emission effect for PM Filter Leaks and PM Filter Tampering for the 2007-2009 and 2010+ model year groups. The PM filter leak was increased from 600 percent to 935 percent and the PM Filter Disabled emission effect was increased from 1000 percent to 2670 percent. This results in a fleet average PM Tampering & Mal-maintenance effect of 100 percent in 2007-2009 and 89 percent in 2010-2012.

Tamper & Malmaintenance
PM Emission Effect

	1994-1997	1998-2002	2003-2006	2007-2009	2010
Federal Emission Standard	0.1	0.1	0.1	0.01	0.01
Timing Advanced	-10%	-10%	-10%	0%	0%
Timing Retarded	25%	25%	25%	1%	1%
Injector Problem	100%	100%	100%	5%	5%
Puff Limiter Mis-set	20%	0%	0%	0%	0%
Puff Limiter Dsabled	50%	0%	0%	0%	0%
Max Fuel High	20%	0%	0%	0%	0%
Clogged Air Filter	50%	50%	30%	2%	2%
Wrong/Worn Turbo	50%	50%	50%	3%	3%
Intercooler Clogged	50%	50%	30%	2%	2%
Other Air Problem	40%	40%	30%	2%	2%
Engine Mechanical Failure	500%	500%	500%	25%	25%
Excessive Oil Consumption	500%	500%	500%	25%	25%
Electronics Failed	60%	60%	60%	3%	3%
Electronics Tampered	50%	50%	50%	3%	3%
EGR Stuck Open	0%	0%	100%	5%	5%
EGR Disabled/Low Flow	0%	0%	-30%	-30%	-30%
NO_X Aftertreatment Sensor	0%	0%	0%	0%	0%
Replacement NO_X Aftertreatment Sensor	0%	0%	0%	0%	0%
NO_X Aftertreatment Malfunction	0%	0%	0%	0%	0%
PM Filter Leak	0%	0%	0%	935%	935%
PM Filter Disabled	0%	0%	0%	2670%	2670%
Oxidation Catalyst Malfunction/Remove	0%	0%	0%	0%	0%
Mis-fuel - EPA	30%	30%	30%	100%	100%

B.9 HC Emission Effects

EPA estimated oxidation catalysts are 80 percent effective at reducing hydrocarbons. All manufacturers will utilize oxidation catalysts in 2007, but only a negligible number were installed prior to the PM regulation reduction in 2007. We assumed that with Tampering and Mal-maintenance, the HC zero level emissions will increase by 50 percent. This still represents a 70 percent reduction in HC emissions between zero-mile 2006 emissions and fully deteriorated 2007 vehicles.

We reduced CARB's HC emission effect for timing advanced because earlier timing should reduce HC, not increase them. The effect of injector problems was reduced to 1000 percent based on EPA's engineering staff experience. We increased the HC emission effect of high fuel pressure (labeled as Max Fuel High) to 10 percent in 1994-1997 years because the higher pressure will lead to extra fuel in early model years and therefore increased HC. Lastly, we used the HC emission effect of advanced timing for the electronics tampering (0 percent) for all model years. The values with 0 percent effect in shaded cells represent areas which have no occurrence rate.

Tamper & Malmaintenance
HC Emission Effect

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

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

Combining all of the emissions effects and failure frequencies discussed in this section, we summarized the aggregate emissions impacts over the useful life of the fleet in the main body of the document in Table 2-10 (NO_X), Table 2-17 (PM), and Table 2-20 (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-1**

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

Appendix C Evaluation of NOx Emission Rates in MOVES2010

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

The purpose of the evaluation was to examine the need for updating the NO_x rates in MOVES2010 based on the analysis of the newly acquired independent data. As discussed in Section 2.1.1.1, HDIUT 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.

C.1 Heavy Heavy-Duty Trucks

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

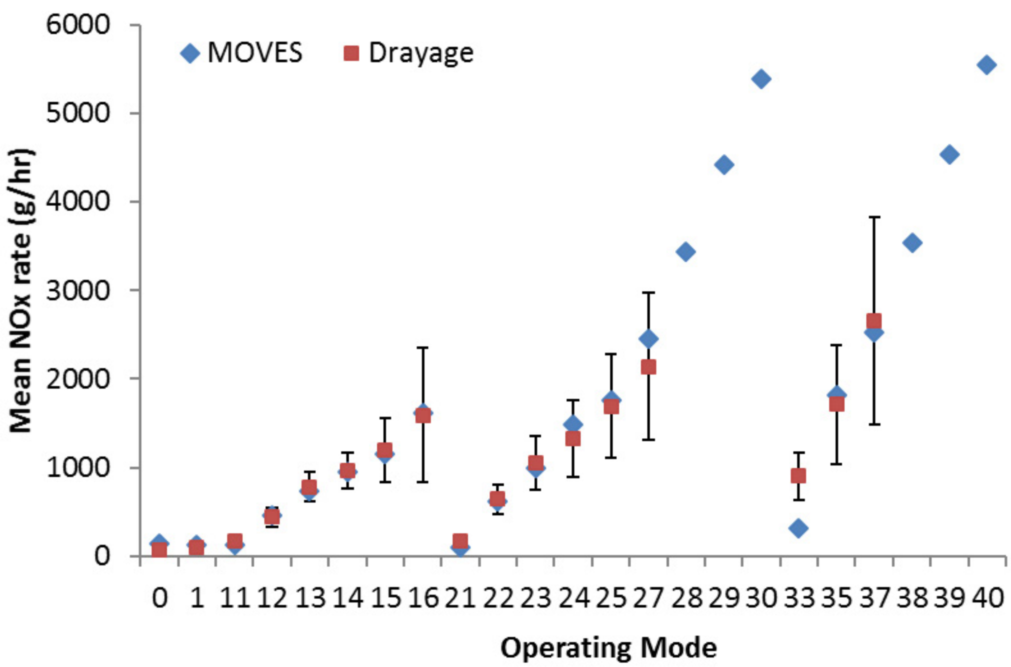


Figure C-1. Comparison of Means: MOVES2010 emission rates vs. Houston Drayage Data (n=8) for model years 1991-1997 HHD trucks. Error bars represent the 95 percent confidence interval of the mean

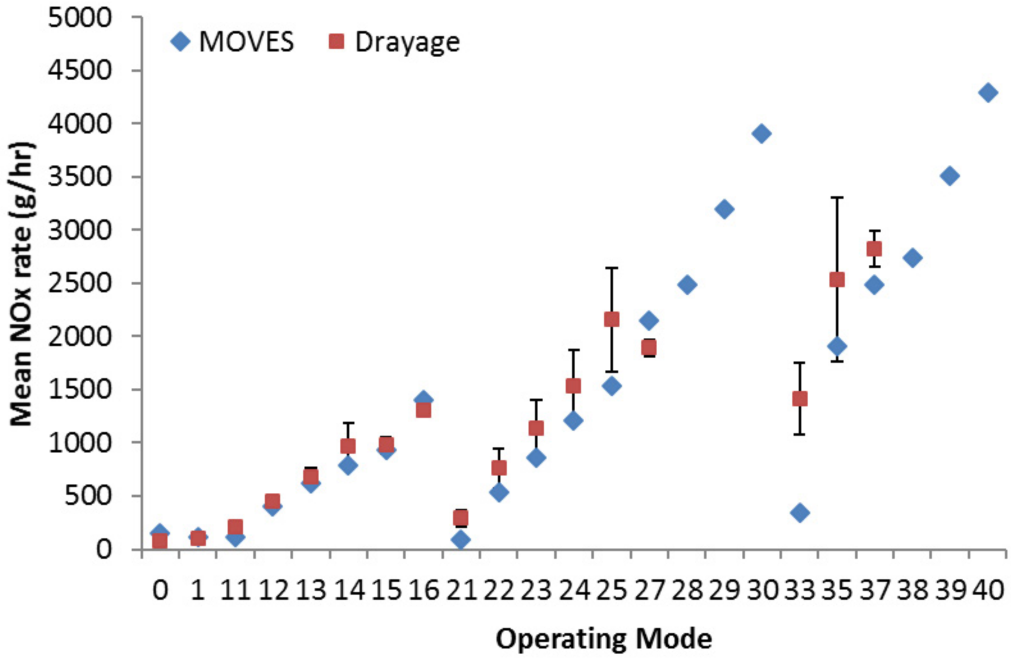


Figure C-2. Comparison of Means: MOVES2010 emission rates vs. Houston Drayage Data (n=1) for model year 1998 HHD trucks. Error bars represent the 95 percent confidence interval of the mean

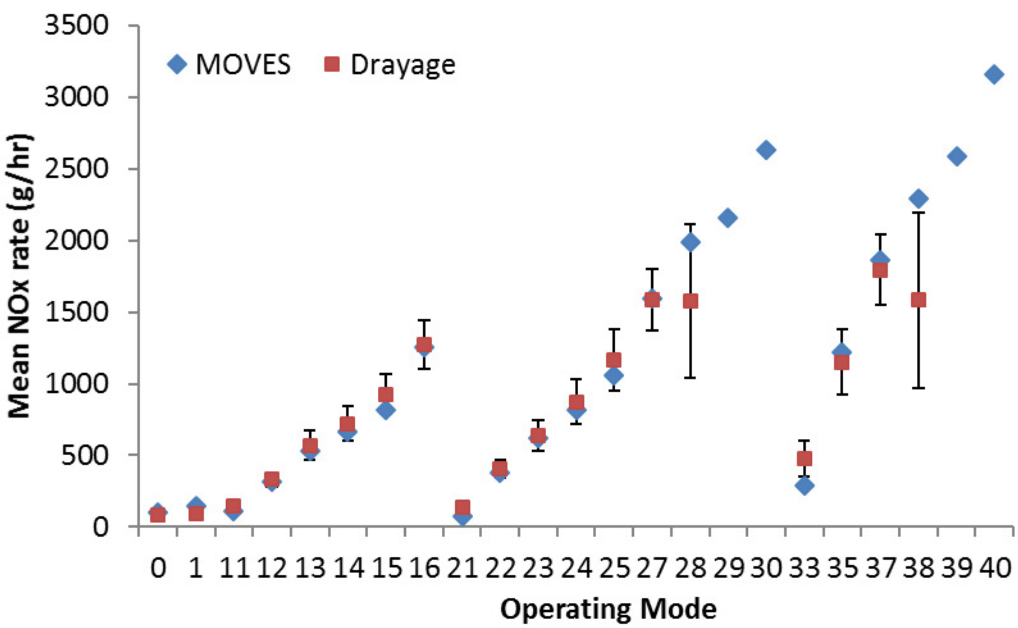


Figure C-3. Comparison of Means: MOVES2010 emission rates vs. Houston Drayage Data (n=10) for model year 1999-2002 HHD trucks. Error bars represent the 95 percent confidence interval of the mean

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

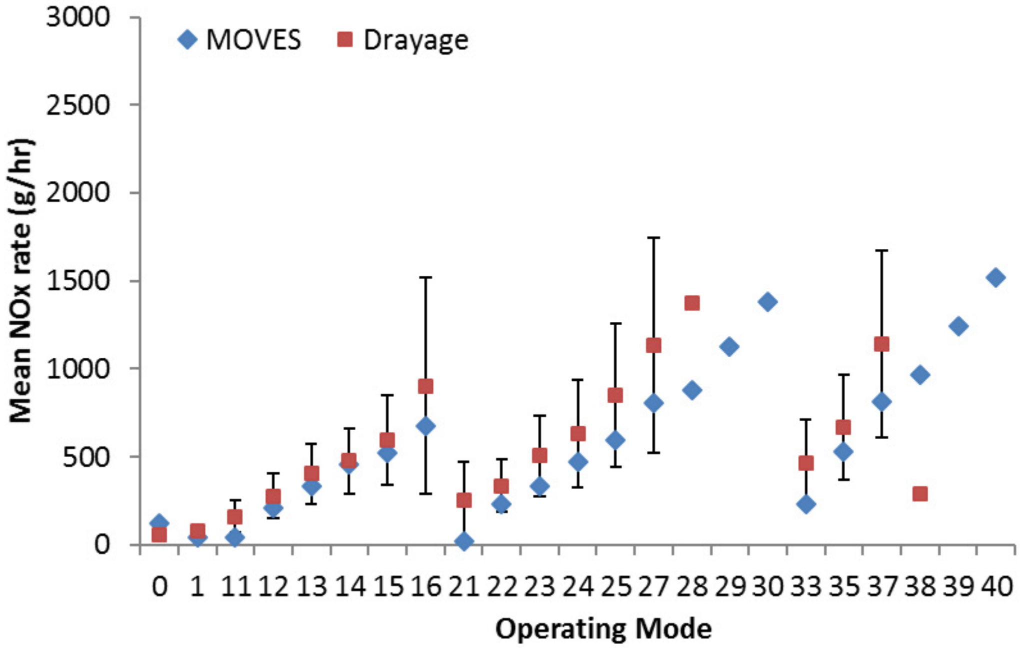


Figure C-4. Comparison of Means: MOVES2010 emission rates vs. Houston Drayage Data (n=8) for model year 2003-2006 HHD trucks. Error bars represent the 95 percent confidence interval of the mean

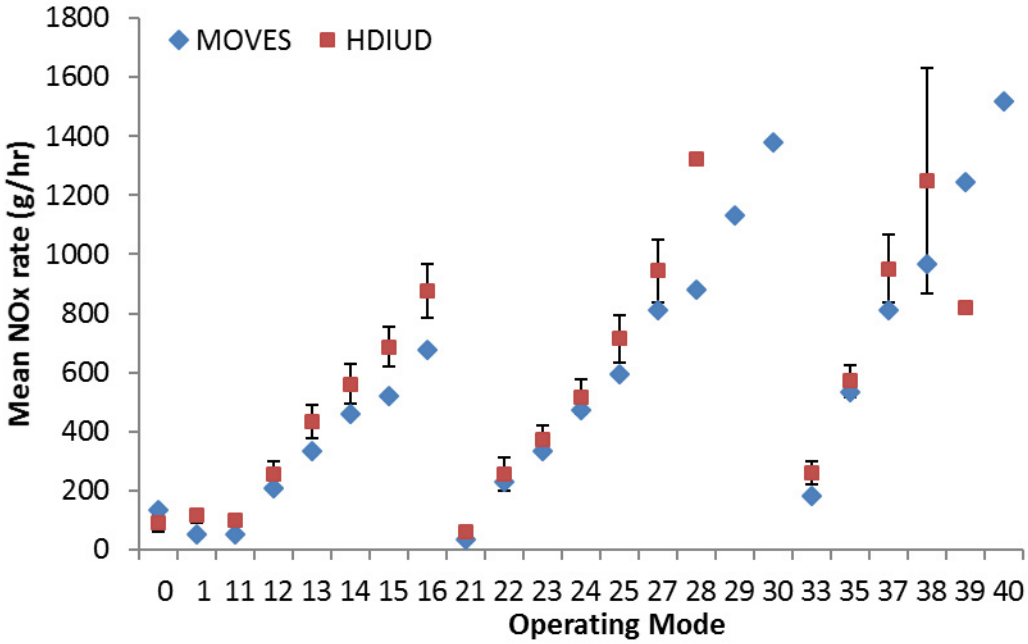


Figure C-5. Comparison of Means: MOVES2010 rates vs. HDIUT (n=40) for model years 2003-2006 HHD trucks. Error bars represent the 95 percent confidence interval of the mean

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

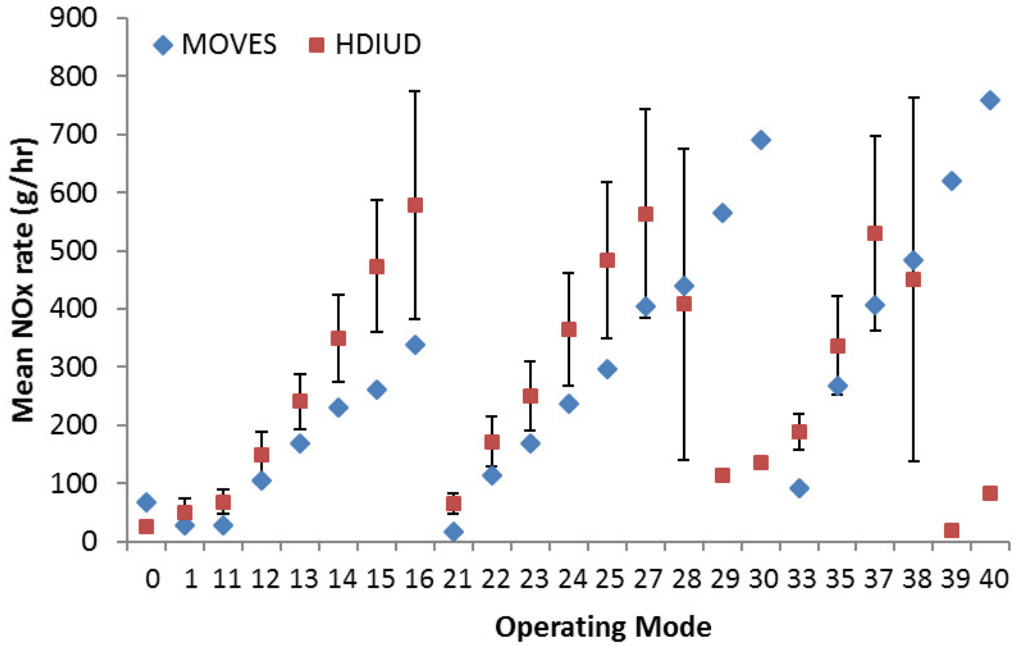


Figure C-6. Comparison of Means: MOVES rates vs. HDIUT (n=68) for model years 2007-2009 HHD trucks. Error bars represent the 95 percent confidence interval of the mean

C.2 Medium Heavy-Duty Trucks

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

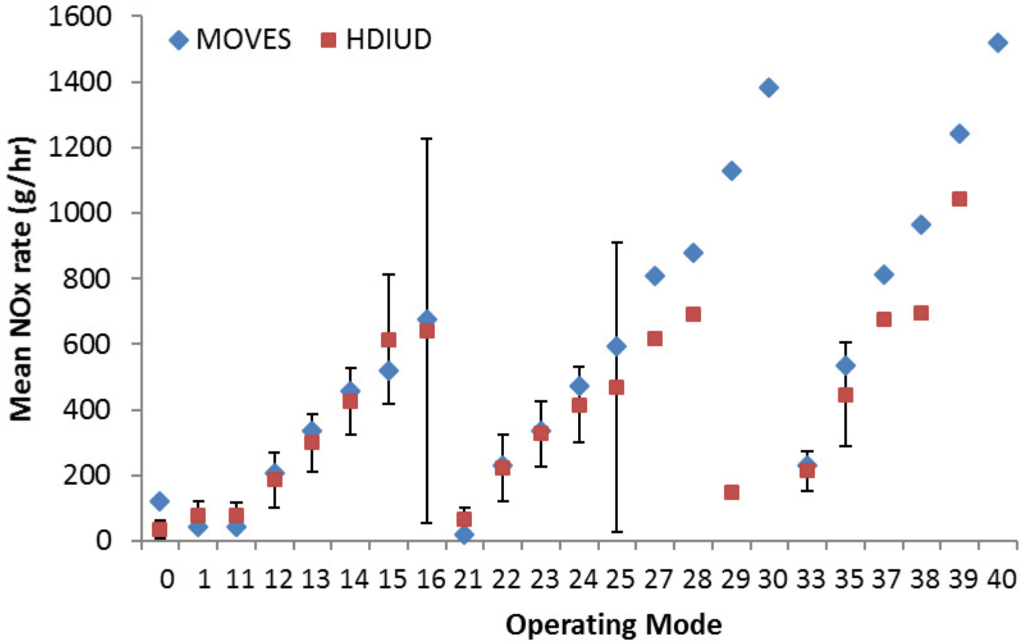


Figure C-7. Comparison of Means: MOVES2010 rates vs. HDIUT (n=25) for model years 2003-2006 MHD trucks. Error bars represent the 95 percent confidence interval of the mean

