Development of Emission Rates for Heavy-Duty Vehicles in the Motor Vehicle Emissions Simulator (MOVES2014)

DRAFT REPORT

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1 Executive Summary

This report describes the analysis conducted to generate emission rates and energy rate inputs representing exhaust emissions and energy consumption for heavy-duty vehicles in MOVES2014. Exhaust emission rate inputs were developed for total hydrocarbons (THC), carbon monoxide (CO), nitrogen oxides (NO_X), and particulate matter (PM). Energy consumption rates were developed based on measurements of carbon dioxide (CO_2), CO and THC. We developed inputs for heavy-duty vehicles powered by both diesel and gasoline fuels, as well as compressed natural gas (CNG) vehicles, although emissions from the heavy-duty sector predominantly come from diesel vehicles. As a result, the majority of the data analyzed were from diesel vehicles.

Estimation of energy consumption rates for heavy-duty vehicles is covered in this report, but emissions of greenhouse gases other than CO_2 are not covered, with the exception of methane emissions from CNG vehicles. Estimation of the emissions of methane and nitrous oxide (N_2O) for gasoline and diesel heavy-duty vehicles are described in a separate report[1]. Ammonia emission rates, and NO2/NO fractions for NOx for heavy-duty vehicles are developed and described in a separate report[2].

Evaporative emissions from heavy-duty gasoline vehicles are not covered in this report. Estimation of evaporative hydrocarbon emissions from heavy-duty gasoline vehicles is described in a separate document[3]. Note that the methods described were developed for light-duty vehicles, but are also applied to heavy-duty gasoline vehicles. The model does not estimate evaporative emissions for diesel-powered vehicles.

Large volumes of continuous ("second-by-second") data from various sources were analyzed, including onboard emissions measurement systems, chassis dynamometer tests, and engine dynamometer tests. Data were collected by a number of entities, including EPA, West Virginia University, and private parties under contract to EPA. For running exhaust emissions, data were analyzed by model year, regulatory class, and operating mode. As with the development of emission rates for light-duty vehicles, operating modes for heavy-duty vehicles 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. For heavy-duty vehicles, we have continued to relate emissions to power output, but in a different way. Rather than normalize the tractive power for each vehicle to its own weight, we scale the power by a fixed multiple designed to fit the resulting means into the existing operating mode framework. We refer to this parameter as "scaled-tractive power" (STP). Because heavy-duty vehicles are primarily regulated on an engine work basis (g/kW-hr), we conclude that the use of STP preserves the emission to power relationship, whereas the use of VSP confounds it, resulting in unintended consequences in estimation of emissions in relation to vehicle size or weight.

Additionally, to address the question of deterioration, 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.

Final emission rates in grams per hour were developed for inclusion in the "EmissionRateByAge" table in the MOVES database. The rates describe the effects of operating mode as well as model year group, which serve as a broad surrogate for changes in technology and emissions standards, especially for NO_X and PM. The MOVES framework and the "EmissionRateByAge" table are discussed in the report documenting the rates for light-duty vehicles[4].

2 Heavy Duty Diesel Emissions

This section details our analysis of data to develop emission rates for heavy-duty diesel vehicles. Three emission processes (running, extended idling, and starts) are discussed. The 'running' process occurs as the vehicle is operating on the road either under load or in idle mode. This process is further delineated by 23 operating modes which will be discussed below. The 'extended idle' process occurs during an extended period of idling operation such as when a vehicle is parked for the night and left idling. Extended idle is generally a different mechanism (usually a higher RPM engine idle to power truck accessories for operator comfort) than the regular 'curb' idle that a vehicle experiences while it is operating on the road.

2.1 Running Exhaust Emissions

MOVES running-exhaust emissions analysis requires accurate second-by-second measurements of emission rates and parameters that can be used to estimate the tractive power exerted by a vehicle. Compared to volumes of data available for light-duty vehicles, the amount of data available for heavy-duty vehicles is small. Light-duty emissions were analyzed with respect to vehicle-specific power (VSP), which represents vehicles' tractive power normalized by their (individual) weights. The model approach used in MOVES was first developed for light-duty vehicles, relying on the VSP concept, and later adapted for use with heavy-duty vehicles. For practical reasons, it was thus desirable to retain the same operating mode structure for heavy-duty emission rates.

While VSP is an effective way to characterize emissions from light-duty vehicles, the range of running weights, coarseness of the VSP bin structure, and work-based (rather than distance-based) emissions standards make VSP-based emissions analysis for heavy-duty diesel vehicles an untenable approach. This report describes how we analyzed continuous "second-by-second' heavy-duty emissions data to develop emission rates applied within the predefined set of operating modes. As mentioned, the emission rates were using scaled-tractive power (STP), rather than VSP. The development of STP is described in greater detail below.

MOVES source bins are groupings of parameters which distinguish differences in emission rates according to physical differences in the source type or vehicle classification. The source bins are differentiated by fuel type (gasoline or diesel), regulatory class (light heavy duty to heavy-heavy duty) and model year group. Stratification of the data sample and generation of the final MOVES emission factors were done according to the combination of regulatory class (shown in Table 1) and the model year group. The regulatory groups were determined based on gross vehicle weight rating (GVWR) classifications. The model year groupings are designed to represent major changes in EPA emission standards.

Table 1. Regulatory Classes for Heavy-Duty Vehicles

Regulatory Class Description	regClassName	regClassID	Gross Vehicle Weight Rating (GVWR) [lb]
Light-heavy duty ≤ 14,000 lb	LHD<=14k	41	8,501 – 14,000
Light-heavy duty 4-5	LHD45	42	14,001 – 19,500
Medium-heavy duty	MHD	46	19,501 – 33,000
Heavy-heavy duty	HHD	47	> 33,000
Urban Bus	Urban Bus[1]	48	N/A
[1] see CFR § 86.091(2).			

Heavy-duty diesel truck emission rates in MOVES are also stratified by age group. Within a particular model year group, these age groups are used to account for the effects of deterioration over time. The age groups used in the model are shown in Table 2.

Table 2. 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	~

2.1.1 Nitrogen Oxides (NOx)

For NOx rates, we stratified heavy-duty vehicles into the model year groups listed in Table 3. These groups were defined based on changes in NOx emissions standards and the outcome of the Heavy Duty Diesel Consent Decree[5], which required additional control of NOx emissions during highway driving for model years 1999 and later. This measure is referred to as the "Not-to-Exceed" (NTE) limit.