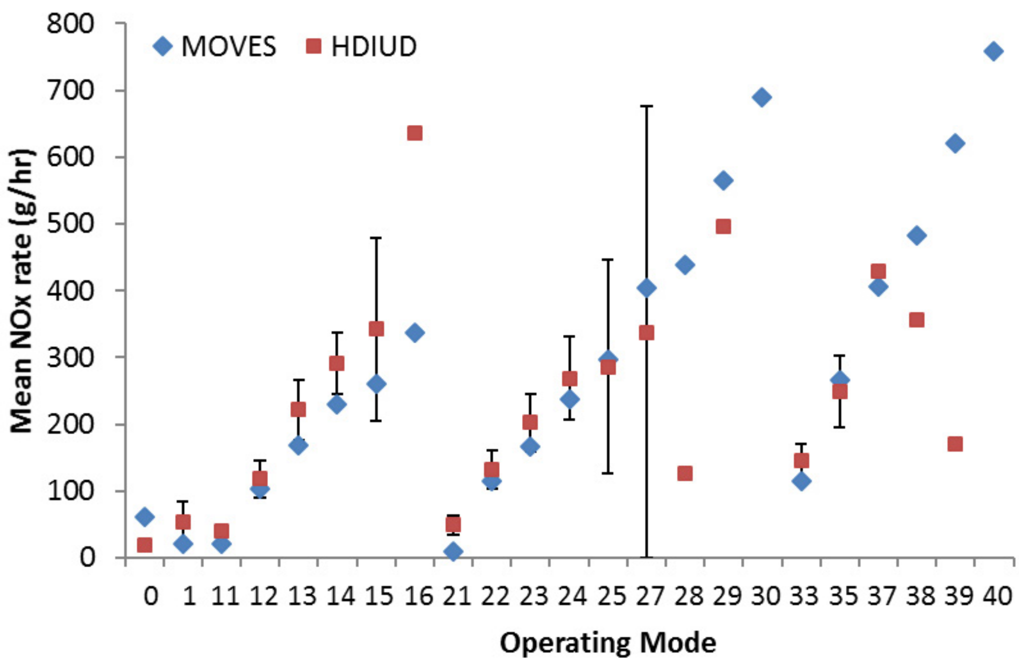


Figure C-8. Comparison of Means: MOVES2010 rates vs. HDIUT (n=71) for model years 2007-2009 MHD trucks. Error bars represent the 95 percent confidence interval of the mean

C.3 Light Heavy-Duty Trucks

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

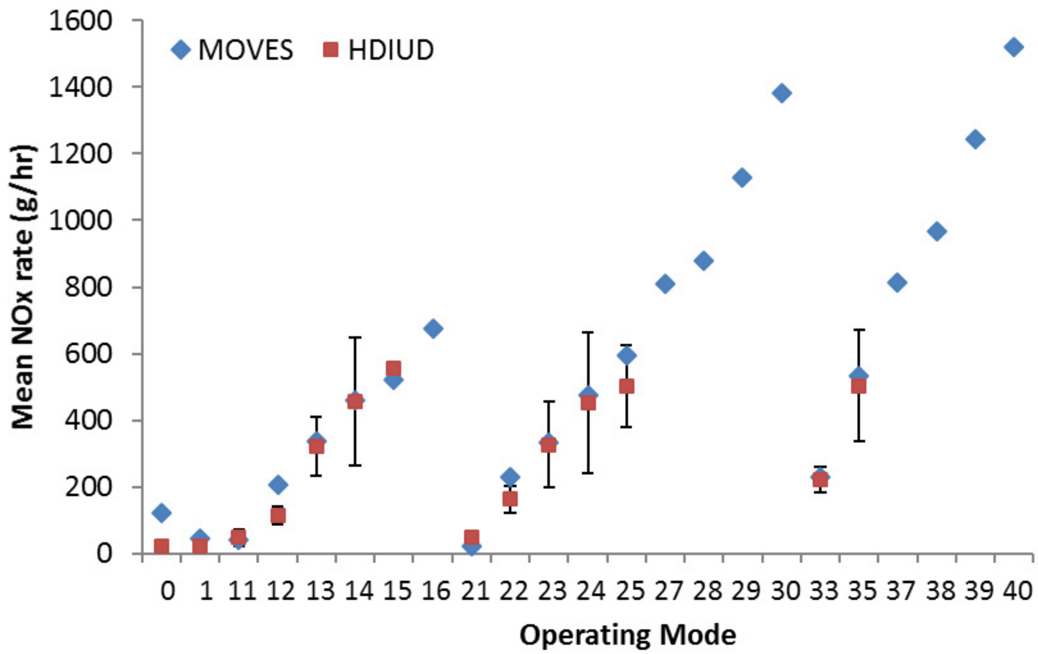


Figure C-9. Comparison of Means: MOVES2010 rates vs. HDIUT (n=15) for model years 2003-2006 LHD45 trucks. Error bars represent the 95 percent confidence interval of the mean

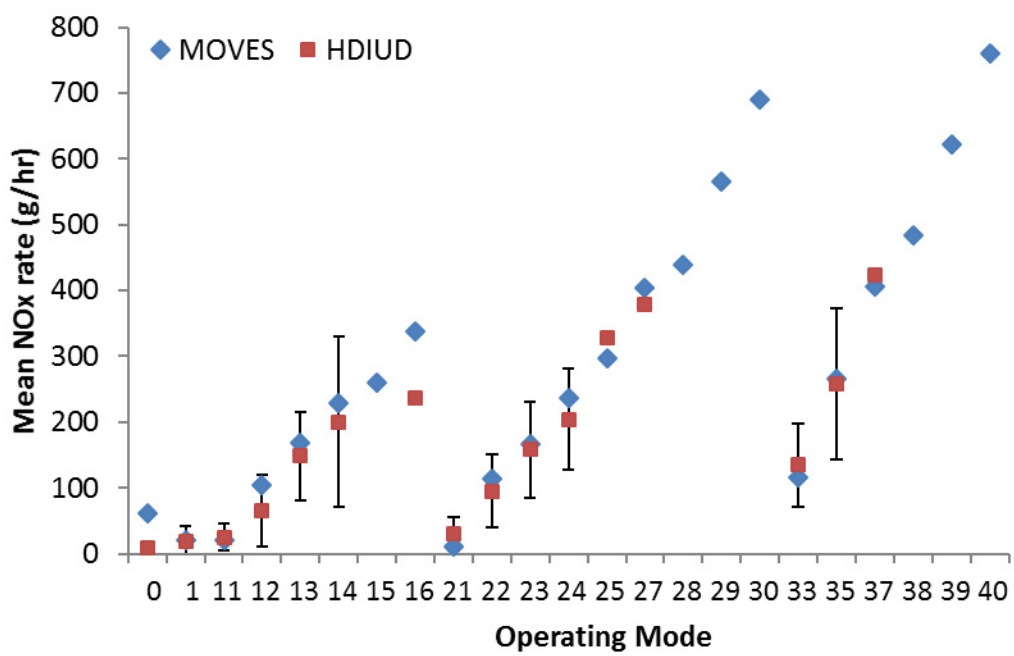


Figure C-10. Comparison of Means: MOVES2010 rates vs. HDIUT (n=24) for model years 2007-2009 LHD45 trucks. Error bars represent the 95 percent confidence interval of the mean

Appendix D Extended Idle Data Summary

Idle NOx Rates (gram/hour) Summary			
Program	**Condition**	**# Samples**	**Mean NOX Emiss Rate**
1991-2006 Low Speed Idle, A/C Off			
McCormick, High Altitude, HDT	Low RPM, AC Off	12	85
Lim, EPA	Low RPM, No access	12	109
Irick, Clean Air Tech & IdleAire		49	87
WVU - 1991-2004	Low RPM, AC Off	48	83
WVU, NCHRP		2	47
Tang, Metro NY 1984-1999		33	81
Calcagno	Low RPM, AC Off	27	120
Brodrick, UC Davis	Low RPM, AC Off	1	104
Storey	Low RPM, AC Off	4	126
	Overall	**188**	**91**
1991-2006 High Speed Idle, A/C Off			
Lim, EPA CCD	High RPM, No access	5	169
Calcagno	High RPM, AC Off	21	164
	Overall	**26**	**165**
1991-2006 High Speed Idle, A/C On			
Lim, EPA CCD	High RPM, AC On	5	212
Brodrick, UC Davis	High RPM, AC On	1	240
Calcagno	High RPM, AC On	21	223
Storey	High RPM, AC On	4	262
	Overall	**31**	**227**
1975-1990 Low Speed Idle, A/C Off			
WVU - 1975-1990	Low RPM, AC Off	18	48
Lim, EPA, CCD, 1985 MY	Low RPM, AC Off	1	20
	Overall	**19**	**47**
1975-1990 High Speed Idle, A/C On (calculated)			
Ratio of 1991-2006 "High Idle, A/C On" to "Low Idle, A/C Off"			2.5
	Overall (calculated)		**115.4**
Calculated Extended Idle MYs 1975-1990:			**69.3**
Calculated Extended Idle MYs 1991-2006:			**136.1**

Idle HC Rates (gram/hour) Summary			
Program	**Condition**	**# Samples**	**Mean HC Emiss Rate**
1991-2006 Low Speed Idle, A/C Off			
McCormick, High Altitude, HDT	Low Idle, AC Off	12	10.2
WVU - 1991-2004	Low Idle, AC Off	48	9.5
Storey	Low Idle, AC Off	4	28
	Overall	**64**	**10.8**
1991-2006 High Speed Idle, A/C On			
Brodrick, UC Davis	High Idle, AC On	1	86
Storey	High Idle, AC On	4	48
	Overall	**5**	**55.6**
1975-1990 Low Speed Idle, A/C Off			
WVU - 1975-1990	Low Idle, AC Off	18	21
	Overall	**18**	**21**
1975-1990 High Speed Idle, A/C On (calculated)			
Ratio of 1991-2006 "High Idle, A/C On" to "Low Idle, A/C Off"			5.2
	Overall (calculated)		**108.2**
Calculated Extended Idle MYs 1975-1990:			**49.8**
Calculated Extended Idle MYs 1991-2006:			**25.6**

Idle CO Rates (gram/hour) Summary			
Program	**Condition**	**# Samples**	**Mean CO Emiss Rate**
1991-2006 Low Speed Idle, A/C Off			
McCormick, High Altitude, HDT	Low Idle, AC Off	12	71
Calcagno	Low Idle, AC Off	27	37
WVU - 1991-2004	Low Idle, AC Off	48	23
Storey	Low Idle, AC Off	4	25
	Overall	**91**	**33.6**
1991-2006 High Speed Idle, A/C On			
Calcagno	High Idle, AC On	21	99
Brodrick, UC Davis	High Idle, AC On	1	190
Storey	High Idle, AC On	4	73
	Overall	**26**	**98.5**
1975-1990 Low Speed Idle, A/C Off			
WVU - 1975-1990	Low Idle, AC Off	18	31
	Overall	**18**	**31**
1975-1990 High Speed Idle, A/C On (calculated)			
Ratio of 1991-2006 "High Idle, A/C On" to "Low Idle, A/C Off"			2.9
	Overall (calculated)		**91.0**
Calculated Extended Idle MYs 1975-1990:			**50.8**
Calculated Extended Idle MYs 1991-2006:			**55.0**

Idle PM Rates (gram/hour) Summary			
Program	**Condition**	**# Samples**	**Mean PM Emiss Rate**
1991-2006 Low Speed Idle, A/C Off			
McCormick, High Altitude, HDT	Low Idle, AC Off	12	1.8
Calcagno	Low Idle, AC Off	27	2.55
WVU - 1991-2004	Low Idle, AC Off	48	1.4
Storey	Low Idle, AC Off	4	0.3
	Overall	**91**	**1.7**
1991-2006 High Speed Idle, A/C On			
Calcagno	High Idle, AC On	21	4.11
Storey	High Idle, AC On	4	3.2
	Overall	**25**	**4.0**
1975-1990 Low Speed Idle, A/C Off			
WVU - 1975-1990	Low Idle, AC Off	18	3.8
	Overall	**18**	**3.8**
1975-1990 High Speed Idle, A/C On (calculated)			
Ratio of 1991-2006 "High Idle, A/C On" to "Low Idle, A/C Off"			2.3
	Overall (calculated)		**8.6**
Calculated Extended Idle MYs 1975-1990:			**5.4**
Calculated Extended Idle MYs 1991-2006:			**2.5**

2007 Extended Idle Emissions calculation:

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

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

Appendix E Developing PM emission rates for missing operating modes

In cases where an estimated rate could not be directly calculated from data, we imputed the missing value using a log-linear least-squares regression procedure. Regulatory class, model year group and speed class (0–25 mph, 25-50 mph and 50+ mph) were represented by dummy variables in the regression. The natural logarithm of emissions was regressed versus scaled tractive power (STP) to represent the operating mode bins. The regression assumed a constant slope versus STP for each regulatory class. Logarithmic transformation factors (mean square error of the regression squared / 2) were used to transform the regression results from a log based form to a linear form. Due to the huge number of individual second-by-second data points, all of the regression relationships were statistically significant at a high level (99 percent confident level). The table below shows the regression statistics, and the equation shows the form of the resulting regression equation.

Table E-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

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

Where :

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

β_1 = a slope term for STP, and

σ^2 = the mean-square error or residual error for the model fit,

STP = the midpoint value for each operating mode (kW/metric ton, see Table 1-3).

Appendix F Heavy-Duty Gasoline Start Emissions Analysis Figures

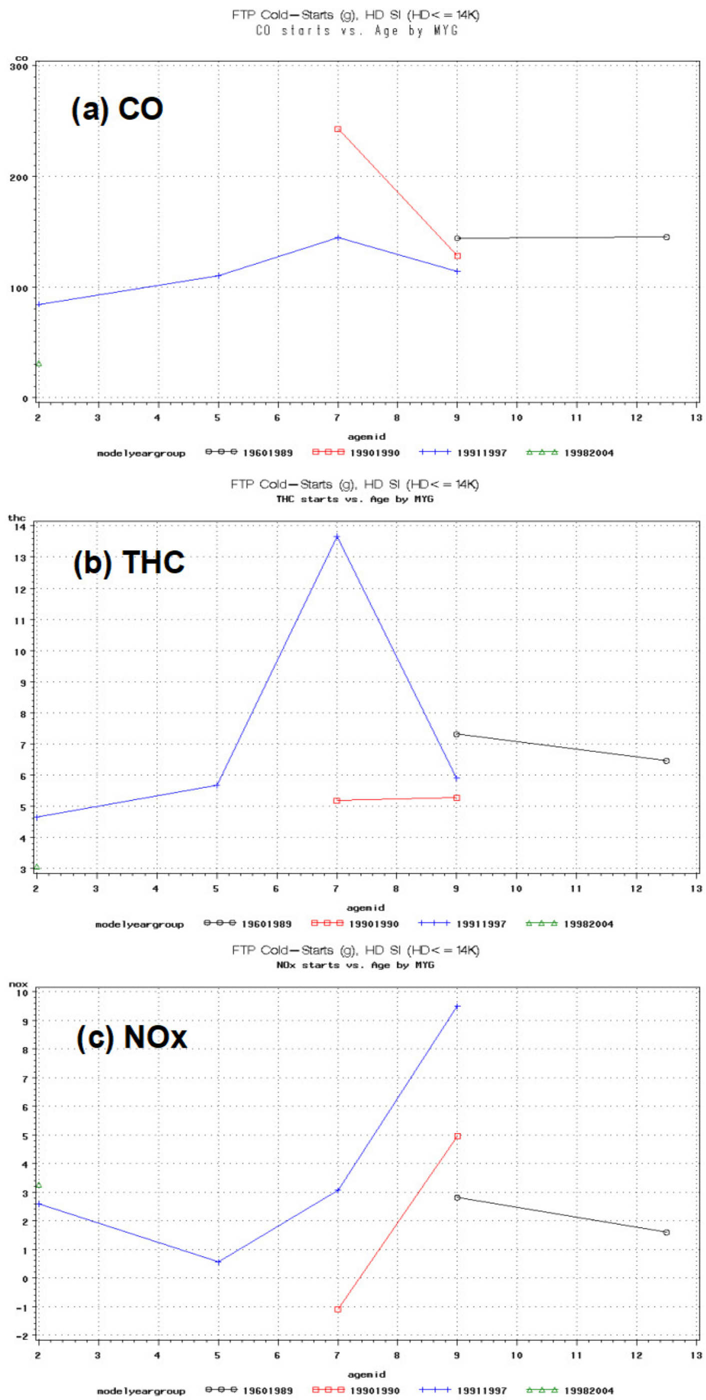


Figure F-1. Cold-Start FTP Emissions for Heavy-Duty Gasoline Vehicles, Averaged by Model-year and Age Groups

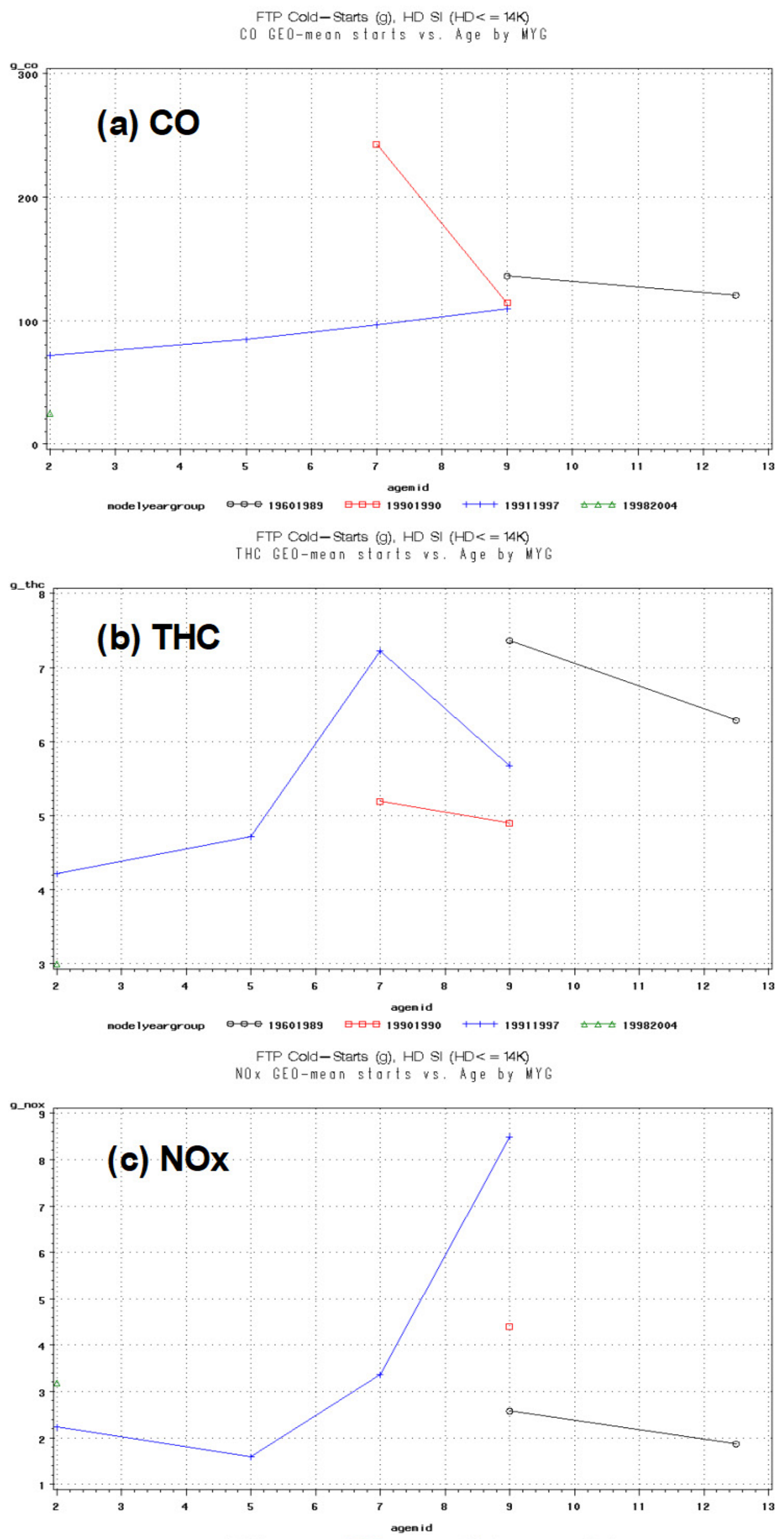


Figure F-2. Cold-Start FTP Emissions for Heavy-Duty Gasoline Vehicles, GEOMETRIC MEANS by Model-year and Age Groups

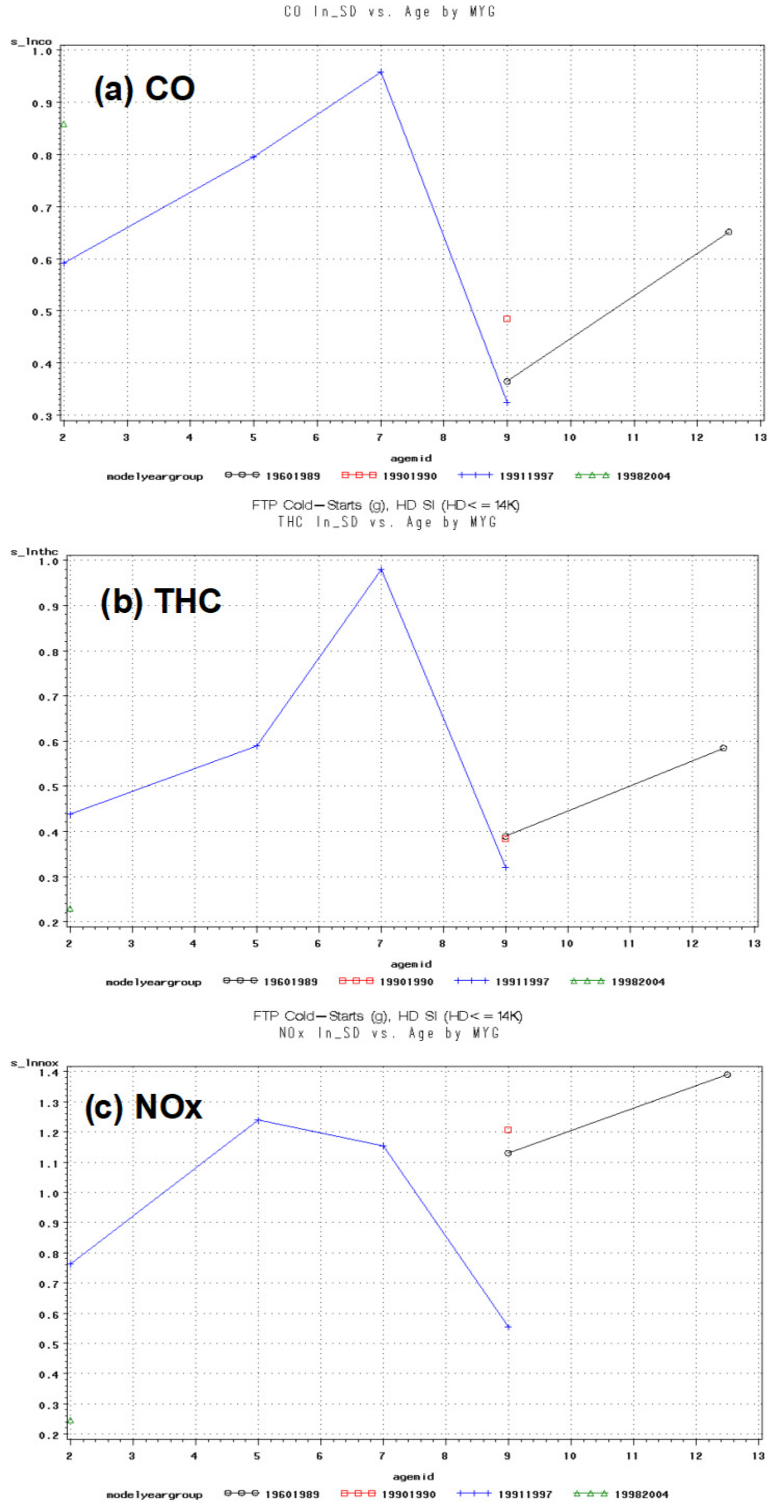


Figure F-3. Cold-start FTP Emissions for Heavy-Duty Gasoline Trucks: LOGARITHMIC STANDARD DEVIATION by Model-year and Age Groups

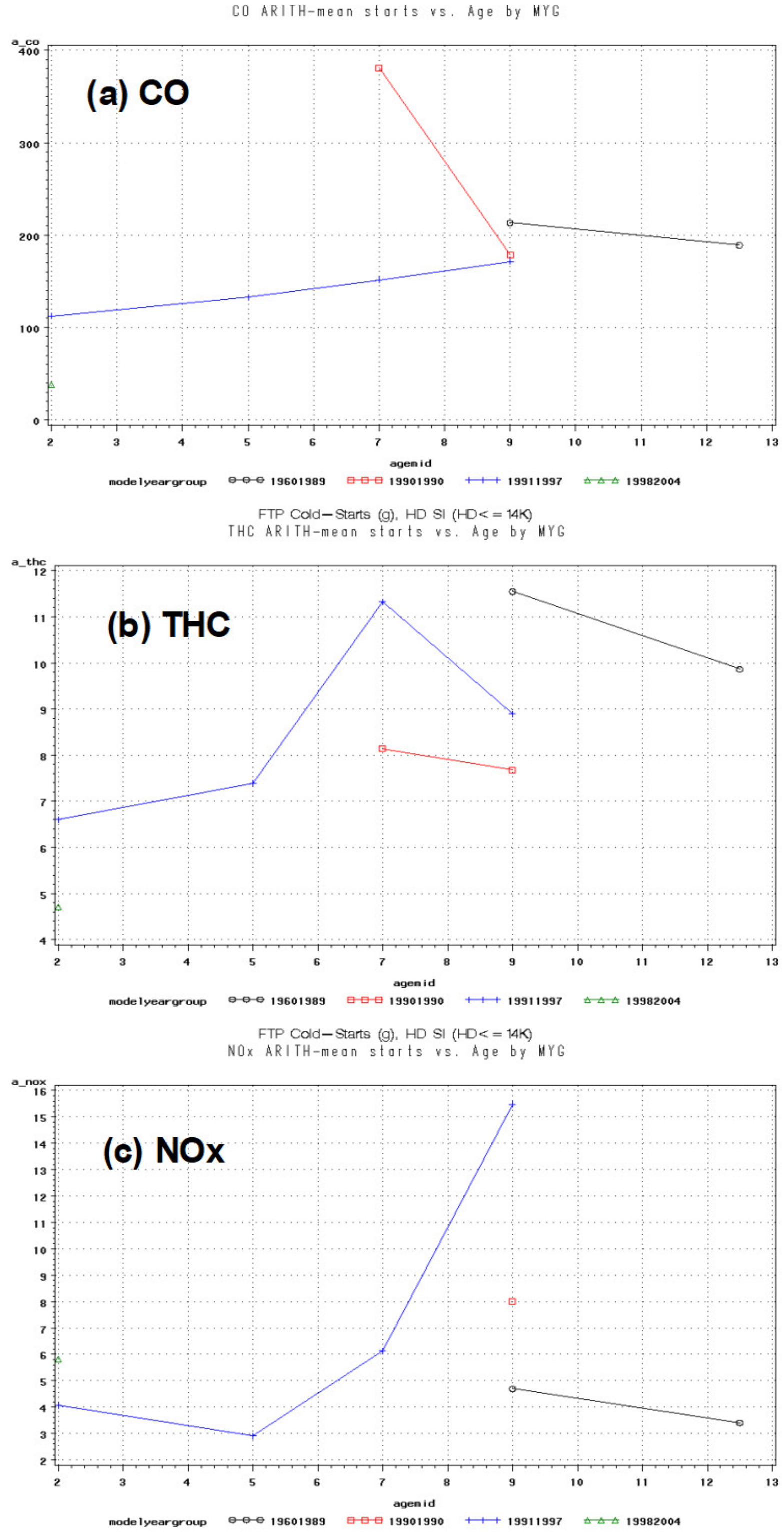


Figure F-4. Cold-Start Emissions for Heavy-Duty Gasoline Trucks: RECALCULATED ARITHMETIC MEANS by Model-year and Age Groups

Table F-1 Emission Standards for Heavy-Duty Spark-Ignition Onroad Engines

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

Appendix G Selection of Fixed Mass Factor (f_{scale}) values for MY 2010+ Heavy-Duty Vehicles

In MOVES_CTI_NPRM, for model year 2010 and newer heavy-duty diesel, gasoline, and CNG running-exhaust emissions OpMode based rates, we discarded the fixed mass factor (f_{scale}) value of 17.1 used in previous MOVES versions, and used the manufacturer-run HDIUT data to estimate new f_{scale} values for LHD, MHD, and HHD weight classes. New f_{scale} values were needed because the 17.1 value was too large, causing emissions rates to remain limited to low and medium power OpModes, and thus requiring gap-filling for high-power OpModes.

The new f_{scale} values for MY 2010+ vehicles are 5.00, 7.00, and 10.00 for LHD (regClass 41 and 42), MHD (regClass 46), and HHD (regClass 47 and 48), respectively. These f_{scale} values are used when analyzing the real-world emissions data that leads to the base emission rates in the MOVES database. The f_{scale} values are also used by the MOVES model, at run time, to convert vehicle activity to OpMode-based time distributions. For consistency, OpMode-based emissions rates and time distributions, for a given regulatory class and model year, must be based on the same f_{scale} value. Glider vehicles (regClass 49) continue to use emission rates from pre-2010 vehicles, and thus their f_{scale} value is unchanged at 17.1. Note that it is not meaningful to compare OpMode based rates based on different f_{scale} values. This appendix describes how we arrived at the f_{scale} values.

The entire MY 2010+ HDIUT data (Section 2.1.1.1) was analyzed using a range of f_{scale} values. For this exercise we analyzed LHD, MHD, and HHD separately, but within those regulatory classes, we did not divide the data set by NO_x FEL or model years. We included the MOVES2014 value (f_{scale} = 17.1) to show how the OpMode distribution would look for a "business as usual" case. It is expected that the f_{scale} for LHD should be lower than MHD, which in turn should be lower than HHD. Our goal was to find f_{scale} values that allow the HDIUT data to cover all OpModes, thus reducing the need for gap-filling while also leaving the highest power OpModes (30 and 40) as not saturated because the HDIUT data is not expected to have very aggressive operation. If the f_{scale} is too big, the high power OpModes are left vacant. On the other hand, if the f_{scale} is too small, a lot of the data gets pushed to the high power OpModes. Both cases are sub-optimal because they reduce the model's capability to distinguish operating modes in a meaningful way.

When analyzing the HDIUT data for various f_{scale} values, we estimated the number of vehicles, time, and mass/time emission rates for criteria pollutants and CO_2 for each OpMode. Vehicle count and time, per OpMode, were first cut criteria during the f_{scale} selection process. We used the CO_2 mass/time rates as an additional check because these rates are known to have consistent and predictable monotonically rising trend within each speed-bin (since higher power demand requires burning more fuel which leads to more CO_2).Table G-1 through Table G-3 show how the choice of f_{scale} values would affect the vehicle count and seconds in each OpMode, for LHD, MHD, and HHD, respectively. The number of seconds is based on the HDIUT-based OpMode time fractions applied to a cycle of one million seconds. Using a unique but representative f_{scale} for each regClass, when combined with a cycle of the same number of total seconds, should result in similar number of seconds in high power OpModes. In other words, we expect LHD, MHD, and HHD vehicles in the HDIUT data set to have somewhat similar time distribution across power modes. Finally, we used the CO_2 mass/time rate trends as an additional metric to pick a final f_{scale} between candidate values that look reasonably good for both vehicle count and time distribution.

Looking at Table G-1 for LHD vehicles, f_{scale} = 2.06 results in every one of the 64 vehicles having operation in OpModes 30 and 40 and significantly more seconds of data than OpModes 29 and 39, respectively. On the other hand, a f_{scale} value of 9.00 or 17.1 meant the high power OpModes had only a couple vehicles and seconds, which is a sign of under-representation in those OpModes. Thus, a suitable f_{scale} value, for LHD, should be between 2.06 and 9.00. Based on further analysis, the final f_{scale} candidates for LHD were 4.00, 5.00, and 6.00. A value of 4.00 seemed too small because we did not expect over 40 (out of 64) vehicles to have operation in OpModes 30 and 40. A value of 6.00 seemed too high because it led to only 40 seconds and 135 seconds of data (from a cycle with a million seconds) in OpModes 30 and 40, respectively. We picked 5.00 as the final f_{scale} value for LHD because it resulted in a reasonable number of vehicles and seconds in the high power OpModes 29, 30, 39, and 40. For confirmation purpose, we also compared the CO_2 mass/time rates for all the f_{scale} values considered during the analysis and Figure G-1 shows a comparison between the final candidates of 4.00, 5.00, and 6.00. As seen in the figure, all three values provide good monotonically increasing trend, though between 5.00 and 6.00, the former is slightly better when looking at OpMode 29 and 30.

For MHD and HHD, we went through similar reasoning and steps as for LHD. Our final f_{scale} values for LHD, MHD, and HHD are 5.00, 7.00, and 10.00, respectively. From Table G-1 - Table G-3, these f_{scale} values lead to comparable vehicle count (20-40 % of total vehicles in the regulatory class) and seconds of data (1000-3000 seconds out of one million) in OpModes 30 and 40.

We did not try to find a precise and even more suitable f_{scale} value. Thus, for example, whether f_{scale} of 4.80 or 5.20 is better than 5.00, for LHD, was not tested. There are diminishing returns for the extra time and effort required for that analysis because: (1) the HDIUT data set lacks certain things such as very aggressive operation or malfunctioning vehicles, so a very suitable value of f_{scale} from this data set might not be as suitable with another data set; (2) comparing closely spaced f_{scale} values does not necessarily provide a clear winner across the board because there’s more than one criteria (vehicle count, time, mass/time rates for various pollutants).

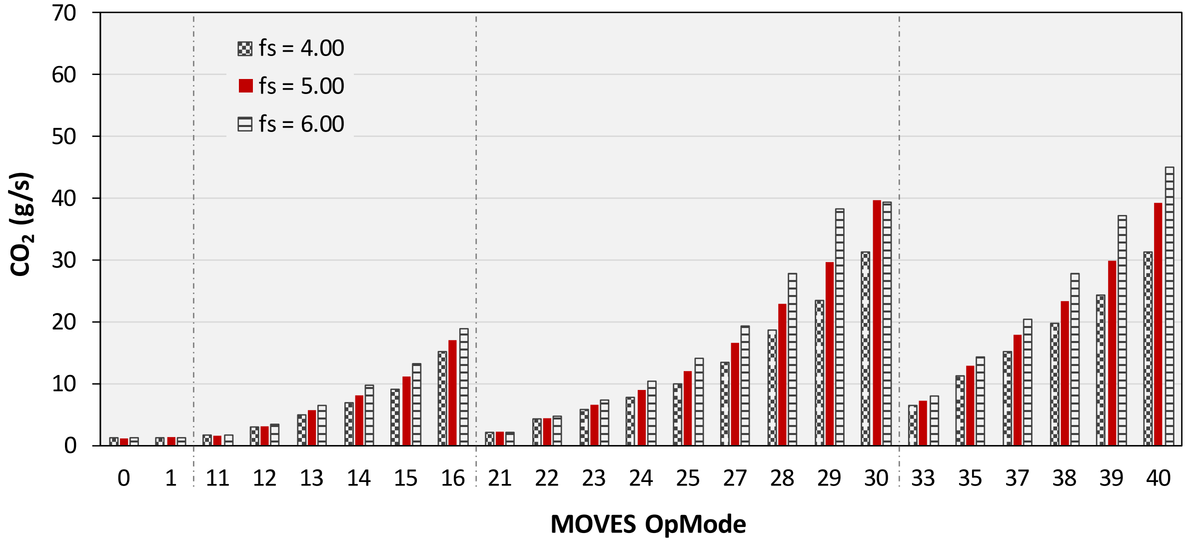
Table G-1 Effect of f_{scale} Value on Vehicle Count and Time for Light Heavy-Duty Vehicles

OpMode	Number of vehicles[1]						Number of seconds based on a cycle with one million seconds[1,2]					
	fs 2.06	fs 4.0	fs 5.0	fs 6.0	fs 9.0	fs 17.1	fs 2.06	fs 4.0	fs 5.0	fs 6.0	fs 9.0	fs 17.1
0	64	64	**64**	64	64	64	41131	41131	**41131**	41131	41131	41131
1	64	64	**64**	64	64	64	358957	358957	**358957**	358957	358957	358957
11	64	64	**64**	64	64	64	46235	46235	**46235**	46235	46235	46235
12	64	64	**64**	64	64	64	15112	24896	**29023**	32878	42842	61989
13	64	64	**64**	64	64	64	10311	14877	**16658**	18290	20756	16153
14	64	64	**64**	64	64	43	8109	11394	**12304**	12431	10835	2387
15	64	64	**64**	64	63	18	6995	8784	**8680**	8092	4190	200
16	64	64	**64**	64	41	1	40203	20778	**14065**	9039	2107	1
21	64	64	**64**	64	64	64	45157	45157	**45157**	45157	45157	45157
22	59	64	**64**	64	64	64	7153	16366	**22038**	28166	47554	92823
23	64	64	**64**	64	64	64	9877	24704	**31884**	38195	49094	41467
24	64	64	**64**	64	64	48	12315	25290	**28989**	30288	26962	6425
25	64	64	**64**	64	64	22	13307	21400	**21274**	19931	11739	850
27	64	64	**64**	64	44	1	25844	28819	**25061**	18770	5671	1
28	64	64	**64**	44	22	2	21514	15281	**8422**	5020	544	5
29	64	64	**42**	23	0	0	16292	5808	**2900**	1161	0	0
30	64	43	**22**	13	2	1	35269	3903	**1002**	40	5	1
33	64	64	**64**	64	64	64	26999	42467	**55797**	73408	142294	267976
35	64	64	**64**	64	64	46	16820	75707	**110862**	131366	129751	18220
37	64	64	**64**	63	44	5	33332	86600	**79892**	67271	13177	7
38	64	63	**62**	44	22	1	46641	52178	**31818**	12100	978	2
39	64	62	**41**	23	1	1	49374	21416	**6167**	1940	1	2
40	64	41	**23**	14	1	1	113054	7852	**1685**	135	18	13

Notes:

[1] Values in bold are for final selected f_{scale}. Shaded cells show instances where using an excessively high f_{scale} value causes data deficit in the higher power OpModes within a speed bin.

[2] Number of seconds = Average OpMode time fraction * cycle with one million seconds. The average OpMode time fraction is the average of the time fraction (for that OpMode) across all vehicles.



Absolute values of OpMode based emissions rates cannot be compared between series with different fscale values.