Table 3. Model year groups for NOx analysis based on emissions standards

Model year group	FTP standard (g/bhp-hr)	NTE limit (g/bhp-hr)
Pre-1988	None	None
1988-1989	10.7	None
1990	6.0	None
1991-1997	5.0	None
1998	4.0	None
1999-2002	4.0	7.0 HHD; 5.0 other reg. classes
2003-2006	2.4	1.25 times the family emission level
2007-2009	1.2	
2010+	0.2	

2.1.1.1 Data Sources

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

ROVER. This dataset includes measurements collected during on-road operation using the ROVER system, a portable emissions measurement system (PEMS) developed by the EPA. The measurements were conducted by the U.S. Army Aberdeen Test Center on behalf of U.S. EPA[6]: This ongoing program started in October 2000. Due to time constraints and data quality issues, we used only data collected from October 2003 through September 2007. The data was compiled and reformatted for MOVES analysis by Sierra Research[7]. The process of analysis and rate development was performed by EPA. The data we used represents approximately 1,400 hours of operation by 124 trucks and buses in model years 1999 through 2007.

The vehicles were driven mainly over two routes:

- "Marathon" from Aberdeen, MD 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).[8,9] This program was initiated as a result of the consent decree between the several heavy-duty engine manufacturers and the US government, requiring the manufacturers to test in-use trucks over the road. Data was collected from 2001 through 2006. The data we used represented approximately 1,100 hours of operation by 188 trucks in model years 1994 through 2003. Trucks were heavily loaded and tested over numerous routes involving urban, suburban, and rural driving. Several trucks were re-acquired and tested a second time after 2-3 years. Data were collected at 5-Hz frequency, which we averaged around each second to convert the data to a 1.0-Hz basis.

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

Heavy-Duty Diesel In-Use testing (HDIU). The in-use testing program for heavy-duty diesel vehicles was promulgated in June 2005 to monitor the emissions performance of the engines operated under a wide range of real world driving conditions, within the engine's useful life.[10] It requires each manufacturer of heavy-duty highway diesel engines to assess the in-use exhaust emissions from their engines using onboard, portable emissions measurement systems (PEMS) during typical operation while on the road. The PEMS unit must meet the requirements of 40 CFR 1065 subpart J. The in-use testing program began with a mandatory two-year pilot program for gaseous emissions in calendar years 2005 and 2006. The fully enforceable program began in calendar year 2007 and is ongoing. The vehicles selected for participation in the program are within the engine's useful life, and generally, five unique vehicles are selected for a given engine family. The data available for use in MOVES2013 were collected during calendar years 2005 through 2010 and represent trucks manufactured in model years 2003 to 2009 (Table 4).

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

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

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

Updating MOVES emission rates currently in use was considered when two conditions were met: (1) when MOVES2010 rates for a specific regulatory-class and model-year-group combination were not based on actual data (i.e., due to gaps in the coverage of ROVER and Consent-Decree testing data[i]) and (2) when the comparisons between MOVES2010 and independent data show a clear indication of disagreement.

From each data set, we used only tests we determined to be valid. For ROVER dataset, due to time constraints, we eliminated all tests that indicated any reported problems, including GPS malfunctions, PEMS malfunctions, etc, whether or not they affected the actual emissions results. For HDIU and Houston Drayage, the time-alignment was visually confirmed by comparing relevant time-series plots, such as exhaust mass-flow rate vs. CO_2 concentration, and exhaust-mass flow rate vs. engine speed, as measured by the ECU. Data was generally aligned within one second. When an issue with the time-alignment was found, efforts were made to realign the data as much as possible. As our own high-level check on the quality of PEMS and ECU output, we, then, eliminated any trip from ROVER, HDIU, and Houston Drayage where the Pearson correlation coefficient between CO_2 (from PEMS) and engine power (from ECU) was less than 0.6. In addition, data were excluded from the analysis when the vehicle speed was not available due to GPS and/or ECU malfunctions, when no exhaust flow was reported, and when a periodic zero correction was being performed on gas analyzers. For the WVU MEMS data, WVU itself reported on test validity under the consent decree procedure and no additional detailed quality checks were performed by EPA. Table 4 shows the total distribution of vehicles by model year group from the emissions test programs above, following evaluation of the validity of the data.

Table 4. Numbers of vehicles by model year group from the ROVER, WVU MEMS, HDIU, and Houston Drayage programs used for emission rate analysis

		Regulatory Class			
Data Source	**MYG**	**HHD**	**MHD**	**LHD**	**BUS**
ROVER and Consent Decree Testing	**1991-1997**	19	-	-	2
	1998	12	-	-	-
	1999-2002	78	30	-	25
	2003-2006	91	32	-	19
HDIU	**2003-2006**	40	25	15	-

[i] Specific subsets of rates used in MOVES2010 rates were forecasted by proportioning to emission standards as described in Section 2.1.1.3.3.

	2007-2009	68	71	24	-
Houston Drayage	**1991-1997**	8	-	-	-
	1998	1	-	-	-
	1999-2002	10	-	-	-
	2003-2006	8	-	-	-

2.1.1.2 Calculate STP from 1-Hz data

With on-road testing, using vehicle speed and acceleration to estimate tractive power is not accurate given the effect of road grade and wind speed. As a result, we needed to find an alternate approach. Therefore, we decided to use tractive power from engine data collected during operation. We first identified the seconds in the data that the truck was either idling or braking based on acceleration and speed criteria shown in Table 9. 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 1. Only torque values greater than zero were used so as to only include operation where the engine was performing work.

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

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. These power loads are not subtracted in the engine torque values that are output from the engine control unit. Heavy-duty trucks use accessories 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. The calculation of the accessory load requirements is derived below.

We grouped the accessories into five categories: cooling fan, air conditioning, engine accessories, alternator (to run electrical accessories), and air compressor. We identified where the accessories were predominately used on a vehicle speed versus vehicle load map to properly allocate the loads. For example, the cooling fan will be on at low vehicle speed where the forced vehicle cooling is low and at high vehicle loads where the engine requires additional cooling. The air compressor is used mostly during braking operations; therefore it will have minimal load requirements at highway, or high, vehicle speeds. Table 5 identifies the predominant accessory use within each of the vehicle speed and load areas.

At this point, we also translated the vehicle speed and engine load map into engine power levels. The power levels were aggregated into low (green), medium (yellow) and high (red) as identified in Table 5. Low power means the lowest third, medium is the middle third, and high is the highest third, of the engine's rated power. For example, for an engine rated at 450 hp, the low power category would include operation between 0 and 150 hp, medium between 150 and 300 hp, and high between 300 and 450 hp.