Figure G-1 Effect of f_{scale} Value on Coverage and Trends of OpMode Based CO_2 for Light Heavy-Duty Vehicles

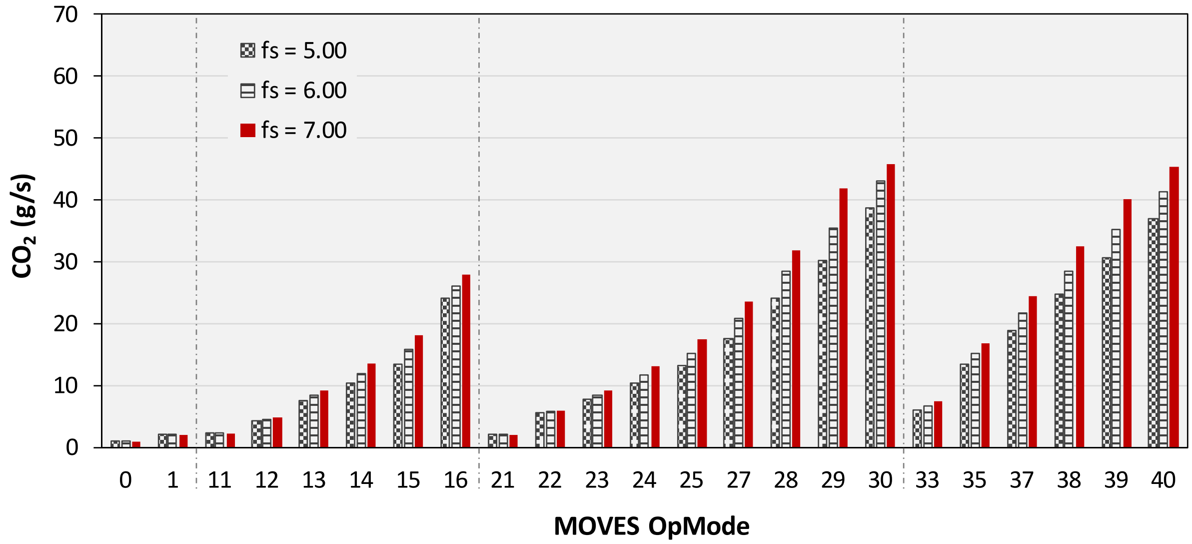
Table G-2 Effect of f_{scale} Value on Vehicle Count and Time for Medium Heavy-Duty Vehicles

OpMode	Number of vehicles[1]						Number of seconds based on a cycle with one million seconds[1,2]					
	fs 4.0	fs 5.0	fs 6.0	fs 7.0	fs 9.0	fs 17.1	fs 4.0	fs 5.0	fs 6.0	fs 7.0	fs 9.0	fs 17.1
0	58	**58**	58	58	58	58	36170	**36170**	36170	36170	36170	36170
1	58	**58**	58	58	58	58	349622	**349622**	349622	349622	349622	349622
11	58	**58**	58	58	58	58	32693	**32693**	32693	32693	32693	32693
12	58	**58**	58	58	58	58	20755	**23825**	26630	29346	34264	48508
13	58	**58**	58	58	58	58	11234	**12492**	13612	14397	15495	16683
14	58	**58**	58	58	58	58	8252	**9101**	9517	9898	10003	7687
15	58	**58**	58	58	58	30	6688	**7014**	7142	7000	6576	1914
16	58	**58**	58	58	58	16	28357	**22855**	18385	14645	8948	496
21	58	**58**	58	58	58	58	44291	**44291**	44291	44291	44291	44291
22	58	**58**	58	58	58	58	10132	**14200**	18827	23955	34436	78404
23	58	**58**	58	58	58	58	19195	**25479**	31609	37379	48401	49534
24	58	**58**	58	58	58	58	21109	**27513**	32401	34297	30771	19215
25	58	**58**	58	58	58	37	22136	**24498**	22647	20428	17498	5111
27	58	**58**	58	58	58	16	32912	**28713**	25621	22502	17220	1306
28	58	**58**	58	58	25	0	18677	**15863**	13842	10424	4619	0
29	58	**58**	46	25	10	0	12105	**10075**	5243	3550	625	0
30	58	**39**	25	14	0	0	17304	**7229**	3379	1034	0	0
33	58	**58**	58	58	58	58	37996	**45307**	54057	64727	92859	212774
35	58	**58**	58	58	58	58	40077	**63649**	87949	107234	130599	92395
37	58	**58**	58	58	57	15	63932	**76693**	81453	80818	72135	3197
38	58	**58**	57	49	30	1	56697	**58308**	51520	44843	11144	1
39	58	**53**	43	25	10	1	45255	**39067**	25466	8307	1628	1
40	53	**39**	26	14	1	0	64411	**25344**	7923	2440	2	0

Notes:

[1] Values in bold are for final selected f_{scale}. Shaded cells show instances where using an excessively high f_{scale} value causes data deficit in the higher power OpModes within a speed bin.

[2] Number of seconds = Average OpMode time fraction * cycle with one million seconds. The average OpMode time fraction is the average of the time fraction (for that OpMode) across all vehicles.



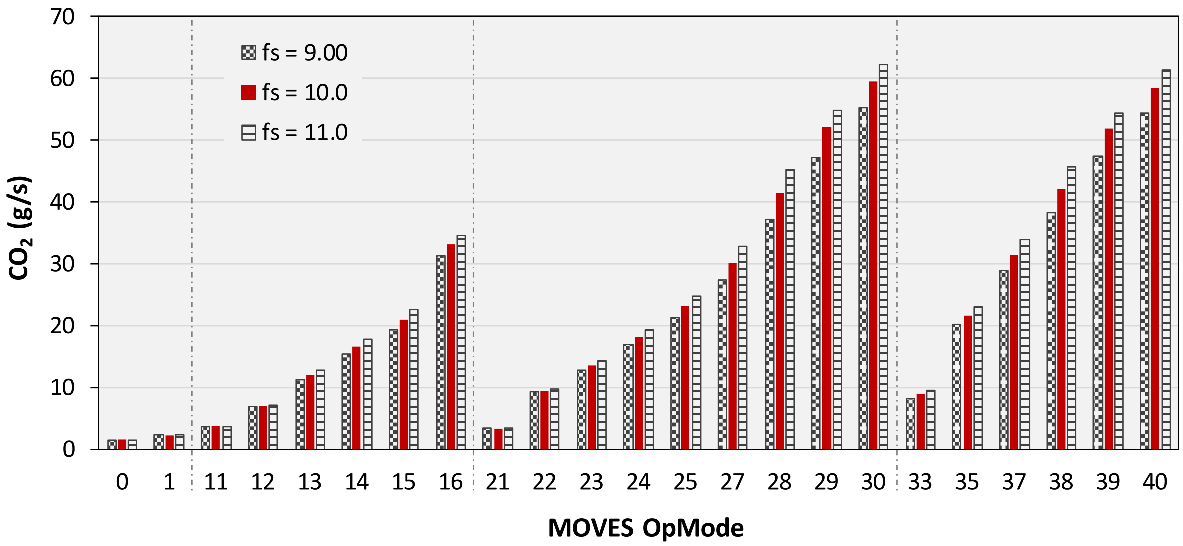
Absolute values of OpMode based emissions rates cannot be compared between series with different fscale values.

Figure G-2 Effect of f_{scale} Value on Coverage and Trends of OpMode Based CO_2 for Medium Heavy-Duty Vehicles

Table G-3 Effect of f_{scale} Value on Vehicle Count and Time for Heavy Heavy-Duty Vehicles

OpMode	Number of vehicles[1]						Number of seconds based on a cycle with one million seconds[1,2]					
	fs 9.0	fs 10.0	fs 11.0	fs 12.0	fs 14.0	fs 17.1	fs 9.0	fs 10.0	fs 11.0	fs 12.0	fs 14.0	fs 17.1
0	159	**159**	159	159	158	159	18010	**18010**	18010	18010	18010	18010
1	159	**159**	159	159	159	159	297662	**297662**	297662	297662	297662	297662
11	159	**159**	159	159	158	159	37453	**37453**	37453	37453	37453	37453
12	159	**159**	159	159	158	159	24580	**25976**	27238	28427	30556	33336
13	159	**159**	159	159	158	159	9472	**9547**	9576	9576	9551	9524
14	159	**159**	159	159	158	159	5545	**5557**	5579	5533	5446	5159
15	159	**159**	159	159	158	159	3938	**3840**	3762	3704	3456	2892
16	159	**159**	159	159	153	152	10041	**8657**	7422	6337	4568	2666
21	159	**159**	159	159	158	159	32325	**32325**	32325	32325	32325	32325
22	159	**159**	159	159	158	159	12785	**14388**	15951	17580	20814	25721
23	159	**159**	159	159	158	159	14276	**15457**	16513	17395	18748	20117
24	159	**159**	159	159	158	159	11401	**11865**	12272	12453	12761	12587
25	159	**159**	159	159	158	159	8967	**9058**	9085	9044	8501	8402
27	159	**159**	159	159	153	154	12410	**11927**	11767	12026	13569	15804
28	154	**154**	154	153	134	27	8660	**9619**	10875	12433	8684	632
29	153	**142**	122	75	8	0	8905	**9822**	6562	2329	185	0
30	114	**59**	10	1	0	0	5861	**1127**	239	4	0	0
33	159	**159**	159	159	158	159	114214	**126216**	139731	154101	186094	237960
35	159	**159**	159	159	158	159	139109	**160667**	176144	186131	189813	176111
37	159	**159**	159	159	153	153	115050	**102440**	91446	83420	74122	61219
38	154	**154**	153	152	131	26	55279	**52010**	50633	47483	27291	2421
39	152	**138**	122	83	9	0	37885	**33033**	19207	6576	391	0
40	114	**65**	11	1	0	0	16174	**3344**	550	0	0	0

Notes:
[1] Values in bold are for final selected f_{scale}. Shaded cells show instances where using an excessively high f_{scale} value causes data deficit in the higher power OpModes within a speed bin.
[2] Number of seconds = Average OpMode time fraction * cycle with one million seconds. The average OpMode time fraction is the average of the time fraction (for that OpMode) across all vehicles.



Absolute values of OpMode based emissions rates cannot be compared between series with different fscale values.

Figure G-3 Effect of f_{scale} Value on Coverage and Trends of OpMode Based CO_2 for Heavy Heavy-Duty Vehicles

Appendix H Comparing Glider Vehicle and MOVES Model Year 2000 Heavy Heavy-Duty Emission Rates

Glider vehicles are new vehicles with older engines. Tailpipe exhaust emissions were measured from two heavy heavy-duty glider vehicles, one each of MY 2016 and MY 2017, at the US EPA's National Vehicle Fuel and Emissions Laboratory (NVFEL) heavy-duty chassis dynamometer. Both glider vehicles were sleeper cab tractors and lacked EGR, DOC, DPF, or SCR emissions control devices. Each glider vehicle was tested on three drive cycles – (1) cold start Heavy-Duty Vehicle Urban Dynamometer Driving Schedule (UDDS) sequence; (2) World Harmonized Vehicle Cycle (WHVC) sequence; (3) Super Cycle (a combination of urban and freeway driving). The vehicles were tested with two sets of road-load coefficients representing 60,000 lbs and 80,000 lbs total vehicle weight. The MOVES OpMode based results shown here are time-weighted average of the various drive cycle and weight combinations. More details about the vehicles, drive cycles, test procedures, and results are available in the EPA report for the glider test program.[154] The data that was analyzed for MOVES included only the tests where the vehicles were operating free of any malfunction indicator lights because MOVES treats tampering and malmaintenance separately.

Since the measured glider emission rates are from only two glider vehicles tested in lab conditions, we decided not to use those rates as-is to estimate fleet-wide real-world glider vehicle emissions from MOVES. Instead, we used the data to identify which model year emission rates in MOVES can best represent contemporary glider vehicles. We know that contemporary glider vehicles typically have re-built powertrains that do not require DOC, DPF, and SCR controls, and likely lack even EGR systems. This meant glider vehicles should compare well with MY 2006 or older emission rates. Thus, we compared the emission rates from the two glider vehicles with regClass 47 (HHD) rates for applicable model year groups in MOVES. MOVES defines emission model year group by pollutant and has emissions rates for one or more model year groups within the MY 1998-2006 period. For example, in MOVES, there are different NO_x rates for MY 1998, MY 1999-2002, and MY 2003-2006. On the other hand, PM and CO_2 (from energy) rates are the same across MY 1998-2006.

A comparison of glider test results versus MOVES base emissions rates for NO_x, THC, CO, CO_2, and PM are presented in Figure H-1 though Figure H-6. Given that glider vehicles lack emissions control devices that provide significant reductions in NO_x and PM, our primary focus was to find the best model year match for these pollutants, with THC and CO as secondary comparison to pick between model years that match equally well for NO_x and PM. The decision to pick a representative model year mostly came down to NO_x because emissions rates for PM are the same for MY 1998-2006. From Figure H-1, it is seen that the NOx emissions from the measured glider vehicles are best represented by the MY 1999-2002 rates in MOVES. Similarly, for THC (Figure H-2), MOVES MY 1998-2002 rates are a better match compared to the MY 2003-2006 rates. The CO rates from the measured glider vehicles are significantly higher than MOVES (Figure H-3), so it is likely that modeled CO emissions for glider vehicles in MOVES will be underestimated. The CO_2 rates from glider vehicles are comparable to the MOVES MY 1998-2006 rates (Figure H-4). When comparing the rates between measured glider vehicles and MOVES, we paid attention to differences in the comparison across OpModes. Typically, within each speed-bin, vehicles spend more time in and thus generate a larger fraction of total emissions from the low and medium power OpModes versus high-power OpModes. Using NO_x and CO_2 as examples, the comparison between measured glider vehicle versus MOVES MY 2000 emission rate for OpModes 27 and 28 are not as good as lower OpModes. However, the difference in these high power OpModes has a lower impact on total inventory because vehicles spend less time in the OpMode. For PM, we have gravimetric filter-based measurement for both gliders and instantaneous measurement using an AVL Micro-Soot Sensor (MSS) for only Glider-2, as seen in Figure H-5 and Figure H-6. We applied MOVES OpMode based PM rates to the OpMode based time distribution for Glider-1 and Glider-2 test cycles to estimate cycle total emissions for MOVES and compared those to the total PM from the gravimetric filter measurements. While Glider-2 filter and instantaneous rates are lower than MOVES MY 1998-2006 rates, the comparison for Glider-1 is much closer. Overall, we believe MOVES MY 1998-2006 PM rates are reasonable for use as glider vehicle PM rates because they are derived from vehicles without DPF, a key PM emissions control device that is absent in most glider vehicles.

Based on these comparisons, we decided to apply the MY 2000 HHD (regClass 47) emission rates for THC, CO, NO_x, PM, and Energy (for CO_2) in MOVES to glider vehicles (regClass 49).

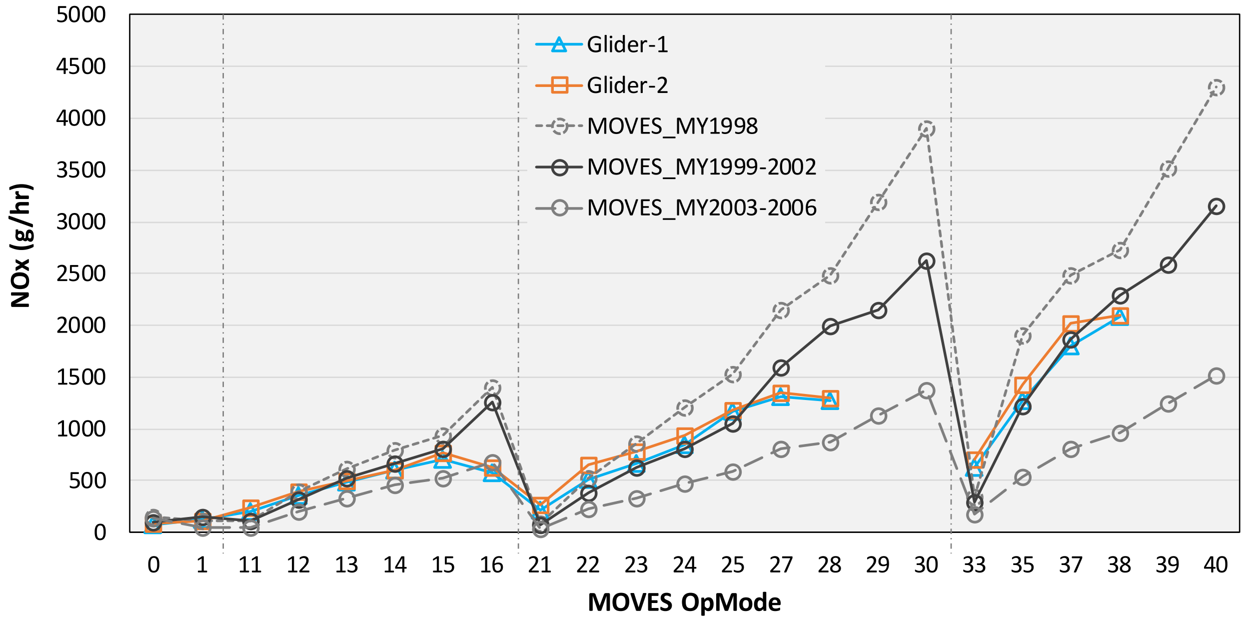


Figure H-1 Comparison of NOx Emission Rates from Glider Vehicle Lab Testing to MOVES regClass 47 (HHD) 1998-2006 Model Years

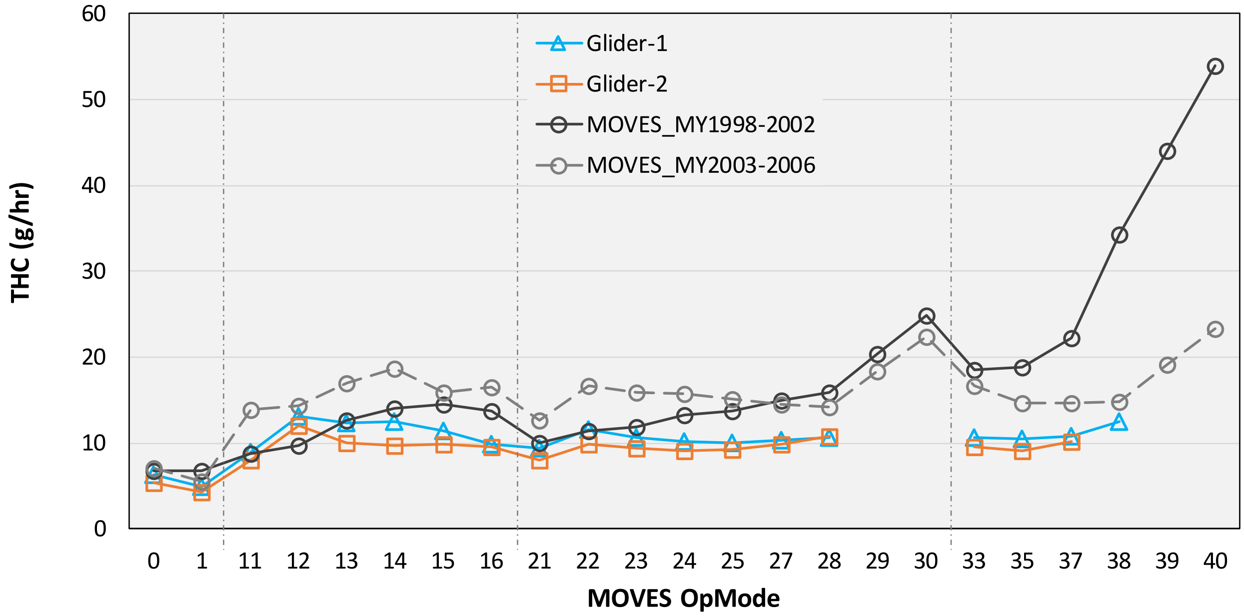


Figure H-2 Comparison of THC Emission Rates from Glider Vehicle Lab Testing to MOVES regClass 47 (HHD) 1998-2006 Model Years

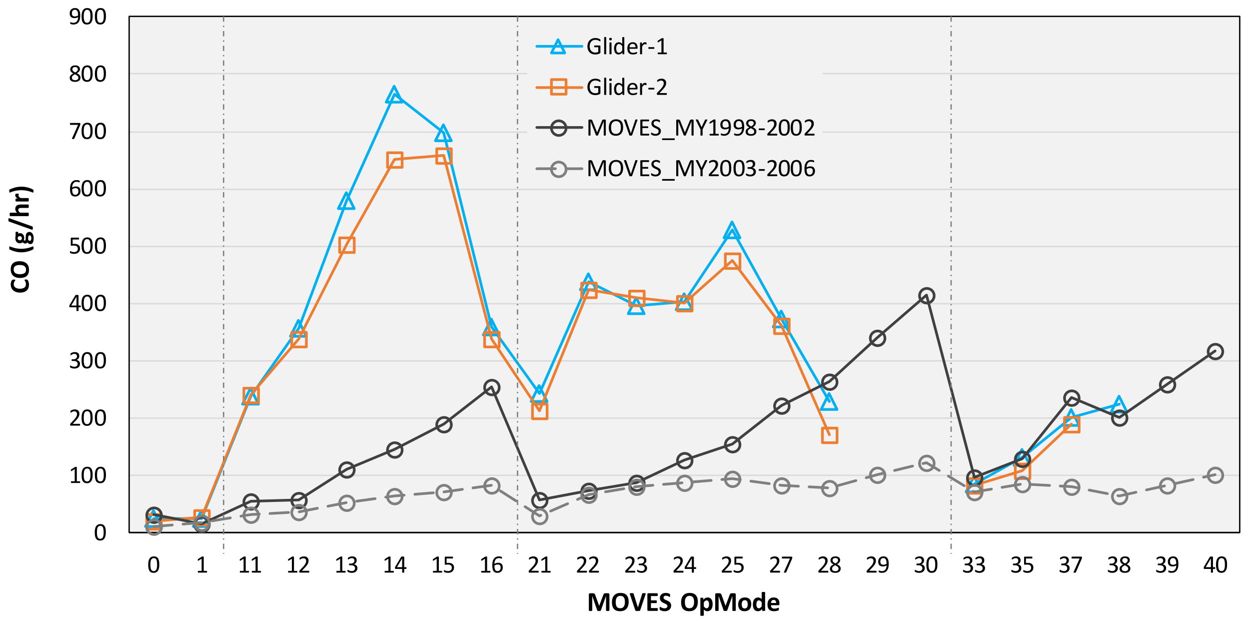


Figure H-3 Comparison of CO Emission Rates from Glider Vehicle Lab Testing to MOVES regClass 47 (HHD) 1998-2006 Model Years

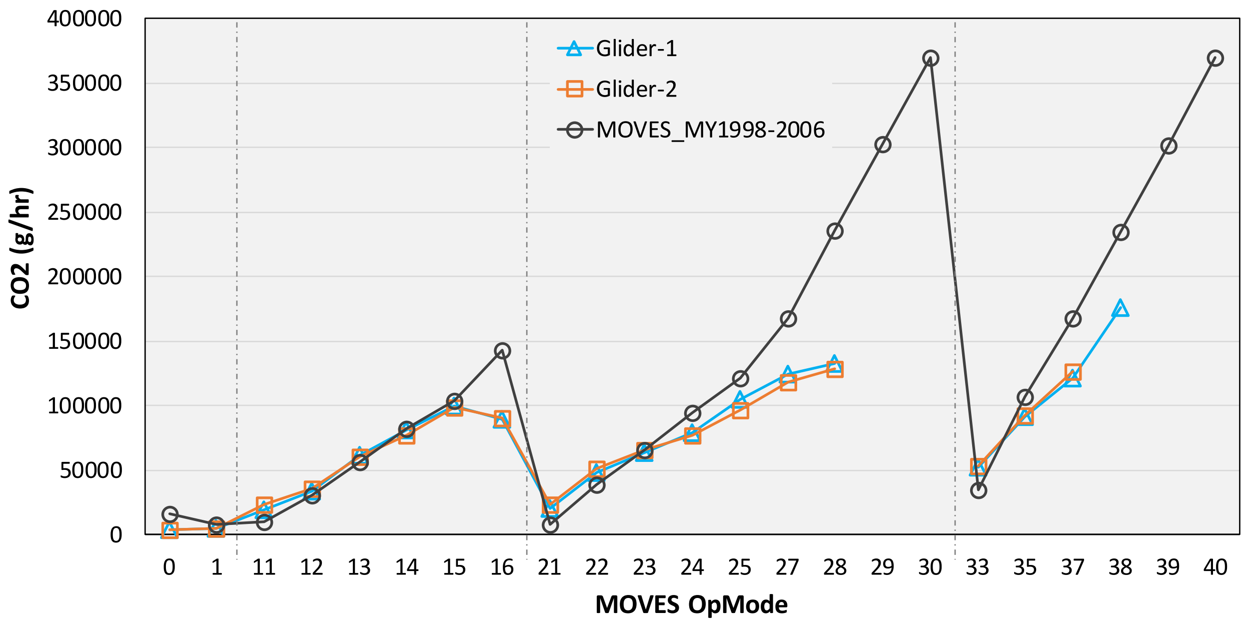


Figure H-4 Comparison of CO_2 Emission Rates from Glider Vehicle Lab Testing to MOVES regClass 47 (HHD) 1998-2006 Model Years

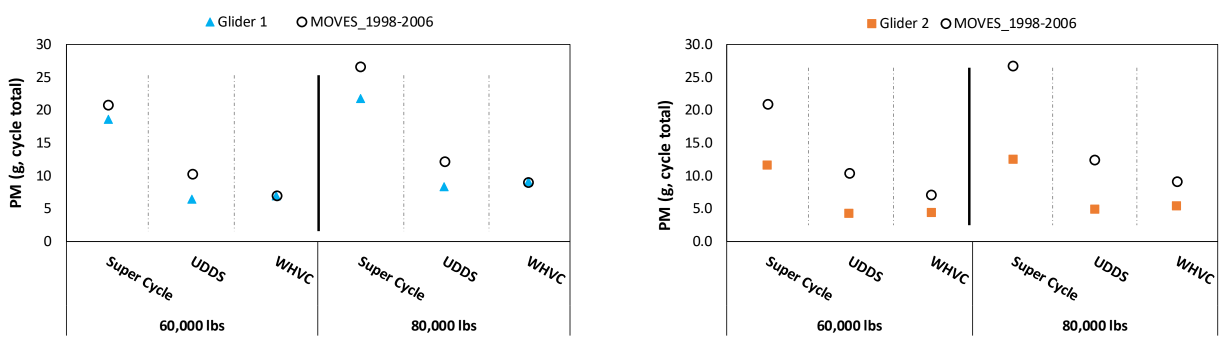


Figure H-5 Comparison of Gravimetric Filter-based PM Emissions from Glider Vehicle Lab Testing to MOVES regClass 47 (HHD) 1998-2006 Model Years

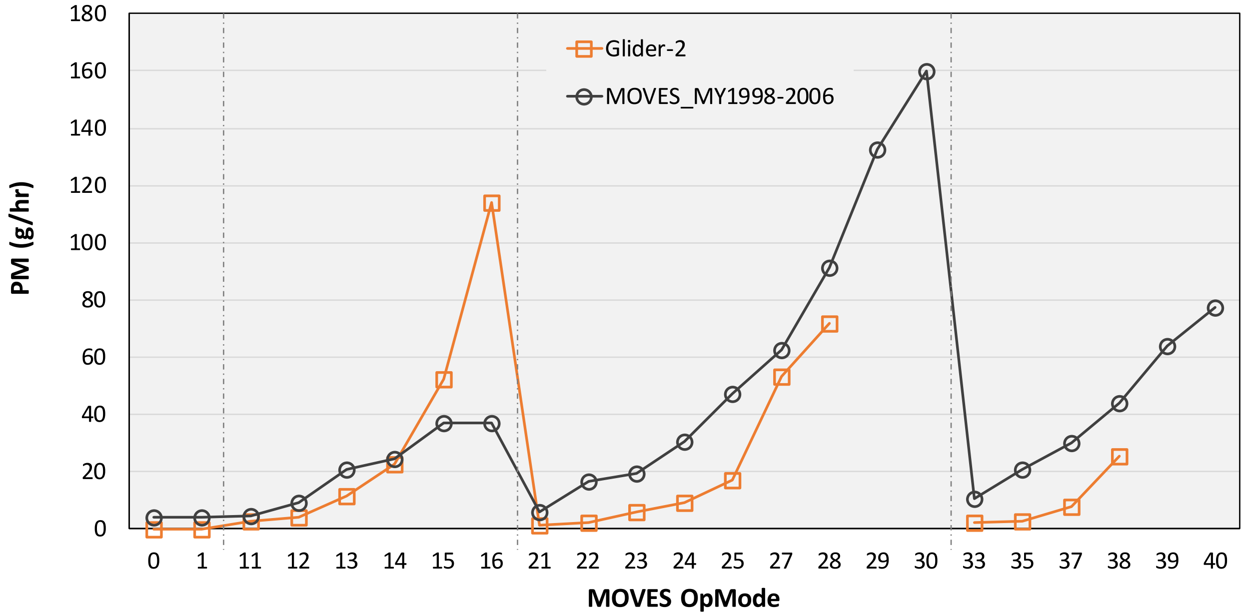


Figure H-6 Comparison of Instantaneous PM Emissions from Glider-2 Lab Testing to MOVES regClass 47 (HHD) 1998-2006 Model Years

Appendix I Tier 3 LHD2b3 Gasoline Emission Rates in MOVES2014

The Tier 3 program affects not only light-duty vehicles (below 8,500 pounds GVWR), but also chassis-certified vehicles between 8,500 and 14,000 pounds GVWR, which are referred to "light heavy-duty" vehicles. The MOVES LHD2b3 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 light heavy-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 7-1. Phase-in fractions for each standard level are also shown in Table 7-2. 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 7-3.

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 therefore remain constant throughout. The projected averaged FTP values for these two vehicle classes are also shown in Table 7-3.

Finally, weighted average values for all four vehicle classes were calculated as shown in Equation I-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 7-3.

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

Equation I-1

Table 7-1 Composite FTP NMOG+NO_x Standards for Class 2b and 3 Vehicles (mg/mi)

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

Table 7-2 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 7-3 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 I-2. Resulting phase-in fractions so calculated are shown in Table 7-4.

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

Table 7-4 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.		

Appendix J PM Composition Measurements from Auxiliary Power Units

Table 7-5 reports the organic carbon (OC), elemental carbon (EC) and total carbon (TC) measurements conducted in the study conducted by Texas Transportation Institute (TTI, 2014[92]). All the measurements were collected on APU 1. TTI collected the particulate sample on quartz fiber filters, and Sunset Laboratory Inc. analyzed the filters using thermal optical reflectance (TOR) using the IMPROVE (Interagency Monitoring of Protected Visual Environments) procedures. Total Carbon (TC) is the sum of Elemental Carbon (EC) and Organic Carbon (OC).

Table 7-5. Organic Carbon, Elemental Carbon, and Total Carbon Measurements from the IMPROVE_TOR measured on APU 1

Sample ID	Minutes	DR	Test	OC	OC uncertainty	EC	EC uncertainty	TC	TC uncertainty	EC/TC ratio
				(μg/cm^2)	(μg/cm^2)	(μg/cm^2)	(μg/cm^2)	(μg/cm^2)	(μg/cm^2)	
APU_005	10	30/1	Hot Test 1	66.35	3.42	12.98	0.75	79.33	4.17	0.16
APU_006	10	30/1	Hot Test 2	65.26	3.36	13.45	0.77	78.70	4.14	0.17
APU_007	10	30/1	Hot Test 3	59.24	3.06	10.51	0.63	69.75	3.69	0.15
APU_009	20	6/1	DPF Hot APU 1	13.85	0.79	0.86	0.14	14.71	0.94	0.06
APU_010	20	6/1	DPF Hot APU 1	14.67	0.83	1.12	0.16	15.79	0.99	0.07
APU_011	20	6/1	DPF Hot APU 1	13.18	0.76	0.93	0.15	14.11	0.91	0.07
APU_012	20	6/1	DPF Cold APU 1	16.62	0.93	1.45	0.17	18.07	1.10	0.08
APU_013	20	6/1	DPF Cold APU 1	15.86	0.89	1.40	0.17	17.27	1.06	0.08
APU_014	20	6/1	DPF Cold APU 1	17.59	0.98	1.56	0.18	19.15	1.16	0.08
APU_015	10	30/1	Cold Test 1	75.74	3.89	9.65	0.58	85.39	4.47	0.11
APU_016	10	30/1	Cold Test 2	73.83	3.79	9.61	0.58	83.44	4.37	0.12
APU_017	10	30/1	Cold Test 3	77.47	3.97	9.90	0.59	87.37	4.57	0.11

Appendix K Peer Review Comments and EPA Response

Peer review is an important element in ensuring the quality and integrity of the MOVES model. Peer review for the exhaust emission rates for heavy-duty vehicles inputs for MOVES was carried out under procedures described in the EPA Peer Review Handbook.[155] A contractor managed the peer review process, selecting qualified independent experts and arranging for letter reviews.

This appendix lists the comments received from peer reviewers on selected sections from a September 2017 version of this report. EPA questions to the reviewers are listed in bold; EPA response to the comments is in italic. Reviewer comments on minor formatting issues and typos are omitted. The peer-reviewed report, charge questions to the peer-reviewers and received peer-review comments, and other associated peer-review materials are located on EPA's science inventory webpage[156].

Note the section, table, and figure references made by the peer-reviewers refer to the September 2017 version of the report and may no longer be consistent with the current report. The EPA responses to the peer-reviewers reference sections, tables and figures in the current report.

K.1 Specific QUESTIONS for Contractor PEER REVIEW CHARGE Letter

We are submitting this material for you to review selected methods and underlying assumptions, their consistency with the current science as you understand it, and the clarity and completeness of the presentation. For this review, no independent data analysis is required. Rather, we ask that you assess whether the information provided is representative of the state of current understanding, and whether incorporating the information into EPA's MOVES model will result in appropriate predictions and conclusions.

The peer-review consists of the material in these attached documents: (1) *Exhaust Emission Rates for Heavy-Duty On-road Vehicles in MOVES201X* and (2) *Emission Adjustments for Temperature, Humidity, Air Conditioning, and Inspection and Maintenance for On-road Vehicles in MOVES201X*

In these documents, we are requesting peer-review for the sections listed below:

1. *Exhaust Emission Rates for Heavy-Duty On-road Vehicles in MOVES201X*
    - *[Section 2.1. – Running Exhaust Emissions]:* this section addresses [updated] data sources, methods, and emission rates for gaseous pollutants from MY2010+ heavy-duty diesel vehicles. EPA has also updated the method for hole-filling missing operating modes. Within Section 2.1, for the gaseous pollutants, the following subsections have not been updated and so are excluded from this peer review: 2.1.1.3.1; 2.1.1.3.3; 2.1.1.4.2; 2.1.1.6; and 2.1.1.7. Please review all of the other subsections within Section 2.1, including those identified below. However, for particulate matter (PM,) you only need to review subsection 2.1.2.2.8 (see below for details).

- *[Section 2.1.2.2.8 Computation of Elemental Carbon and Non-Elemental Carbon Emission Factors]:* this section addresses EC/PM factors for pre-2007 vehicles based on speciation data from the E55-59 report.
- *[Section 2.1.4. Energy]:* this section addresses energy rates for MY 2010+ vehicles, including the impact of the heavy-duty Phase 2 greenhouse gas (GHG) emissions standards rulemaking.
- *[Section 2.2.- Start Exhaust Emissions]:* this section addresses gaseous and $PM_{2.5}$ start emission rates for MY 2010+ heavy-duty diesel vehicles.
- *[Section 2.3. – Extended Idling Exhaust Emissions]:* heavy-duty diesel extended idle and auxiliary power unit emission rates have been updated to reflect current data and the adoption of the heavy-duty Phase 2 GHG emissions standards
- *[Section 3.1.3 Energy Consumption for Heavy-duty Gasoline Vehicles]:* heavy-duty gasoline energy rates have been updated to reflect the adoption of the heavy-duty Phase 2 GHG emissions standards.
- *[Section 3.2.3 Soak Time Adjustments]:* EPA has not made updates, but considered updating the gasoline soak time adjustments based on new data
- *[Chapter 4 Introduction and Section 4.2. – Development of Running Exhaust Emission Rates]:* this section addresses gaseous and $PM_{2.5}$ emission rates for MY 2007+ heavy-duty CNG vehicles, which rates apply to all heavy-duty CNG source types.

2. *Emission Adjustments for Temperature, Humidity, Air Conditioning, and Inspection and Maintenance for On-road Vehicles in MOVES201X*
    - *[Chapter 3. Humidity Adjustments]* This chapter has been included in this peer-review because it is pertinent to the updates EPA has made to the heavy-duty diesel emission rates in the *Exhaust Emission Rates for Heavy-Duty On-road Vehicles in MOVES201X* report.

Although, the peer-review charge is limited to the sections outlined above, we have provided the full draft reports to you for context. Comments made on the other chapters in the report are outside the scope of the peer-review, and any comments made outside of the charge will be addressed at EPA's discretion. This report references other MOVES201X draft reports. We will provide these to you at your request, but we do not anticipate that they will be needed for this work.

We request you provide us comments on substantive content sequentially. These will be listed as an appendix to the final published report, along with EPA's responses. Comments on organization, formatting, and other minor issues are welcome, but should be provided separately.

Below are questions to define the scope of the review; we are not expecting individual responses to the questions, but would like them to help guide your response.

General Questions to Consider:

1. Does the presentation describe the selected data sources sufficiently to allow the reader to form a general view of the quantity, quality and representativeness of data used in the

analysis? Are you able to recommend alternate data sources that might better allow the model to estimate national or regional default values?

2. 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 while developing the model inputs? Are examples selected for tables and figures well-chosen and effective in improving the reader's understanding of approaches and methods?

3. 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 instances involving reasonable disagreement in adoption of methods as opposed to instances where you conclude that current methods involve specific technical errors.

4. 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 are appropriate and reasonable? If not, and you are able to do so, please suggest alternative assumptions that might lead to more reasonable or accurate model inputs.

5. Are the resulting model inputs appropriate and, to the best of your knowledge and experience, reasonably consistent with physical and chemical processes involved in mobile source emissions, formation and control? Are the resulting model inputs empirically consistent with the body of data and literature with which you are familiar?

Specific Questions:

In addition to the general review, we request specific responses to the following questions:

Exhaust Emission Rates for Heavy-Duty On-road Vehicles in MOVES201X

1. [Section 2.1.1.3.2.] For a given regulatory class and NO_x FEL group, we did not distinguish emissions rates between model years. Currently available HDIU data set is limited to data from MY 2010-2013 engines. Are there any studies that show NO_x emissions of engine families, with similar NO_x FEL levels, have changed significantly in recent model years due to improvements in engine management or thermal management strategies or catalyst formation?
2. [2.1.1.2, and 2.1.1.4.1] We are considering updating the fixed mass factor (f_{scale}) values for heavy-duty vehicles (regClassID 40 through 48). The details are provided in Appendix 2 of this charge letter. What might be a better method to estimate an appropriate fixed mass factor for each regClassID? In addressing this question, you may find the background information on the f_{scale} discussed in Section 1.3, pertinent to this question.
3. [Section 2.1.2.2.6] For MY 2010+ PM rates, we initially decided not to use the HDIUT data because the numbers were scarce or low, raising concerns about the quality of the data.

Since the trends look fine we would like feedback on whether the HDIUT PM rates are of expected magnitude. Additional details are provided in Appendix 3 of this charge letter.

4. [Section 2.3.1.] We generated our pre-2007 NO_x, HC, and CO extended idle emissions rates assuming 33% of trucks idle at 1000 RPM or higher engine speeds during extended idle. Can the reviewers recommend better sources or techniques for estimating the prevalence of “high idle” during extended idling?
5. [Section 2.3.1.] We assume MHD (regClassID 46) and HHD (regClassID 47) combination long-haul trucks have the same extended idle emission rates. Do the reviewers agree? Or can they point to sources that suggest different emission rates based on engine size?

Emission Adjustments for Temperature, Humidity, Air Conditioning, and Inspection and Maintenance for On-road Vehicles in MOVES201X

1. [Section 3.2.]: Are you aware of any studies examining the effect of intake air humidity on tailpipe NO_x for model year 2010 and beyond heavy-duty engines/vehicles?