Table 5. Accessory use as a function of speed and load ranges, coded by power level

Load \ Speed	Low	Mid	High
Low	Cooling Fan Air cond. Engine Access. Alternator Air Compress	Air cond. Engine Access. Alternator Air Compress	Air cond. Engine Access. Alternator
Mid	Cooling Fan Air cond. Engine Access. Alternator Air Compress	Cooling Fan Air cond. Engine Access. Alternator Air Compress	Air cond. Engine Access. Alternator
High	Cooling Fan Air cond. Engine Access. Alternator Air Compress	Cooling Fan Air cond. Engine Access. Alternator Air Compress	Cooling Fan Air cond. Engine Access. Alternator

We next estimated the power required when the accessory was "on" and percentage of time this occurred. The majority of the load information and usage rates are based on information from "*The Technology Roadmap for the 21st Century Truck*."[12]

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.1.

The total accessory loads $P_{loss,acc}$ listed below in Table 6 are subtracted from the engine power determined from Equation 1 to get net engine power available at the engine flywheel. For LHD vehicles, we assumed negligible accessory losses.

Table 6. Estimates of accessory load in kW by power range

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

We then accounted for the driveline efficiency. The driveline efficiency accounts for losses in the wheel bearings, differential, driveshaft, and transmission. The efficiency values were determined through literature searches. Driveline efficiency $\eta_{driveline}$ varies with engine speed, vehicle speed, and vehicle power requirements. Using sources available in the literature, we estimated an average value for driveline efficiency.[13,14,15,16,17,18,19,20,21] Table 7 summarizes our findings.

Table 7. Driveline efficiencies found through literature research

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

Based on this research, we used a driveline efficiency of 90% for all HD regulatory classes.

Equation 2 shows the translation from engine power P_{eng} to axle power P_{axle}.

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

Finally, we scaled the axle power by a multiplicative factor f_{scale} to fit light-duty operating-mode ranges. The MHD, HHD, and Bus classes were scaled by 17.1, which is approximately the average running weight for all heavy-duty vehicles, and the LHD trucks were scaled by 2.06, which is equivalent to the fleet-average mass of light commercial trucks in MOVES. Table 8 shows the values selected for the scaling factor.

Table 8. Power scaling factor f_{scale}

Regulatory Class	Power scaling factor
MHD, HHD, Bus	17.1
LHD	2.06

Equation 3 shows the conversion of axle power to scaled tractive power using the method explained above.

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

We then constructed operating mode bins defined by STP and vehicle speed according to the methodology outlined earlier in MOVES development[22] and described in Table 9. The implementation of STP in MOVES for heavy-duty emission rates is the same as that of VSP for light-duty emission rates. We will refer to the units of STP as scaled kW or skW.

Table 9. Definition of the Operating Mode Attribute for Heavy-Duty Vehicles (opModeID)

Operating Mode	Operating Mode Description	Scaled Tractive Power (STP_t, skW)	Vehicle Speed (v_t, mph)	Vehicle Acceleration (a, mph/sec)
0	Deceleration/Braking			$a_t \leq -2.0$ OR ($a_t < -1.0$ AND $a_{t-1} < -1.0$ AND $a_{t-2} < -1.0$)
1	Idle		$-1.0 \leq v_t < 1.0$	
11	Coast	$STP_t < 0$	$0 \leq v_t < 25$	
12	Cruise/Acceleration	$0 \leq STP_t < 3$	$0 \leq v_t < 25$	
13	Cruise/Acceleration	$3 \leq STP_t < 6$	$0 \leq v_t < 25$	
14	Cruise/Acceleration	$6 \leq STP_t < 9$	$0 \leq v_t < 25$	
15	Cruise/Acceleration	$9 \leq STP_t < 12$	$0 \leq v_t < 25$	
16	Cruise/Acceleration	$12 \leq STP_t$	$0 \leq v_t < 25$	
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	$30 \leq STP_t$	$50 \leq v_t$	

2.1.1.3 Calculate emission rates

2.1.1.3.1 Means

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

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

where

n_j = the number of 1-Hz data points for each vehicle j,

n_{veh} = the total number of vehicles,

$r_{p,j,i}$ = the emission rate of pollutant p for vehicle j at second i,

$\bar{r}_p$ = the mean emission rate (meanBaseRate) for pollutant p.

For NOx, 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.

2.1.1.3.2 Statistics

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

$$s^2_{with} = \frac{\sum_{j=1}^{n_{veh}} (n-1) s^2_{veh}}{n_{tot} - n_{veh}} \qquad \textbf{Equation 5}$$

where

s_{veh}^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_{betw}^2 (by source bin, age group, and operating mode) using the mean emission rates for individual vehicles ($\bar{r}_{p,j}$) as shown in Equation 6.

$$s_{\text{betw}}^2 = \frac{\sum_{j=1}^{n_{\text{veh}}} \left(\bar{r}_{p,j} - \bar{r}_p\right)^2}{n_{\text{veh}} - 1} \qquad \textbf{Equation 6}$$

Then, we estimated the total variance by combining the within-vehicle and between-vehicle variances to get the standard error $s_{\bar{r}_{pol}}$ (Equation 7) and dividing the standard error by the mean emission rate to get the coefficient-of-variation of the mean $c_{v,\bar{r}_{pol}}$ (Equation 8).

$$s_{\bar{r}_{pol}} = \sqrt{\frac{s_{\text{betw}}^2}{n_{\text{veh}}} + \frac{s_{\text{with}}^2}{n_{\text{tot}}}} \qquad \textbf{Equation 7}$$

$$c_{v,pol} = \frac{s_{\bar{r}_{pol}}}{\bar{r}_{pol}} \qquad \textbf{Equation 8}$$

2.1.1.3.3 Hole Filling and forecasting

2.1.1.3.3.1 Heavy-Duty Trucks (HHD, MHD, Bus, and LHD not equipped with Lean NOx Traps)

Since the data only covered model years 1994 through 2009, we needed to develop a method to forecast emissions for future model years and back-cast emissions for past model years. For future model years (2010-and-later), we decreased the emission rates for all operating mode bins by a ratio proportional to the decrease in the applicable emissions standards. Starting in MY2010, the NOx standard for all heavy-duty trucks is 0.2 g/bhp-hr. We projected that almost all of these trucks will be using SCR after-treatment technology, which we assume to have a 90 percent NOx reduction efficiency from levels for MY2006 levels (2.4 g/bhp-hr), and thus, we estimated the rates for model year 2010 and later by decreasing MY2003-2006 rates by 90 percent.