K.2 Proposal to Update Fixed Mass Factor (f_{scale})

This was an appendix to the peer review charge letter.

For background on this proposal, see the following sections in the *Exhaust Emission Rates for Heavy-Duty On-road Vehicles in MOVES201X* report:

1. Section 1.3 – Provides background and overview regarding scaled tractive power (STP) and the assignment of operating modes.
2. Section 2.1.1.1 – Describes the heavy-duty diesel in-use (HDIU) data set, which is used for the preliminary analysis presented here.
3. Section 2.1.1.2 – Describes the method for calculating scaled tractive power (STP) and the role of the fixed mass factor (f_{scale}) in the STP equations.
4. Section 2.1.1.3.2 – Describes how the average emission rates are estimated from second-by-second data. Note that the preliminary results presented here are based on only the 0.20 NO_x family emission limit (FEL) group vehicles and do not incorporate production volume weighting. This is because the issue with f_{scale} values applies to all NO_x FEL groups and is unaffected by production volume weighting.
5. Section 2.1.1.4.1 – Describes the approaches for hole-filling missing operating modes, which is the issue we are trying to address in this proposal by assigning more appropriate f_{scale} values.

We are considering updating the fixed mass factors (f_{scale}), because the changes planned to be made to MOVES201X will now allow varying f_{scale} by regulatory class. In MOVES2014, f_{scale} value is 2.06 for regClassID 40 and 17.1 for regClassIDs 41 through 48. The underlying need for the update to the f_{scale} framework comes from calculation of base emissions rates for light and medium heavy-duty regulatory classes. Recall that f_{scale} is the only term in the denominator of the equation to calculate STP, while the numerator estimates power at the wheel based on road-load coefficients or engine torque. Compared to heavy heavy-duty vehicles, the numerator term for light and medium heavy-duty vehicles is generally a smaller quantity. Thus, for light and medium heavy-duty vehicles, using an f_{scale} of 17.1 constrains the data to lower OpModes since the calculated STP never gets high enough. Which in turn means, we have to apply hole-filling for high power OpModes within each speed-bin. Although this is less of an issue for heavy heavy-duty vehicles, binning data in to OpModes can be improved by assigning a more appropriate f_{scale} value. We believe constraining real-world data to a few OpModes by using f_{scale} of 17.1 reduces the ability of the model to differentiate the effect of vehicle type and activity on the emissions.

Based on the above discussion, we are considering assigning a different f_{scale} value to each regulatory class such that it allows the emissions data to be spread over as many OpModes as reasonably possible. We propose to apply this update in MOVES201X only to model year (MY) 2010 and beyond because we are updating the emission rates for only MY 2010+ heavy-duty vehicles for MOVES201X. The emission rates for MY 2009 and older are unchanged from MOVES2014 and thus, f_{scale} values for those model years remain the same as well.

Figure K-1. and Figure K-2. are based on preliminary analyses of the data from HDIUT program and show how different f_{scale} values affect OpMode-based emissions rates for light heavy-duty diesel (LHDD) and medium heavy-duty diesel (MHDD) vehicles, respectively. All the LHDD analyses presented here are based on the same data sub-set of 42 vehicles, each with a MY 2010+

engine certified as LHDD and NO_x FEL up to 0.20 g/bhp-hr. The only difference between these analysis variations is the f_{scale} value used to calculate the STP and in turn assign an OpMode to each second of data. Similarly, all the MHDD analyses presented here have different f_{scale} values but are based on the same data sub-set of 16 vehicles, each with a MY 2010+ engine certified as MHDD and NO_x FEL up to 0.20 g/bhp-hr. As mentioned previously, this preliminary analysis does not include LHDD and MHDD data for other NO_x FEL groups. In Figure K-1., if the data is analyzed with f_{scale} of 17.1, there are no data points for OpModes 27 through 30. When f_{scale} is reduced from 17.1 to 9.00, we get emission rates for OpModes 27 and 28, and a further reduction of f_{scale} to 6.00 allows the data to populate OpModes 29 and 30. A similar (but not identical) effect is seen for the low-speed OpModes (11 through 16) and high-speed OpModes (33 through 40) emission rates for LHDD vehicles, and low/medium/ high-speed OpMode emission rates for MHDD vehicles (Figure K-2.). Thus, there is a strong case to reduce the f_{scale} for most regulatory classes from its current value of 17.1. The final value of f_{scale} for each regulatory class will be based on further analyses.

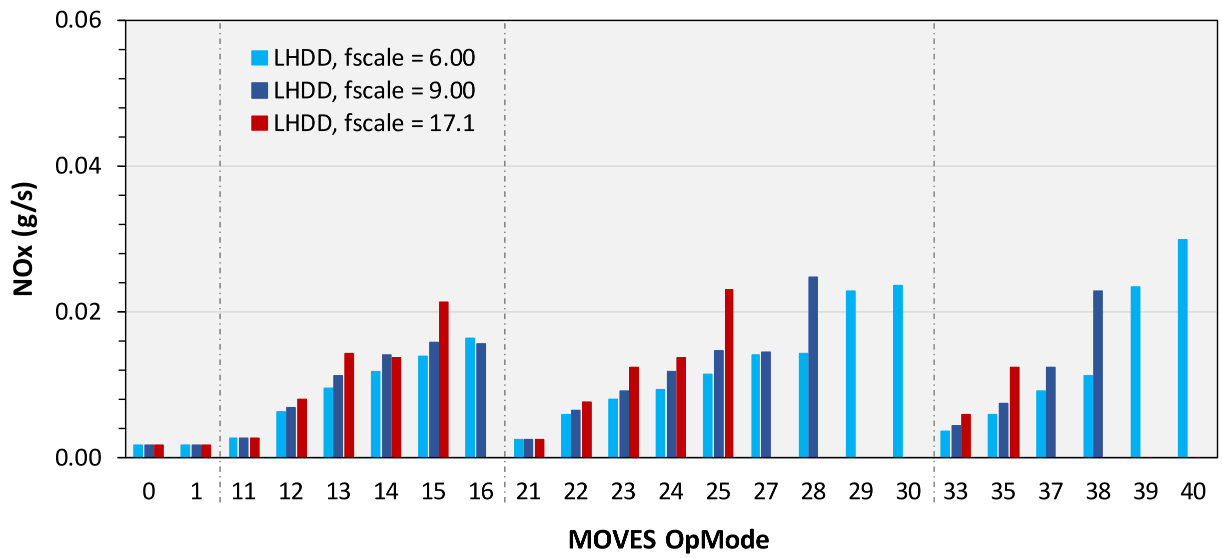


Figure K-1. NO_X Emission Rates for MY 2010-2013 Light Heavy-Duty Diesel (LHDD) Vehicles Calculated Using Various F_{scale} Values (n = 42 Vehicles in the NO_X FEL 0.20 Group)

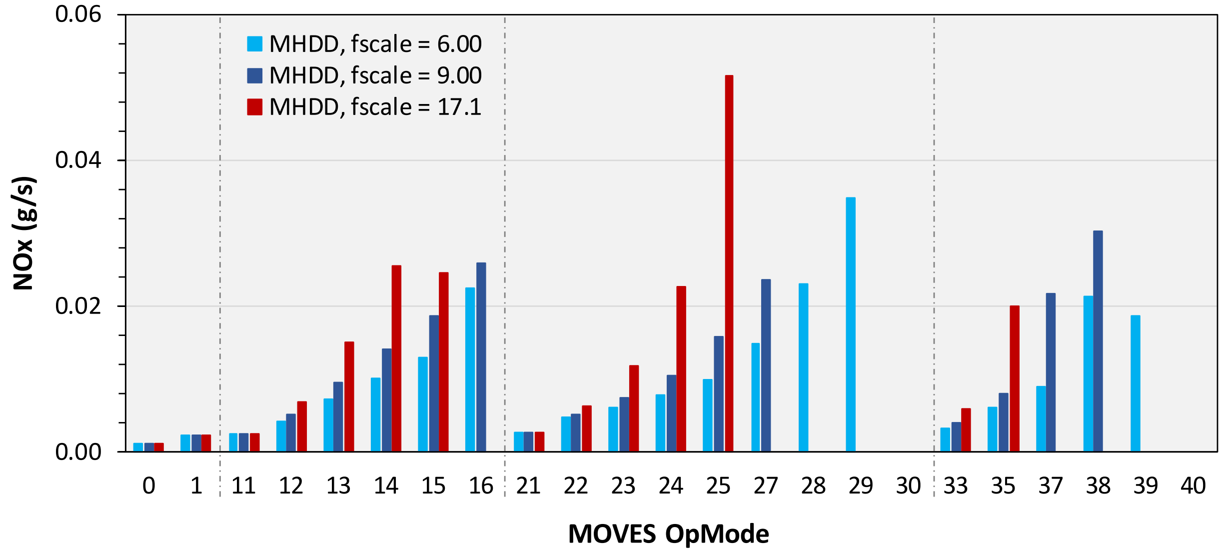


Figure K-2. NO_X Emission Rates for MY 2010-2013 Medium Heavy-Duty Diesel (MHDD) Vehicles Calculated Using Various F_{scale} Values (n = 16 Vehicles in the NO_X FEL 0.20 Group)

Table K-1 shows how, for the LHDD and MHDD data sub-sets, the vehicle count per OpMode is affected by the choice of f_{scale}. As the f_{scale} is reduced from 17.1 to 6.00, more vehicles are able to have data points assigned to high power OpModes within a speed-bin. For example, for LHDD, when f_{scale} is 17.1 all 42 vehicles have some seconds of data in OpMode 23, only 9 vehicles in OpMode 25, and no vehicles in OpModes 27 through 30. However, if the f_{scale} is reduced to 6.00, OpModes 27 through 30 get populated, though the highest power OpModes (29 and 30) have only a few vehicles.

Table K-1. Number of Vehicles by OpMode for Light Heavy-Duty Diesel (LHDD) and Medium Heavy-Duty Diesel (MHDD)

OpMode	Number of Vehicles					
	LHDD (Total 42 Vehicles)			MHDD (Total 16 Vehicles)		
	f_{scale} = 6.00	f_{scale} = 9.00	f_{scale} = 17.1	f_{scale} = 6.00	f_{scale} = 9.00	f_{scale} = 17.1
0	42	42	42	16	16	16
1	42	42	42	16	16	16
11	42	42	42	16	16	16
12	42	42	42	16	16	16
13	42	42	42	16	16	16
14	42	42	25	16	16	16
15	42	41	9	16	16	1
16	42	23		16	16	
21	42	42	42	16	16	16
22	42	42	42	16	16	16
23	42	42	42	16	16	16
24	42	42	27	16	16	16
25	42	42	9	16	16	5
27	42	24		16	16	
28	24	9		16		
29	9			9		
30	4					
33	42	42	42	16	16	16
35	42	42	26	16	16	16
37	42	25		16	16	
38	25	9		16	4	
39	9			6		
40	5					

K.3 Proposal to Update Particulate Matter (PM) Emission Rates for MY 2010+

This was an appendix to the peer review charge letter.

For background on this proposal, see the following section in the *Exhaust Emission Rates for Heavy-Duty On-road Vehicles in MOVES201X* report:

1) Section 2.1.2.2.6 – Describes the estimation of PM rates for MY 2007 and later heavy-duty vehicles equipped with diesel particulate filters (DPFs)

In past versions of MOVES, PM emission rates for DPF equipped vehicles (MY 2007 and later) were estimated by reducing PM emission rates from non-DPF vehicles (MY 2006 and earlier) by a factor of 27.7. Note that this is a much greater reduction than what the standards require, a reduction of 10 times, due to the high efficacy of DPFs observed in the certification data.

While analyzing the HDIUT data for MY 2010+ vehicles, we also estimated the PM emission rates. However, our initial decision was to not use the PM measurements from the HDIUT data to update the MOVES default rates because either the PM data was zero for about half of the measurements (as discussed in more detail below) or, when non-zero, the measured rate was very low and could be near the detection limit of the portable emissions measurement system (PEMS). In this appendix, we are presenting the PM rates from the HDIUT data and ask you to comment if the rates are what you would expect from DPF equipped vehicles.

PM concentrations and mass per time emission rates are shown in Figure K-3. and Figure K-4., respectively. These rates are based on analysis of 65 heavy heavy-duty diesel (HHDD) vehicles, each with a MY 2010+ engine equipped with DPF and SCR and with NO_x FEL up to 0.20 g/bhp-hr. While the absolute rates are small, both concentration and mass per time analysis show an increasing trend for higher power OpMode (within a speed bin). The trend is more fully developed in the mass per time analysis (Figure K-4.) because it includes the effect of exhaust flow rate, which is also expected to increase for higher power OpModes within a speed bin.

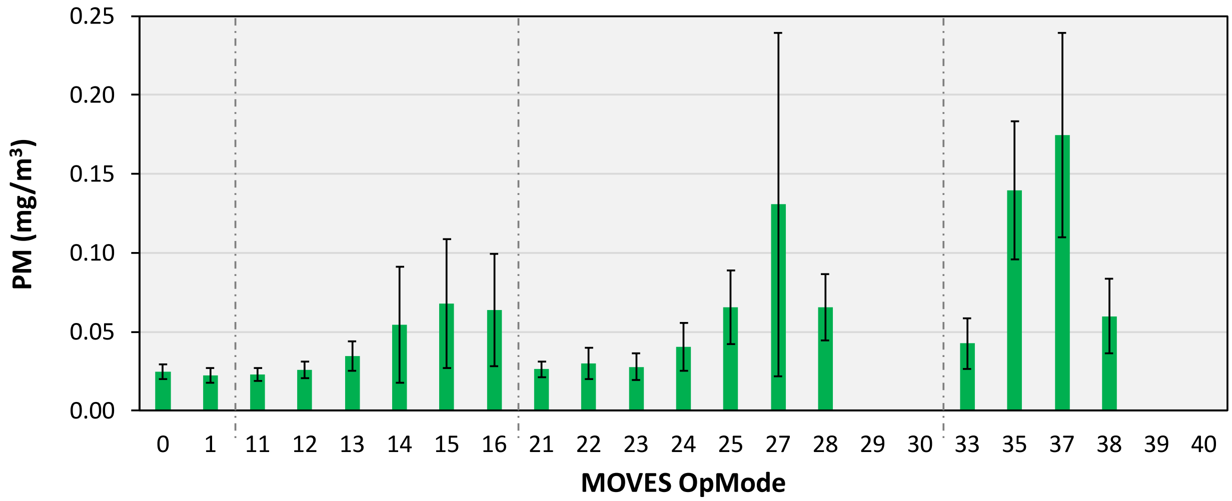


Figure K-3. PM Concentration Rates for MY 2010-2013 Heavy Heavy-Duty Diesel (HHDD) Vehicles (n = 65 Vehicles in the NO_X FEL 0.20 Group)

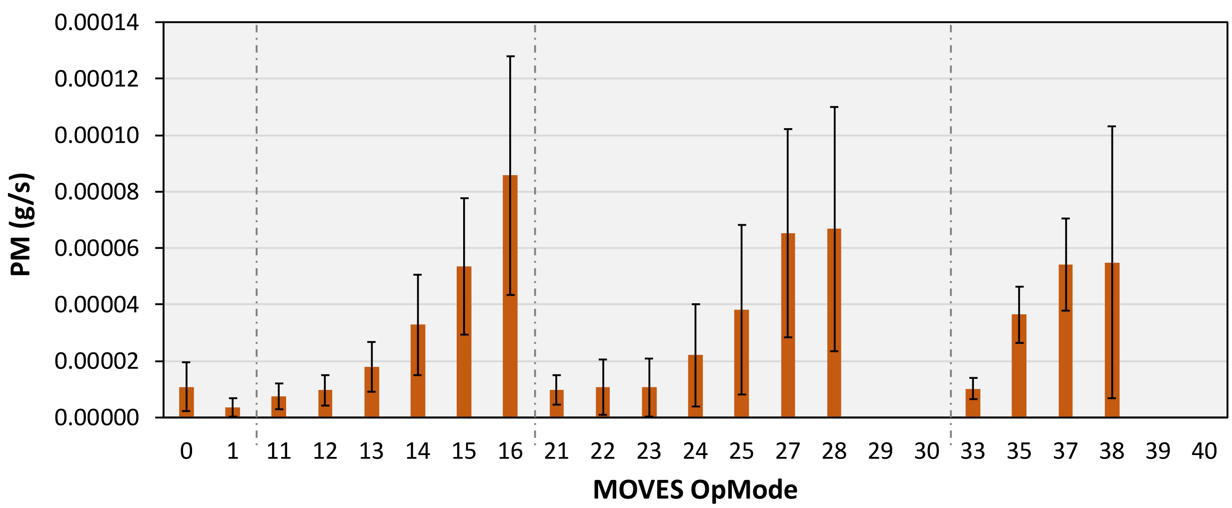


Figure K-4. PM Emission Rates for MY 2010-2013 Heavy Heavy-Duty Diesel (HHDD) Vehicles (n = 65 Vehicles in the NO_X FEL 0.20 Group)

While the trends across OpModes are as expected, our concern is mainly with the very low rates that might be close to or below the detection limit of the PEMS used in these tests. Also, these rates are significantly lower than the current default rates in MOVES2014, which were scaled down much more than the expected reduction from just comparing the pre- and post-2006 PM standards.

Table K-2 shows the number of HDIUT vehicles with reported PM rates in each of the OpModes and also compares the PM rates from HDIUT with MOVES2014. On average, half of the 65 vehicles reported non-zero PM data. If a vehicle had a mass per time rate less than $1*10^{-6}$ g/s in an OpMode, the vehicle was not included in the count for that OpMode, which is why the number of vehicles in the g/s column is often less than the number of vehicles in the mg/m^3 column. The vehicle count increases for higher power OpModes in the medium-speed bin and are the highest for the high-speed bin. This could be because more PM is emitted in these OpModes allowing more vehicles to exceed the measurement or reporting threshold. The HDIUT data based PM g/s rates are, on average, about 90% below the MOVES2014 default rates.

Using the default national activity (age distributions, speed distributions, road type distributions, drive cycles, VMT, meteorology), MOVES2014 estimates that the fleet average $PM_{2.5}$ emission rates for a 0-3 year age, model year 2010, long-haul combination diesel truck (including running and starts) is 33.5 mg/mile. If we assume the HDIUT g/s rates are 90% lower than the MOVES2014 across all operating modes, the HDIUT rates then would yield long-haul combination truck diesel $PM_{2.5}$ emission rates around ~3.3 mg/mile (assuming similar activity as MOVES2014).

We looked at the PM g/mile emission rates, reported in the literature, for MY 2010+ heavy-duty diesel vehicles equipped with DPF and SCR and having NO_x FEL up to 0.20 g/bhp-hr. Quiros et al. (2016)[157] report an average of 7.5 mg/mile over six cycles (local, regional, interstate, urban, near-dock, and hill climb). Without the near-dock and hill climb cycles, the average PM emission rate is about 6.0 mg/mile. Dixit et al. (2017)[158] report an average rate of 0.40 mg/bhp-hr (over local, regional, and UDDS cycles) which comes to 1.6 mg/mile if we use a conversion factor of 4.0 bhp-hr/mile. Thiruvengadam et al. (2015)[159] report an average of 6.2 mg/mi (over local, regional, and UDDS cycles).