For model year 1990, we increased the 1991-1997 emission rates by 20 percent to account for the reduction in NOx standard from 6.0 to 5.0 g/bhp-hr from 1990 to 1991. For 1989 and earlier model years, we increased the 1991-1997 model year group emission rates by 40 percent, which is proportional to the increase of the certification levels from the 1991 model year to the 1989 model year. We assumed that emission levels did not change by model year for 1989 and earlier.

For MHD and HHD trucks, the maximum operating mode represents a tractive power greater than 513 kW (STP= 30 skW × 17.1). This value exceeds the capacity of most HHD vehicles, and MHD vehicles and buses exert even lower levels. As a result, data are very limited in these modes.

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

For certain model years, such as 1998, data existed for HHD trucks, but not MHD or buses. In these cases, the ratio of standards between the missing regulatory class and HHD regulatory class from the 1999-2002 model year group was used to calculate rates for the missing class rates by multiplying that ratio by the existing HHD emission rates for the corresponding model year group.

2.1.1.3.3.2 Pickup trucks equipped with Lean NOx Traps

To meet NOx emissions standards for the 2010 model year, the use of after-treatment will probably be needed. For example, Cummins decided to use after-treatment starting in 2007 in engines designed to meet the 2010 standard and used in vehicles such as the Dodge Ram. The technology adopted for this purpose was the "Lean NOx Trap" (LNT). This technology allows for the storage of NOx during fuel-lean operation and conversion of stored NOx into N_2 and H_2O during brief periods of fuel-rich operation. In addition, to meet particulate standards in MY 2007 and later, heavy-duty vehicles are equipped with diesel particulate filters (DPF). At regular intervals, the DPF must be regenerated to remove and combust accumulated PM to relieve backpressure and ensure proper engine operation. This step requires high exhaust temperatures. However, these conditions adversely affect the LNT's NOx storage ability, resulting in elevated NOx emissions.

In 2007, EPA acquired a truck equipped with LNT and DPF and performed local on-road measurements, using portable instrumentation. We used the PEMS and ECU output to assign operating modes and calculate emission rates by the same methods used to develop the heavy-heavy-duty truck NOx rates. While analyzing these data, we distinguished regimes of PM regeneration from normal operation based on exhaust temperature, with temperatures exceeding 300°C assumed to indicate PM regeneration. We performed the emission rate by operating mode analysis separately for each regime, and weighted the two regimes together based on an assumed PM regeneration frequency of 10 percent of VMT. This value is an assumption based on the limited data available. We will look for opportunities to update this assumption based on any additional information that becomes available.

Because we assume that LNT-equipped trucks account for about 25 percent of the LHDDT market, we again weighted the rates for the two LHD regulatory classes for model years 2007 and later. For MY 2007-09, we assume that the remaining 75 percent of LHD diesel trucks will not have after-treatment and will exhibit the 2007-2009 model year emission rates described earlier in this section. Starting in MY2010, we assume that the remaining 75 percent of LHD diesel trucks are equipped with SCR, and exhibit 90 percent NOx reductions from 2006 levels, described in Section 2.1.1.3.3.1.

2.1.1.3.3.3 Summary

Table 10 summarizes the methods used to estimate emission rates for each regulatory–class/model-year-group combination. The emission rates based on the analysis of ROVER and Consent Decree testing data were used to populate the rates in MOVES2010. For MOVES2014, we made a decision to update the emission rates, for MYG2007-2009 for HHD and MYG2003-2006 for LHD, based on the comparison of the emission rates in MOVES2010 to HDIU and Houston Drayage data, discussed in Section 2.1.1.5. For all other combinations of regulatory classes and model year groups, the rates from MOVES2010 were retained in MOVES2014.

Table 10. Summary of methods for heavy-duty diesel NOx emission rate development for each regulatory class and model year group

Model year group	HHD	MHD	Bus	LHD
Pre-1988	Proportioned to certification levels	Proportioned to certification levels	Proportioned to certification levels	Proportioned to certification levels
1988-1989	Proportioned to certification levels	Proportioned to certification levels	Proportioned to certification levels	Proportioned to certification levels
1990	Proportioned to certification levels	Proportioned to certification levels	Proportioned to certification levels	Proportioned to certification levels
1991-1997	Data analysis[1,3]	Proportioned to HHD	Data analysis	Proportioned to HHD
1998	Data analysis[1,3]	Proportioned to HHD	Proportioned to HHD	Proportioned to HHD
1999-2002	Data analysis[1,3]	Data analysis[1]	Data analysis[1]	MHD engine data

				with LHD scale factor
2003-2006	Data analysis[1,3]	Data analysis[1,3]	Data analysis[1]	Data analysis[2]
2007-2009	Data analysis[2]	Proportioned to standards[3]	Proportioned to standards	Data (LNT), and proportioned to standards (non-LNT)[3]
2010 +	Proportioned to standards	Proportioned to standards	Proportioned to standards	Proportioned to standards

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

An important point to note is that we did not project increases in NOx emissions with age for vehicles not equipped with NOx after-treatment technology (largely 2009 model year and earlier). This is because of a few reasons:

- The WVU MEMS data did not show an increase in NOx emissions with odometer (and consequently, age) during or following the regulatory useful life[23]. 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.

We estimated tampering and mal-maintenance effects on NOx emissions to be small compared to other pollutants – around a 10 percent increase in NOx over the useful life of the engine. Our tampering and mal-maintenance estimation methods are discussed below and detailed in Appendix A.2.

2.1.1.3.4 Tampering and Mal-maintenance

Table 11 shows the estimated aggregate NOx emissions increases due to T&M. It also shows the values that we actually used for MOVES emission rates. As previously mentioned, we assumed that in engines not equipped with aftertreatment, NOx does not increase due to T&M or deterioration.