Table K-2. Comparison of PM Emission Rates from HDIUT Data and MOVES2014

	HDIU (n = 65 vehicles, MY 2010-2013, NO_x FEL 0.20 Group)				MOVES2014 MY 2013	HDIU *vs* MOVES2014
	PM (mg/m3)		PM (g/s) * 10^6		PM (g/s) * 10^6	PM (g/s)
OpMode	n	Rate	n	Rate	Rate	% Reduction
0	32	0.025	12	10.9	45.3	76
1	30	0.022	5	3.6	49.5	93
11	31	0.023	16	7.5	51.5	85
12	31	0.026	20	9.7	108.7	91
13	31	0.034	27	18.0	242.1	93
14	30	0.054	27	32.9	286.2	88
15	30	0.068	30	53.5	435.8	88
16	29	0.064	28	85.8	435.8	80
21	32	0.026	18	9.7	69.4	86
22	35	0.030	27	10.8	197.3	95
23	36	0.028	26	10.7	228.7	95
24	38	0.040	31	22.0	361.4	94
25	35	0.065	34	38.3	555.4	93
27	38	0.131	37	65.3	736.1	91
28	6	0.066	6	66.8	1071.6	94
29	0	-	0	-	1560.1	-
30	0	-	0	-	1882.4	-
33	52	0.043	38	10.3	127.0	92
35	52	0.140	42	36.5	244.3	85
37	50	0.175	47	54.2	355.6	85
38	6	0.060	5	55.0	517.7	89
39	0	-	0	-	753.7	-
40	0	-	0	-	909.4	-

K.4 Comments from Arvind Thiruvengadam Ph.D.

Dr. Thiruvengadam peer-reviewed sections the of the report in September 2017 according to the charge outlined in the previous section. At the time of this review, Dr. Thiruvengadam was an Assistant Professor with the Department of Mechanical and Aerospace Engineering and the Center for Alternative Fuels, Engines, and Emissions at West Virginia University. Dr. Thiruvengadam's comments are unedited but formatted to be consistent with the format of this report. EPA responses to the comments are in italic.

General Questions

The report was very informative and I have suggested comments based on my experience and understanding of the methodologies documented in the report. Overall the approach, methodologies and data sources used for the development and upgrade of the MOVES model are very sound. The report identifies holes in the data, which published literature does not discuss and some of the information would require dedicated research to fill the gap.

Thank you

Section 2.1 Heavy-Duty Vehicle Emissions

2.1.1.1: Data Sources: The EPA has used data from 3 main sources; a) ROVER, b) Consent Decree Testing, c) HDIUT testing, d) Houston drayage data. The three data sources represent heavy-duty vehicle emissions for three distinct time periods of stringency in emission standards. The quality of the data is representative of the analyzer technology available during the different time periods. Reviewer believes it is important to mention the accuracy levels of the analyzers that were used during the collection of data. If exact values are not available, reviewer believes it is important to caveat that "data collected during ROVER and Consent decree testing could have higher variation due to the use of prototype PEMS equipment". The current technology PEMS equipment are comparable to laboratory grade analyzers and maybe associated with lesser variations and errors. Are the emissions rates from in-use testing corrected for measurement errors? In other words, was a measurement allowance added to the reported values?

The following text was added to the main report after a brief description of the data sets: "The data sets represent the accuracy of the instruments at the time of measurement. PEMS devices continue to make improvements on a variety of factors that affect measurement accuracy, such as sensor response, sample conditioning, and noise reduction. When determining whether or not the tested vehicle meets the in-use emissions standard, an "accuracy margin for portable in-use equipment" (commonly referred to as measurement allowance) is added onto the standard; increasing the vehicle compliance margin. The accuracy margins vary by model year and type of measurement method and are described in 40 CFR 86.1912. This is done to prevent measurements that are biased-high from affecting the compliance decision. Since the true value for each second of data is unknown and errors could be biased-high or -low, the in-use emission rates used in MOVES from each of these data sets are not adjusted to reflect the measurement allowance."

The report clearly explains the additional data processing (time alignment, completeness of data, etc.) and data filtering performed by EPA before incorporation into the model. This section of the report does not seem to indicate the check for carbon balance versus ECU reported fueling as another sanity check to validate exhaust flow measurement and or CO2 measurement. Was this analysis performed by EPA or did the EPA rely only on the data providers to perform this analysis? I believe the exhaust flow measurement system is subject to a lot of errors associated with condensation and drift of pressure transducers, hence this analysis is important to check for accuracy of measuring mass flow of exhaust.

The HDIU data used to update the 2010MY+ emission rates were gathered by the manufacturers and submitted to EPA as required by EPA regulations. We added this text to the main body where we describe the checks on the HDIUT data used for MY 2010+ emissions rate update: "We did not verify the accuracy of exhaust flow rate measurement and CO_2 *measurement using techniques such as carbon-balance versus ECU reported fuel rate data. Such verifications are* *assumed to have been done (by the manufacturer) before data is submitted to EPA since they are included in 40 CFR 1065 subpart J that manufacturers are required to meet."*

The methods and procedures employed to convert source data to model input is appropriate and detailed. The reviewer would like some clarification in regards to the activity distribution of the data and the data binning approach used in the calculation. In specific:

The data obtained from the HDIUT testing will be primarily of long-haul truck operation characterized by predominant highway based operation. Although this might not affect emission rates of early model year vehicles, the use of this data could be biased towards high speed operation and lower NO_x emissions from SCR. Is there a distribution of what percentage of data from HDIU testing consists of low-speed transients?

.The HDIUT data includes LHD, MHD, and HHD vehicles with a wide variety of operational conditions. In Section 2.1.1.1, we added this text and a citation to a conference presentation that includes information on time and NOx emissions by OpMode:
"The operational conditions include a wide range of driving speeds, transient and steady-state conditions, engine loads, and exhaust temperature conditions that have implications for emissions control efficacy, particularly for NO_x.[160] For the HHD class, out of a total 159 vehicles, 109 were line-haul, 46 were delivery, and the remaining were marked as "Other" in the metadata. We plan to expand the characterization of the MY 2010+ HDIUT data set, in a future update to the report, by adding summary information on vehicle age distribution, odometer reading, idling time duration, and OpMode based time and miles travelled."

In this section the report does not adequately explain how the 1Hz or 5 Hz continuous data from the different sources are segregated into the different operating modes and emissions rates for the different operating modes are calculated. Is a moving average type binning method is applied?

To determine the emission rate for an operating mode, each second of data is binned into its corresponding operating mode. No moving average binning method is applied. The method to determine emission rate per OpMode is described in sections 2.1.1.2 (Calculate STP from 1-Hz data) and 2.1.1.3 (Calculate emission rates). No changes were made to the main document.

Reviewer believes instantaneously assigning the emissions rate to different opmodes will lead to a lot of inaccuracies due to thermal inertia of aftertreatment systems, inaccuracies in broad cast torque of ECU, time alignment errors etc.

We do not view the variations in OpMode-based emission rates as inaccuracies, but rather variations that we want to capture. We do realize that history effects will impact the results, therefore, we attempt to include the largest set of data available to capture these effects. Thus, for example, the emission rate for OpMode 35 is meant to be the average rate that is representative of the variety of operational conditions seen in the real-world, including instances when the SCR aftertreatment was hot (low NO_x rate) or cold (high NO_x rate). The HDIUT data is required to be gathered in compliance with the requirements in 40 CFR 1065 Subpart J, which minimizes the inaccuracies of ECU reported engine torque and requires time alignment. We believe any *remaining errors have a small effect on the OpMode-based emission rate when it is based on the average of a large sample, as is the case with the HDIUT data set.*

2.1.1.4.1 Hole-filling Missing Operating Modes

Figure 2-3 shows the missing real-world data in the different operating modes

The figure supports the fact that the opmodes 29, 30, 39, and 40 fall in the ranges that are beyond the power rating of most HD trucks. Also the speed combination of greater than 50 and between 25 and 50 at those high operating modes is probably not possible for a fully loaded truck at 80,000 lbs. Even if there is an engine rating that can deliver that high engine power, the operation has to occur on a positive grade, and during this operation the vehicle cannot physically reach those speed bins. Should the EPA consider eliminating those speed bins, since they are not physically possible? Or is there any data to indicate otherwise to have those bins for HD application.

The OpMode modal model for heavy-duty uses a fixed mass factor, called f_{scale}*, and the binning is based on a scaled power-demand concept. We have adopted new fscale values such that all the OpMode bins, including those mentioned by the reviewer, are populated by real-world data. The method to decide new fscale values is described in Appendix G of this report.*

Figure 2-10 accurately represents the decreasing emissions rate with newer model year group. Does the projection from 2013-2050 assume no change to emissions standard?

The projection that rates are same from 2013-2050 will be updated to 2015-2060 based on changes we have made since the last review. Currently, we have removed the 2010+ rates from Figure 2-11 and added an explanatory note below the figure. It is correct that MOVES only reflects emissions standards, or regulations that can affect emission rates, that have been adopted. In the graph discussed here, the rates for 2013-2050 are shown separately than 2010-2012 because HD OBD was supposed to phase-in during 2010-2012 and be fully implemented in 2013. In MOVES, HD OBD is expected to reduce the impact of T&M on emission rates (see Appendix B).

Post 2007 PM emissions from DPF equipped vehicles are below detection limits. Tampering and mal-maintenance adjustments seem appropriate. However, the report does not seem to address data related to DPF malfunctions or failures. Can data from manufacturers shed light on the level of DPF malfunction due to various engine related faults such as stuck EGR valves, injector failure, turbo failure etc. These types of failures are common, and although there is not enough published literature related to these, manufacturer warranty claims should suggest rates of failure. The reviewer believes, engine related DPF failure events could be more common that tampering or malmaintenance.

ARB's data on T&M is incorporated in the model, as shown in Appendix B, and includes DPF failures. We will update the effects of these factors in the future as more data becomes available.

The EC and OC fraction of PM from pre and post 2007 model year vehicles are accurately represented. The report suggests that bulk of the EC/non-ECPM data was obtained from the ACES study. This study could be representative of just one engine model and the cycle used in this work was an extended 16 hr long cycle. Reviewer believes that the EPA should consider the use of data from chassis dynamometer testing from a wide range of drive cycles to compare the results obtained from the ACES study.

Unregulated greenhouse gas and ammonia emissions from current technology heavy-duty vehicles, Arvind Thiruvengadam, Marc Besch, Daniel Carder, Adewale Oshinuga, Randall Pasek, Henry Hogo & Mridul Gautam, Journal of the Air & Waste Management Association Vol. 66 , Iss. 11,2016

We have clarified the text that the ACES Phase 1 study is based on the testing of four engines. We also added this text to the MOVES speciation report, where the derivation of the $PM_{2.5}$ speciation values are documented: The ACES Phase 1 derived EC fraction of 9.9% falls within the range of EC fraction of total carbon emissions (2 to 20%) reported from Thiruvengadam et al. 2016.[161]

Page 51: HC and CO emissions from 2010 and beyond base rates: The report suggests that the quality of HC and CO are not applicable here because instruments conform to requirements of 40 CFR part 1065. The measurement of HC with a FID detector has been standard and based on the reviewer's experience there hasn't been quality issues associated with FID measurement. However, one the frequently observed issues with PEMS measurement is related to CO. The use of a single cell NDIR for both CO and CO2 causes severe drifts in the analyzer during the test period. However, during the zero and span check the drift is nonexistent due to the use of dry calibration gas and zero gas. This drift readings have resulted in high CO emissions. Since, the standard for CO is high, and the focus has always been on NO_x, the results of CO and issues related to the measurement of it using PEMS has been rarely documented.

We added this text to Section 2.1.3.2:
"Based on the HDIUT data it is not possible for us to determine if CO emission rates are affected by the drift in the CO measurement. We looked at the CO emissions for each of the 93 vehicles in the HHD 0.20 FEL group and confirm the high average CO rate is not due to a few outliers. Further, the CO emission rate for the MHD vehicles is not as high and that for the LHD vehicles (= 13.45 g/hr for OpMode 24) is even lower. Based on the available data and trends, we are unable to confirm whether or not the high CO emissions for the HHD vehicles is real or an artifact of CO sensor drift. Thus, we decided to accept the reported CO emission rates as valid."

Figure 2-21: The time-specific CO emissions rates seem to be very high. The report suggests that the figure includes the T&M effects, but the emission rates seem to be overestimated. The highest CO emissions form a post 2010 truck was observed from the non-SCR Navistar engine certified at 0.50 g/bhp-hr. The DOC is a robust aftertreatment system that shows little deterioration through the life of the engine. Furthermore, higher op-modes should technical show lower CO emissions due to *(sentence was truncated in the text received by EPA)*

See response to previous comment.

Section 2.1.4 Energy
Page 61 line 3:" Second, the truck weights and road load coefficients are updated to reflect lower vehicle weight…."

It should be made clear in this sentence that the "lower vehicle weight" is lowering of curb weight of truck and trailer by using light weight material. The sentence reads like that trucks will carrying lesser payload.

We clarified the text as suggested by the reviewer.

Table 2-21. Does the table represent the energy consumption reduction from the engine alone or a diesel engine+chassis+trailer combination?

The reductions result from a combination of improvements to the engine and other improvements outside of aerodynamics and tire rolling resistance. The text has been modified to reflect this.

In the study conducted by WVU and a report published by ICCT it is projected that by employing various engine based technology pathways HD engine will have a maximum fuel consumption reduction of 7.9% and 18.3% for the 2017 and 2020+ model years respectively. MHD will have a 10.6% and 19.5% reduction in fuel consumption for 2017 and 2020+ model years respectively.

http://www.theicct.org/sites/default/files/publications/HDV_engine-efficiency-eval_WVUrpt_oct2014.pdf

The numbers in table 2-21 corroborates this projection. However, if the vehicle improvements are factored, then the projections in WVU study could be more.

Our projections for future energy rates are based on manufacturers meeting the Heavy-Duty GHG Phase 1 and Phase 2 standards, not exceeding them. We will continue to refine the energy rates in the future with actual data.

2.2 Start Exhaust Emissions

The report does not clearly explain the definition of a fully warmed engine (is it just engine or engine and aftertreatment system). Also since the start emissions is a function of soak, what portion of the operation after the start is "start emissions"?

Start emissions represent the emissions that occur after the vehicle is started but before the engine and aftertreatment are fully warmed up. There are a variety of accepted ways to define start emissions, including the stabilization of engine coolant temperature or the achievement of a minimum aftertreatment temperature. Each manufacturer has a different control strategy for managing start emissions and the time it takes to achieve fully warm operation depends on operating conditions and drive cycle. Therefore, it is important to have a consistent definition. As noted in Section 2.2of the report, EPA defines start emissions for the MOVES model as the increase in emissions due to an engine start after the vehicle or engine has soaked for a minimum of 12 hours. That is, we use the difference in emissions between a test cycle with a cold start and the same cycle in fully warm operation without a cold start. In practice, the warm cycle often includes a hot start, however, we assume the hot start has a negligible influence on the difference between the cold cycle and warm cycle. We use the FTP cycles as the test cycle because they were *developed based on real-world driving and provide a large set of data. For heavy-duty diesel and gasoline engines, which are certified using the Heavy-Duty Engine Federal Test Procedure (FTP) cycle, the test procedure for certification requires that manufacturers run the engine over the FTP cycle with a cold start and then repeat the cycle with a warm start. Similarly, heavy-duty complete vehicles are certified using the light-duty vehicle FTP cycle that includes a cold start in Bag 1 and a warm start in Bag 3. We use the difference in the emissions between the tests with cold start and warm start conditions as the start emission in MOVES.*

2.2.1.1: The report suggests no data available for HHD or MHD trucks for the start emissions. Can data from the OEMS and other research labs that perform FTP certification testing fill this gap? The first 100-200 seconds of the cold FTP will provide the start exhaust emissions for engines. Also, the cold start of an SET engine dynamometer cycle will provide the start idle emissions for pre-2010 model year engines. Although the duration of the start exhaust emissions would be small, it would give an understanding of the magnitude of emissions rate and the duration of engine warmup.

As noted in Section 2.2of the report, HD engine manufacturers started to report as part of their application for certification to EPA the FTP results for the cold start and warm start separately in 2016, before that time they only reported the composite result. For the post-2010 model year engines, we used this data to update the start emission rates. Because we did not have data on older model year engines, updating the start emission rates for pre-2010 engines were outside the scope of the update for MOVES201x.

2.2.1.2: Is there a reference to the use of equation 2-24? Warm engine is defined as the opening of the thermostat, which corresponds to a certain coolant temperature. An integration of emissions until a coolant temperature that corresponds to the initial opening of the thermostat could be a better estimation of start emissions.

Data set from a CARB and SCAQMD funded project, published in the journal paper by Quiros et al. could provide real-world start emissions data from post MY 2013 HDD.

As noted in the responses above, EPA defines start emissions as the difference in emissions between a test cycle with a cold start (at least 12 hours of soak time) and a warm start for the MOVES model. Start emissions in MOVES are modeled as an additive number of grams of emissions per vehicle start. Because the emission data over the FTP cycle is provided in terms of grams per brake horsepower-hour (g/bhp-hr), Equation 2-24 is simply a conversion from emissions in g/bhp-hr to grams. With respect to the suggested dataset from CARB and SCAQMD, we appreciate the suggested data source. After review of the paper, we determined that we would not be able to determine the start emissions in a consistent manner with the FTP results that were used for the update.

The reviewer believes that the method for estimation of start emissions can be revised. Inferring it from FTP data is not sufficient for actual start emissions characterization. In the real-world it is observed that, irrespective of soak time, the warmup period of engine and aftertreatment system is fairly quick and the negative impact on emissions is greatly reduced.

As noted in the previous responses, we agree that there are several methods to determine start emissions. By using the approach we have chosen, we capture the total emissions due to a cold start regardless of whether the warmup period for a specific engine is fairly quick or not. If a manufacturer's control strategy leads to a quick warmup, then the difference in emissions will likely be small and that data is included in our analysis.

2.2.4 Start Energy Rates

Since fleet fuel consumption plays an important role in the HDD market, manufacturers mostly employ rapid engine warmup procedure to reduce fuel consumption. Intake throttling, higher fueling and intake manifold heating are some of the strategies that maybe used during start. The report correctly identifies that the fraction of start energy is very little compared to the total energy used by HDD, however it is also to be noted that significant auxiliary power loading can take place after a long start. Air compressor and alternator loading can be higher, particularly for applications such as urban bus. Data from OEM can shed light on the warm-up strategies employed and the energy consumption.

We agree that manufacturers have a strong incentive to both minimize fuel consumption and control emissions during the engine warmup. The use of FTP data to determine the start emissions takes into account the reviewer's concern about considering OEM's warmup strategies. EPA accounts for the auxiliary power load impacts of items such as the alternator and air compressor in MOVES separately, as described in Section 2.1.1.2

Section 2.3.2: Figure 2-46. Trucks certified to operate or idle in California must either be enabled with 5 minute auto idle shut-off or conform to the 30 g/hr optional idle NO_x standard. The time-specific emissions rate shown in figure 2-46 show a small fraction of trucks with idle emissions at or below the 30 g/hr NO_x.

The extended idle NOx emissions depend on the ambient temperature, engine speed, and auxiliary loads experienced by the engine. As shown in the figure noted by the reviewer, under lab conditions, the NOx emissions for 2010 MY and later were approximately 30 grams per hour. However, the engine often idles at higher revolutions per minute and higher load settings when the operator requests heating and/or cooling which leads to higher NOx emissions.

Page 95 Line 16: The assumption of trucks under warranty will have substantially fewer aftertreatment failures need to be revisited. DPF failures do not occur because of faulty aftertreatment system. A combination of engine control system failure leads to DPF failure. Frequently a stuck EGR valve causes increased soot loading leading to DPF failure. The OBD strategies in most cases do not pick up failed DPF or other system failures. Warranty data presented by David Quiros by ARB in CRC real-world workshop should shed light on DPF failure rates.

In MOVES, we make the assumption that there is a likelihood that failures will be fixed sooner and therefore will have a lower emissions impact while the engine/aftertreatment is under warranty and the repair costs are covered by the manufacturer. Later in the vehicle's life when it is no longer under warranty, the operator may have less incentive to repair issues that do not affect *performance of the vehicle. EPA agrees with the reviewer that additional data should be considered and we will conduct updates to tampering and malmaintenance in future MOVES releases as additional data becomes available.*

Chapter 4
The reviewer believes that the contribution of refuse trucks would be similar to that of transit buses fueled by CNG. These two captive fleets are largest in CNG usage in California.