Table 11. Fleet-average NOx emissions increases from zero-mile levels over the useful life due tampering and mal-maintenance

Model years	NOx increase from T&M analysis [%]	NOx increase in MOVES [%]
1994-1997	10	0
1999-2002	14	0
2003-2006	9	0

2007-2009	11	0
2010-2012 SCR	77	77
2010-2012 LNT	64	64
2013+	58	58

As described in Appendix A.2, these emissions increases are combined with information in Table 60 to estimate the emissions increase for each age group prior to the end of the useful life for each regulatory class. With the introduction of aftertreatment systems to meet regulatory requirements for MY 2010 and later, EPA expects tampering and mal-maintenance to substantially increase emissions over time compared to the zero-mile level. Though 77 percent may appear to be a large increase in fleet-average emissions over time, it should be noted that the 2010 model year standard (0.2 g/bhp-hr) is about 83 percent lower than the 2009 model year effective standard (1.2 g/bhp-hr). This still yields a substantial reduction of about 71 percent from 2009 zero-mile levels to 2010 fully deteriorated levels. As more data becomes available for future model years, we hope to update these tampering and mal-maintenance and overall aging effects.

2.1.1.3.5 Defeat Device and Low-NO_x Rebuilds

The default emission rates in MOVES for model years 1991 through 1998 are intended to include the effects of defeat devices as well as the benefits of heavy-duty low-NO_x rebuilds (commonly called reflash) that occurred as the result of the heavy-duty diesel consent decree. Reflashes reduce NOx emissions on 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 assume that NO_x emissions were elevated for only the top two speed ranges in the running exhaust operating modes (>25mph). To modify the relevant emission rates to represent reflash programs, we first calculated the ratios emission rates in modes 27 and 37 to that for opMode 16, for model year 1999 (the first model year with not-to-exceed emission limits). We then multiplied the MY 1999 ratios by the emission rates in mode 16 for model years 1991 through 1998, to get estimated “reflashed” emission rates for operating modes 27 and 37. This step is described in Equation 9 and Equation 11. To estimated “reflashed” rates in the remaining operating modes, we multiplied “reflashed rates by ratios of the remaining operating modes to mode 27 for MY1991-98, as shown in Equation 10 and Equation 12.

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 9**

$$\bar{r}_{reflash,91-98,\mathrm{OM}x} = \bar{r}_{reflash,91-98,27}\left(\frac{\bar{r}_{91-98,\mathrm{OM}x}}{\bar{r}_{91-98,27}}\right)$$ **Equation 10**

Operating modes (OM) 31-40

$$\bar{r}_{reflash,91-98,37} = \bar{r}_{91-98,16}\left(\frac{\bar{r}_{1999,37}}{\bar{r}_{1999,16}}\right)$$ **Equation 11**

$$\bar{r}_{reflash,MY1991-1998,OMx} = \bar{r}_{reflash,91-98,37}\left(\frac{\bar{r}_{91-98,\mathrm{OM}x}}{\bar{r}_{91-98,37}}\right)$$ **Equation 12**

The default emission rates were also slightly adjusted for age for the consent decree model years. An EPA assessment shows that about 20 percent of all vehicles eligible for reflash had been reflashed by the end of 2008.[24] We assumed that vehicles were receiving the reflashes after the heavy-duty diesel consent decree (post 1999/2000 calendar year) steadily, such that in 2008, about 20 percent had been reflashed. We approximated a linear increase in reflash rate from age zero.

2.1.1.4 Sample results

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

Figure 1 and Figure 2 show that NOx emission rates increase with STP for HHD trucks. Figure 3 adds the MHD and bus regulatory classes, with the error bars removed for clarity. As expected, the emissions increase with power, with the lowest emissions occurring in the idling/coasting/braking bins.

Figure 1. Trends in NOx Emissions by operating mode from HHD trucks for model year 2002

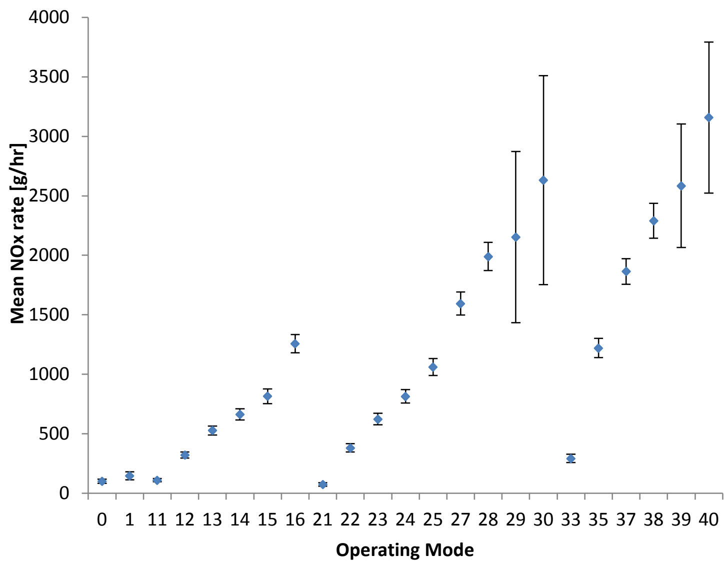
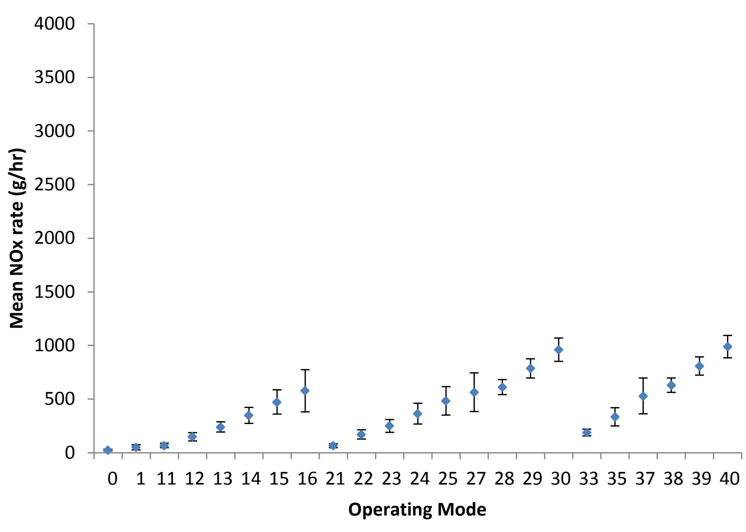
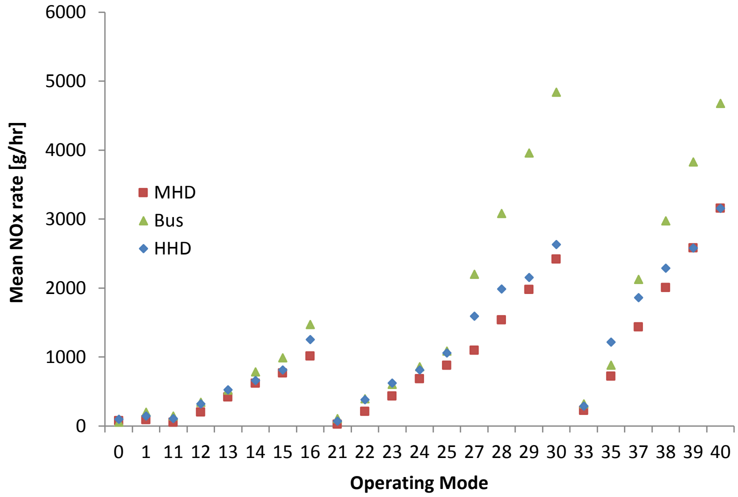


Figure 2. Trends in NOx Emissions by operating mode from HHD trucks for model year 2007



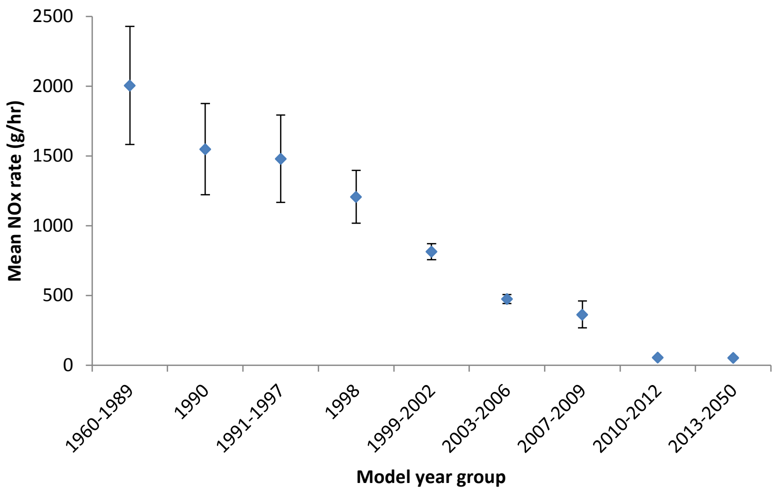
The highest operating modes in each speed range will rarely be attained due to the power limitations of heavy-duty vehicles, but are included in the figures (and in MOVES) for completeness. Nearly all of the activity occurs in modes 0, 1, 11-16, 21-28, and 33-38, with activity for buses and MHD vehicles usually occurring over an even smaller range. In some model year groups, the MHD and HHD classes use the same rates, based on lack of significant differences between those two classes' emission rates.

Figure 3. Trends in NOx emissions by operating mode from MHD, HHD, and 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 4, which shows decreasing NOx rates by model year group for a sample operating mode (#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 NOx standards. Increasingly stringent emissions standards have caused NOx emissions to decrease significantly.

Figure 4. Trends in NOx by model year for HHD trucks in operating mode 24



Age effects were only implemented for after-treatment-equipped trucks (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 5. Relative Standard Errors (based on coefficients-of-variation for means) from previous model year groups were used to estimate uncertainties for MY 2010.

Figure 5. Modeled NOx trends by age for model year 2010 for operating mode 24

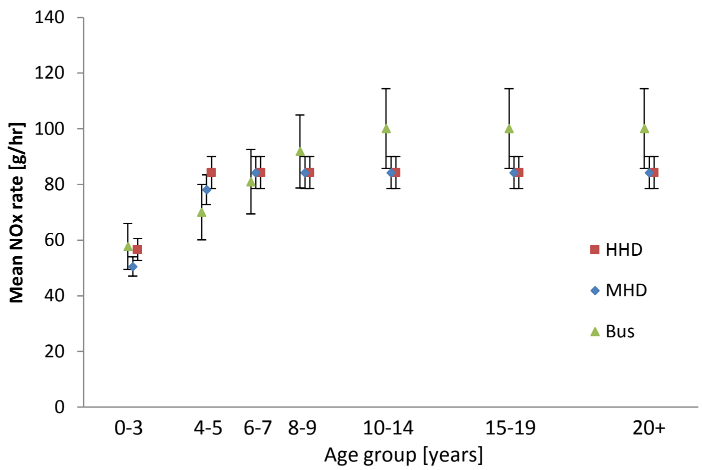


Figure 6 and Figure 7 shows the mean emission rates for LHD trucks for model years 2003-2006 and 2007-2009, respectively. The estimated uncertainties are greater than for the other heavy-duty regulatory classes, since there were fewer vehicles in our test data. As described previously, model years 2007-2009 vehicles includes vehicles with LNTs (with NO_x increases during PM regeneration) and vehicles without any aftertreatment.

Figure 6. Mean NOx rates by operating mode for model years 2003-2006 LHD trucks age 0-3

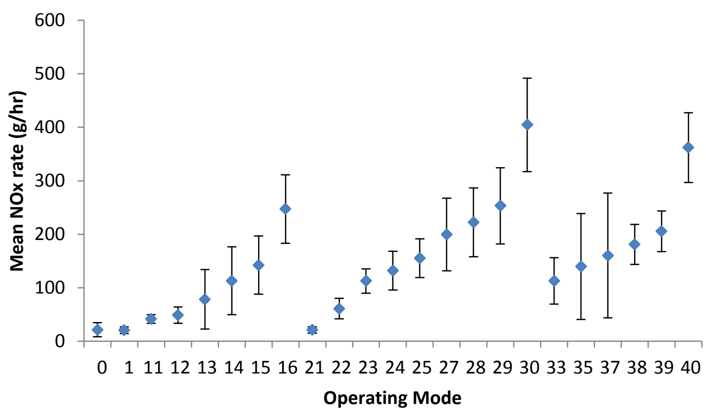
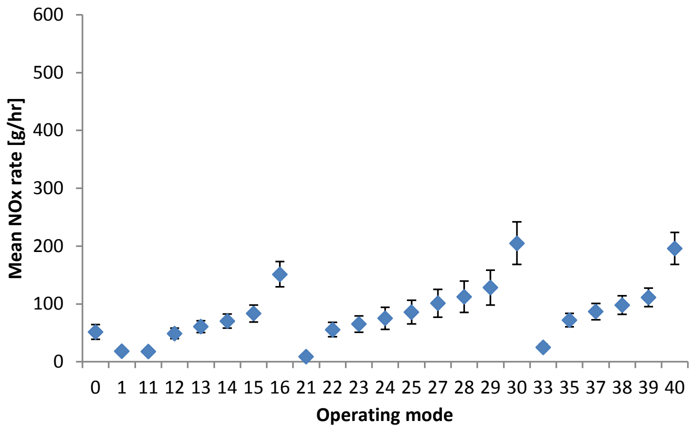


Figure 7. Mean NOx rates by operating mode for model years 2007-2009 LHD trucks age 0-3



2.1.1.5 Evaluation of NOx Emission Rates in MOVES2010

This section presents the results from the efforts to verify the NOx emission rates in MOVES2010 by comparing the rates in the database to the emissions data from the Heavy Duty In-Use and Houston Drayage data programs. The HDIU data includes results for HHD, MHD, and LHD trucks, whereas the Houston Drayage data only includes HHD trucks.