We added the following text and citation to the introduction paragraph for section 5:
".... and in solid waste collection or refuse truck fleets.[109]"
[109] Boyce, B. 2014. Cummins Westport - Heavy Duty Natural Gas Engines for Trucks and Buses, presented at the Southeast Alternative Fuels Conference & Expo, October 22, Raleigh, NC, USA.

Table 4-1: Is there a reason has listed only literature pertaining to pre-2007 CNG transit buses. Below studies funded by CARB and SCAQMD shows emissions rate from newer natural gas transit buses

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

SCAQMD funded study conducted by WVU and UCR tested CNG transit buses over multiple driving cycles.

Thank you for providing the additional sources. Section 4.1 is carry-over information that describes why EPA made changes to MOVES2014 for natural gas emission rates, as described in Section 4.2.2.1. As noted in Sections 4.2.2.2 and 4.2.2.3, the rates for the MY 2007-2009 were scaled with certification data and MY 2010+ emission rates were updated using the HDIUT data.

Section 4.2.13 Table 4-2. For 2007-2009. Were there lean-burn NG engines certified above 0.20 g/bhp-hr during that time period. Cummins ISLG achieved 0.20 as early 2007?

Yes, the 2007-2009 MY lean burn NG engines were certified to NOx levels above 0.20 g/bhp-hr. Manufacturers certified stoichiometric NG engines with 3-way catalysts both above and below 0.20 g/bhp-hr NOx, depending on the engine.[aa]

Specific Questions:

2.1.1.3.2 The study by Quiros et al has limited data that supports the fact that since the inception of SCR control in 2010, significant advancements in thermal management, urea dosage strategy, SCR

[aa] U.S. EPA. Annual Certification Data for Vehicles, Engines, and Equipment. See https://www.epa.gov/compliance-and-fuel-economy-data/annual-certification-data-vehicles-engines-and-equipment

formulations have taken place. Real-world emissions rates have in general reduced since MY 2010. Although Quiros et al. discuss a very limited dataset, this CARB and SCAQMD funded study compared to other previous chassis dynamometer work, documented in (Thiruvengadam et al, Dixit et al.) has shown considerable reduction in NO_x emissions rate from MY 2013, and 2014 HD diesel engines.

Real-world emissions from modern heavy-duty diesel, natural gas, and hybrid diesel trucks operating along major California freight corridors. DC Quiros, A Thiruvengadam, S Pradhan, M Besch… -Emission Control Science and Technology, 2016

Emission rates of regulated pollutants from current technology heavy-duty diesel and natural gas goods movement vehicles. A Thiruvengadam, MC Besch, P Thiruvengadam… - Environmental science & technology, 2015

Poornima Dixit, J. Wayne Miller, David R. Cocker, Adewale Oshinuga, Yu Jiang, Thomas D. Durbin, Kent C. Johnson, Differences between emissions measured in urban driving and certification testing of heavy-duty diesel engines, In Atmospheric Environment, Volume 166, 2017, Pages 276-285, ISSN 1352-2310, https://doi.org/10.1016/j.atmosenv.2017.06.037.

The focus of the MOVES201X update was to appropriately reflect the implementation of the 2007/2010 NO_x *standards by the manufacturers and their use of engines certified to various family emission limit levels. The HDIUT data used in the analysis is predominantly MY 2010-2013 engine families, a handful of engine families from MY 2014, and even fewer from MY 2015. We will receive additional HDIUT data each year into the future and expect newer model years will have greater representation. Thus, if we see a consistent difference between MY 2010-2013 and MY 2014+, we will update our model year splits to better represent industry trends.*

2.1.1.2 and 2.1.1.4.1: The current fscale of 17.1 results in STP values significantly higher than the maximum engine rating available in the HD segment. The reviewer believes that the fsacle can be chosen that the maximum tractive power is always less than the average maximum available power rating of all the engine models. This would also be able to fill some of the high power opmodes of downsized engines working at full load. Fscale could be calculated as a linear fit between vehicle power and CO_2 emissions should provide a better estimate of fscale relevant to each regulatory category.

We undertook a study that used the HDIUT data set to select more appropriate fscale values for each of the HD regClasses for MY 2010+. The method and results are described in Appendix G.

2.1.2.2.6 The PM data from the HDIUT program would be primarily in the NTE region. Depending on the type of PM PEMS employed the variation in PM measurement could be significant. Since, both gravimetric and the PM sensor measure below detection limit, the use of in-use PM emissions rate must be avoided.

Figure 3 in attachment B shows an appropriate trend with slightly increasing PM concentrations at higher load opmodes. This has been observed in many in-use studies and can be attributed to the slight drop in filtration efficiency due to the passive regeneration of DPF at high exhaust temperatures.

For the post 2007 engines, the use of the AVL soot sensor data could be useful to update PM numbers at a higher confidence level. Although the soot sensor only records soot mass, this would still account for bulk of PM emissions and even marginal drop in filtration efficiency.

We used the PM emissions data from the HDIUT data set to update the PM rates. We followed the plan proposed at the MOVES Review Work Group on December 6, 2017. The final PM rates were presented at the April 10, 2019 work group. We added the following text to section 2.1.2.3: "We compared our HHD $PM_{2.5}$ rates against values reported in the literature.[157,158,159] For a MOVES national scale run, the $PM_{2.5}$ rate for a MY 2015, age 0-3, HHD vehicle was about 2.3 mg/mi. Other studies have reported PM rates in the range of 1-7 mg/mi for MY 2010+ vehicles equipped with DPF and SCR and certified to NO_x standard of 0.20 g/bhp-hr. The rates from the MOVES-run and other studies are dependent on driving cycle, however, since the MOVES rates are within the range of reported values, we decided to use the HDIUT based $PM_{2.5}$ data for the update. For the same MOVES run, the $PM_{2.5}$ rates for LHD2b3, LHD45, MHD, and Urban Bus were 4.9 mg/mi, 4.8 mg/mi, 14.6 mg/mi and 2.2 mg/mi. The OpMode based $PM_{2.5}$ rates for MHD vehicles are higher compared to other regClasses. We do not have a reason to suspect the MHD data nor do we have a confirmed explanation of why the emission rate is comparatively higher."

We acknowledge the challenges in measuring PM emissions during in-use testing for vehicles with high efficiency DPF filters. EPA is continuing to increase our capability to measure second-by-second PM data which will help inform future MOVES updates.

Section 2.3.1: The data collected by EPA for extended idling emissions seems to be comprehensive. The practice of using high idle is very subjective and depends on the truck driver and their practices. There is increase in idle speed as hoteling loads are added to the engine, and this may result in engine rpm going up to 1000 rpm. The best method to establish the practice of using high idle would be to conduct a survey of fleets. Also, telemetry based data collection (PAMS) can also shed light on the percentage of time high idle is being used.

In the case of vehicles equipped with auto idle shut-off, reviewer believes the high idle switch disables the auto-idle shut-off and hence could prompt drivers to use it more often.

Thank you for your suggestions. Currently, we do not plan to conduct fleet surveys or initiate new PAMS-based data collection to supplement our existing data, but will continue to follow others' vehicle data collection efforts to identify candidate datasets to update future MOVES versions.

Section 2.3.1 Reviewer believes that the extended idle emissions rate will be different for MHD and HHD due to the engine size difference and the thermal inertias associated with the engine and aftertreatment system. The HDIUT program from OEM should have sufficient data characterizing extended idling from MHD. One of the main differences in a MHD idle activity is that, in general MHD are used for short delivery applications and do not necessarily idle like a HHD vehicle.

We also expect there will be some emissions rate differences between MHD and HHD, but we do not have a reliable source for MHD rates. EPA's manufacturer-run in-use testing program does not include sufficient extended idle data for the MHD vehicles tested. While we do consider off-network idle in this new version of MOVES for all engines and vehicles, we continue to limit "extended idle" to the combination long-haul trucks, which would not include the short delivery applications the reviewer suggests would cause the MHD-HHD differences.

K.5 Comments from Josia Zietsman Ph.D., P.E.

Dr. Zietsman peer-reviewed sections the report in September 2017 according to the charge outlined in the previous section. At the time of the review, Dr. Zietsman was the Division Head and Senior Research Engineer with the Environment and Air Quality Division with the Texas A&M Transportation Institute and the Texas A&M University System. Dr. Zietsman's comments are unedited, but formatted to be consistent with the format of this report. EPA responses to the comments are in italic.

General Questions:

The MOVES model is comprehensive and the proposed changes/updates to the HDDV onroad emission rates will result in an improvement to the current version. In general, the report does a good job of describing the data and assumptions, and did a good job in using the best available methodologies. However, there are certain areas where additional clarity can be provided and methods can be improved, as noted below and in response to the specific questions.

Section 2.1.1.1 – In the description of data collected through the various initiatives it is not clear which one collected data for buses even though Table 2.2 shows that some bus data was collected.

The ROVER test program included both buses and trucks. We say this in the main text, "The data we used represents approximately 1,400 hours of operation by 124 trucks and buses of model years 1999 through 2007."

Section 2.1.1.2 – the power loss assumptions, as noted, is not very data driven. Can some measurements be implemented (at the axle, for example) to validate the assumptions or to potentially replace the need for calculating the losses.

We acknowledge the need to conduct future work to improve the estimates currently in MOVES. We added this text in the main document:
"We plan to revisit the accessory load losses and driveline efficiency numbers used here as additional data, particularly for MY 2010+ vehicles, becomes available. It is possible that future test programs might acquire accessory load information from the ECU and axle efficiency data is available through certification information during the HD GHG Phase 2 compliance program."

Section 2.1.1.3.2 (Pg 20) – Creation of NO_x FEL groups – a table will help in clarify of the information with regards to FEL groupings.

We substituted the bulleted list with a table showing the FEL groupings. See Table 2-6.

Section 2.1.1.8 – In discussing Sample Results one wonders about the effect of alternative fuels such as CNG and biodiesel as well as electrification moving forward.

As discussed in Section 4, we describe the MOVES201X updates to heavy-duty natural gas emission rates and vehicle categories. We will continue to monitor the evolution of the electrification in the heavy-duty sector and consider the appropriate updates to future versions of MOVES. We are interested in additional data on biodiesel. MOVES does not include biodiesel effects for MY 2007+ vehicles as discussed in the fuel effects report.[46]

Section 2.2.1.1 – it is mentioned that no temperature adjustments are applied to CO, PM or NO_x diesel start emissions. It is warranted to state why that is the case. Likely because the effect is much greater on HC.

As discussed in Section 2.4.1 of the MOVES Emission Adjustment report, the emissions data only showed a clear trend of HC emissions with ambient temperature. No clear trend was observed for CO or NOx. Also as stated in Section 2.4.2 of the MOVES Emissions Adjustment Report, the reviewed studies suggest that temperature does influence cold start PM emissions from diesel vehicles. However, at this time, MOVES does not include temperature adjustments to diesel start emissions due to limited data on diesel engines and because diesel starts are a minor contributor to particulate mass emissions to the mobile-source emission inventory. The diesel emission temperature effects can be revisited as additional data become available in future versions of MOVES.

Section 2.2.3.1. (Pg 73) – add explanation for why the base cold start emissions rates are zero for NO_x and HC

In Section 2.2.1.1, we discuss the data used to derive the base cold start emission rates for pre-2010 model year engines. The data supports zero start emissions for both NOx and HC. We added a cross-reference pointing to Section 2.2.1.1. The sentence reads as:
"For medium and heavy heavy-duty vehicles (regulatory classes MHD, HHD, and Urban Bus) only the CO soak fractions are applied to the cold-start emissions, because the base cold start HC and NO_x *emission rates for medium and heavy heavy-duty emission rates are zero (see Section 2.2.1.1)."*

Section 2.2.3.2 – It is stated that the emission reduction report discusses the impact of temperature on cold start emission rates for opMode 108. Why is this effect not included?

We clarified in Section 2.2.3.3 that the ambient temperatures effects are applied to starts of all soak lengths. The temperature for the cold-start effects for opMode 108 is included in Table 2-39.

Section 2.3.1 (Pg 86) – why the large increase in NO_x extended idle emissions rate between pre-1990 and 1990-2006 MYs?

We do not have a good technical reason, except this is what the available data indicates, as shown in Appendix D.

Specific Questions:

1. [With respect to Section 2.1.1.3.2]: For a given regulatory class and NOX FEL group, EPA did not distinguish emissions rates between model years. The currently available HDIU data set is limited to data from MY 2010-2013 engines. Are there any studies that show NOX emissions of engine families, with similar NOX FEL levels, have changed significantly in recent model years due to improvements in engine management or thermal management strategies or catalyst formation?

The current approach of not distinguishing emissions rates between MYs in a regulatory class seems reasonable, however, it is clear that more in-depth testing and research needs to be done. For example, a pair of studies performed by TTI using the on–road heavy duty measurement system (OHMS) showed high levels of NO_x for newer model trucks, likely linked to SCR functionality/exhaust temperature – reports available here: http://www.nctcog.org/trans/air/hevp/DieselIM/. A couple of other studies also showing NO_x emissions differences between vehicles of same type with slight different MYs include:

1. Kotz, A.J., Kittelson, D.B., Northrop, W.F. et al. Emiss. Control Sci. Technol. (2017) 3: 153. https://doi.org/10.1007/s40825-017-0064-4 (for buses)
2. In-Use NO_x Emissions from Model Year 2010 and 2011 Heavy-Duty Diesel Engines Equipped with Aftertreatment Devices, Chandan Misra, John F. Collins, Jorn D. Herner, Todd Sax, Mohan Krishnamurthy, Wayne Sobieralski, Mark Burntizki, and Don Chernich. Environmental Science & Technology 2013 47 (14), 7892-7898, DOI: https://doi.org/10.1021/es4006288

The focus of the MOVES201X update was to appropriately reflect the implementation of the 2007/2010 NO_x standards by the manufacturers and their use of engines certified to various family emission limit levels. The HDIUT data used in the analysis is predominantly MY 2010-2013 engine families, a handful of engine families from MY 2014, and even fewer from MY 2015. We will receive additional HDIUT data each year into the future and expect newer model years will have greater representation. Thus, if we see a consistent difference between MY 2010-2013 and MY 2014+, we will update our model year splits to better represent industry trends.

2. [With respect to Sections 2.1.1.2 and 2.1.1.4.1]: EPA is considering updating the fixed mass factor (fscale) values for heavy-duty vehicles (regClassID 40 through 48). The details are provided in Attachment A of this Peer Review Charge. What might be a better method to estimate an appropriate fixed mass factor for each regClassID? In addressing this question, you may find the background information on the fscale discussed in Section 1.3 pertinent.

In my opinion, a focused research project collecting empirical data would be useful, to revisit the concept of a fixed mass factor, or to provide some form of benchmarking or possible linkage to physical characteristics of the vehicle and engine. Given that the fixed mass factor is a scaling constant without any physical/dimensional properties, the selection of the number can be viewed as arbitrary and open to potential scrutiny or even lawsuits. An analogy for this “revised” factor would be something like the Reynolds number.

A further point to consider is the probability of vehicles actually operating in the extreme OpModes that currently do not have data in them. More empirical data collection can be used to verify this.

We undertook a study that used the HDIUT data set to select more appropriate fscale values for each of the HD regClasses for MY 2010+. The method and results are described in Appendix G. *The values represent a balance between covering the entire operating modes of vehicle activity and having sufficient emissions data to develop the emission rate for each operating mode. In our reasoning we explain how the new fscale values allow the highest power OpMode to accommodate for vehicles operating under extreme loads. In our current data sets, we do not sufficient emissions data for extreme load conditions, so this is something we will continue to look out for as future improvement.*

3. [With respect to Section 2.1.2.2.6]: For MY 2010+ PM rates, EPA initially decided not to use the HDIUT data because the numbers were scarce or low, raising concerns about the quality of the data. Since the trends look fine, EPA would like feedback on whether the HDIU PM rates are of expected magnitude. Additional details are provided in Attachment B of this Peer Review Charge.

The order of magnitude of the numbers seem reasonable. The challenge is always measuring PM at such low levels, close to equipment detection limits. This is also noticed in the large error bars in the data, and there is a clear need for additional data collection for newer MYs and continuing the efforts to develop more accurate testing equipment. It is also not clear if effect of regeneration is included in the data and that needs to be clarified.

The emission rates based on the MY 2010+ HDIUT data set includes DPF regeneration events. We acknowledge the need to improve the modeling to include the impact of DPF regeneration. Currently, real world data on regeneration is sparse. We will continue to gather data and perform literature searches both on the emissions impact of regeneration and its frequency to inform future versions of MOVES. We added this text in Section 2.1.2.3:

*“***DPF Regeneration Events:**

MOVES does not separately model the change in emissions, for any pollutant, from DPF regeneration events. However, the HDIUT data set used to update the MY 2010+ PM rates includes DPF regeneration events. Thus, the emission rates, for PM and other pollutants, includes the effects of DPF regen events. Modern DPFs have catalyzed substrate that allow them to undergo passive regeneration when the vehicle is operating at high-speeds and/or high-loads such that the exhaust temperature is sufficient to induce the regeneration. The passive regen events are “silent” and happen in the background without any regeneration code in the ECU data. On the other hand, the active regeneration events are where the ECU actively raises the temperature in the exhaust so that the soot captured in the DPF can be combusted. One way to increase the temperature is to inject additional fuel which gets burned off and raises the temperature. We analyzed the “Regen_Signal” column in the quality-assured 1 hz emissions data files for 77 vehicles in the HHD 0.20 NO_x FEL group to estimate the frequency and count of regen events. It is our understanding that the "Regen_Signal" flag only accounts for active regen events. There were 11 vehicles with the Regen_Signal set to "Y" and the regen events totaled 60,576 seconds, which is about 18% of the data from just those 11 vehicles and 3% of the data from all 77 vehicles.

Ideally, we would like to have detailed information on the frequency of regeneration events, by OpMode, in the real-world and the effect of the regeneration event on emission rates. Until we have that level of detailed data, we conclude that the emission rates in MOVES for MY 2010+ HD vehicles are somewhat representative, on average, of the effect of DPF regeneration events."

4. [With respect to Section 2.3.1]: EPA generated its pre-2007 NOX, HC, and CO extended idle emissions rates assuming 33% of trucks idle at 1000 RPM or higher engine speeds during extended idle. Can you recommend better sources or techniques for estimating the prevalence of "high idle" during extended idling?

Additional driver interviews are a possibility, especially since the UC-Davis study that the 33% number came from is now dated. Further, on-board diagnostic data extracted via data loggers would be a good source. Several large fleets are likely implementing these to collect a range of data, and companies also exist to provide tracking services to fleets, such as http://www.teletracnavman.com/

Thank you for your suggestions. We agree that additional driver interviews and vehicle data collection would provide valuable insight, but we do not plan to initiate new efforts at this time. We recognize that the 2004 UC-Davis study is dated, but note that we applied it to pre-2007 emission rates, so it is likely representative of engines from that era.

5. [Also with respect to Section 2.3.1]: EPA assumes MHD (regClassID 46) and HHD (regClassID 47) combination long-haul trucks have the same extended idle emission rates. Do you agree? Or can you point to sources that suggest different emission rates based on engine size?

We are aware of at least one study (performed by TTI) which looked at idle emissions from Class 4, 6 and 8 trucks. There were differences in emissions rates, and it warrants revisiting this assumption. Report - Characterization of Exhaust Emissions from Heavy-Duty Diesel Vehicles in the HGB Area – available at http://tti.tamu.edu/documents/0-6237-1.pdf ; see graph on Page 48 as an example.

Thank you for your suggestion. We evaluated the TTI study and found that the idle rates were gathered after 1 hour with low engine speeds and varying emission rates were presented. However, engines in the Class 8 (sourcetype 62) vehicles are not clearly distinguished as MHD and HHD. There are differences between Class 6 and Class 8 rates, as expected, but Class 6 engines are not used in Class 8 vehicles and are not representative of MHD engines used in sourcetype 62s. It's *important to note that HHD engines are used in 95% or more of the sourcetype 62 vehicles and any change to the MHD will have very little impact on the overall inventory.*

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