As discussed in Section Data Sources, HDIU and Houston Drayage data have become available after the MOVES2010 release and have served two purposes – to evaluate the rates in MOVES2010 and to be used as a new data source 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 a clear indication of disagreement.

2.1.1.5.1 Heavy-Heavy Duty Trucks

Figure 8 through Figure 10 show that MOVES2010 rates for pre-2003 model years are generally in good agreement with the Houston Drayage data and within the range of uncertainty of means calculated from these data. The error bars represent the 95% confidence intervals of the mean. MOVES rate is lower in the high speed operating modes (33 and above) compared to 1998 model year trucks (Figure 9). However, only a single truck is represented in the Houston Drayage data. 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 8. Comparison of Means: MOVES emission rates vs. Houston Drayage Data (n=8) for model years 1991-1997 HHD trucks

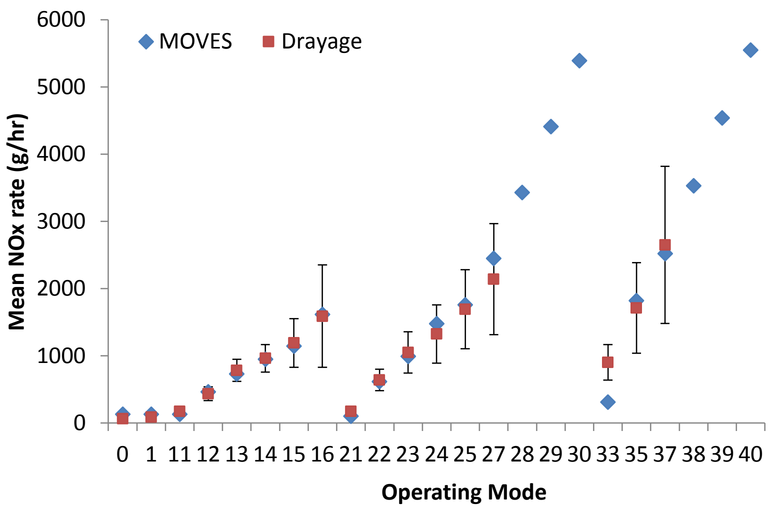


Figure 9. Comparison of Means: MOVES emission rates vs. Houston Drayage Data (n=1) for model year 1998 HHD trucks

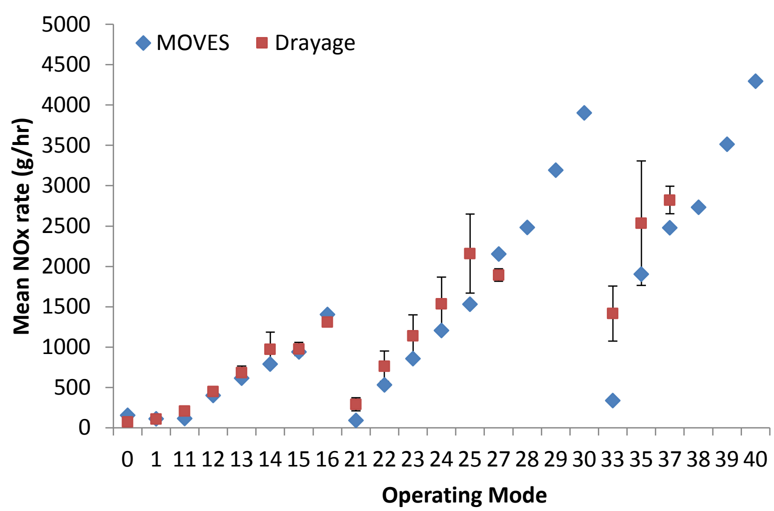
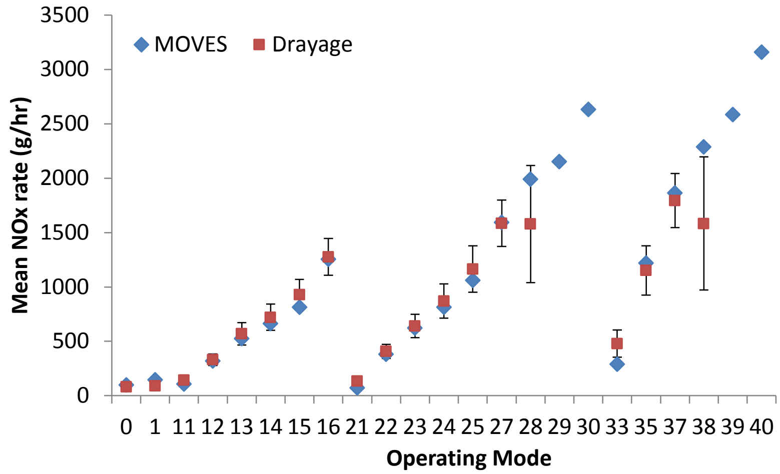


Figure 10. Comparison of Means: MOVES emission rates vs. Houston Drayage Data (n=10) for model year 1999-2002 HHD trucks



In Figure 11 and Figure 12, MOVES rates for model years 2003-2006 are compared to results from the Houston Drayage and HDIU datasets, respectively. Although MOVES' rates for middle and high speed operating modes are lower, it is within the 95% confidence intervals of the mean of Houston Drayage data in Figure 11. When compared to HDIU data in Figure 12, MOVES is generally within the variability of the data except for the low speed operating modes. Although both comparisons showed that MOVES rates are slightly lower, since the rates in MOVES2010 for model years 2003-2006 were also based on the analysis of the testing data (ROVER and Consent Degree Testing), no change was made to the rates in MOVES2014.

Figure 11. Comparison of Means: MOVES emission rates vs. Houston Drayage Data (n=8) for model year 2003-2006 HHD trucks

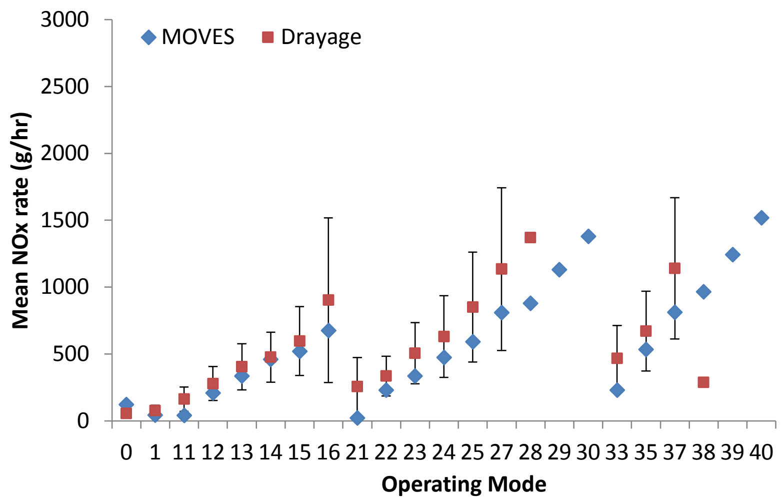
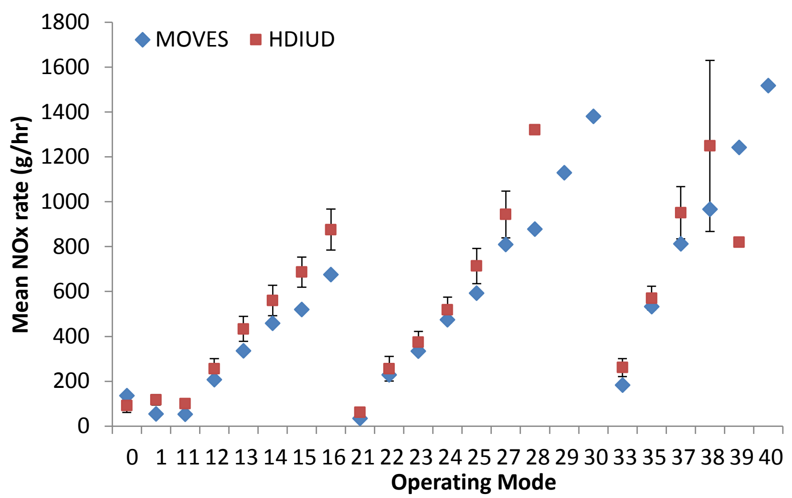
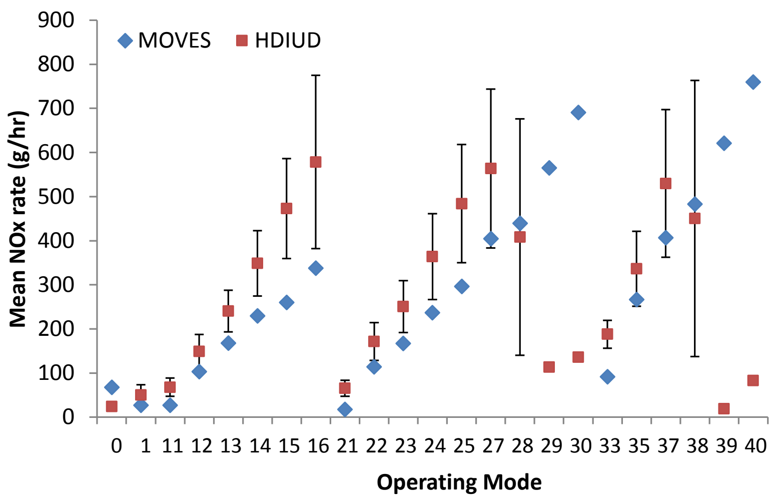


Figure 12. Comparison of Means: MOVES rates vs. HDIU (n=40) for model years 2003-2006 HHD trucks



In the MOVES2010 database, rates for model years 2007-2009 were forecasted from those for MYG 2003-2006 based on the ratio of emissions standards for these two model-year groups, as described in Section 2.1.1.3.3. 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, the availability of the HDIU dataset makes it possible to compare the projected rates to a set of relevant measurements. Figure 13 shows that the MOVES rates are lower than corresponding means from the HDIU data and are generally outside the uncertainty of these means across operating modes. Because the rates for this model year group met the two conditions described above in Section 2.1.1.5, this subset of rates was updated in MOVES2014 on the basis of HDIU data.

Figure 13. Comparison of Means: MOVES rates vs. HDIU (n=68) for model years 2007-2009 HHD trucks



2.1.1.5.2 Medium-Heavy Duty Trucks

Figure 14 and Figure 15 show that MOVES rates for MHD trucks compare well with the HDIU data for both model years groups 2003-2006 and 2007-2009. The data is generally scarce in high-power operation modes, and thus, no 95% confidence interval was calculated. The comparisons validated the MOVES2010 rates for MHD trucks, and no change was made in MOVES2014.

Figure 14. Comparison of Means: MOVES rates vs. HDIU (n=25) for model years 2003-2006 MHD trucks

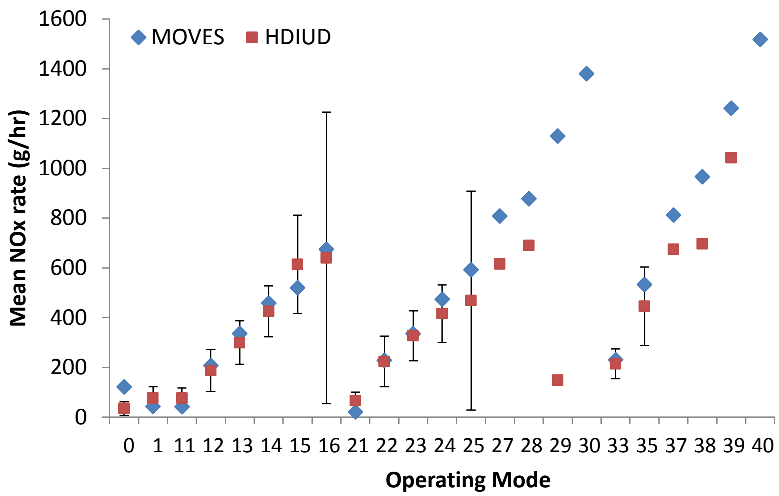
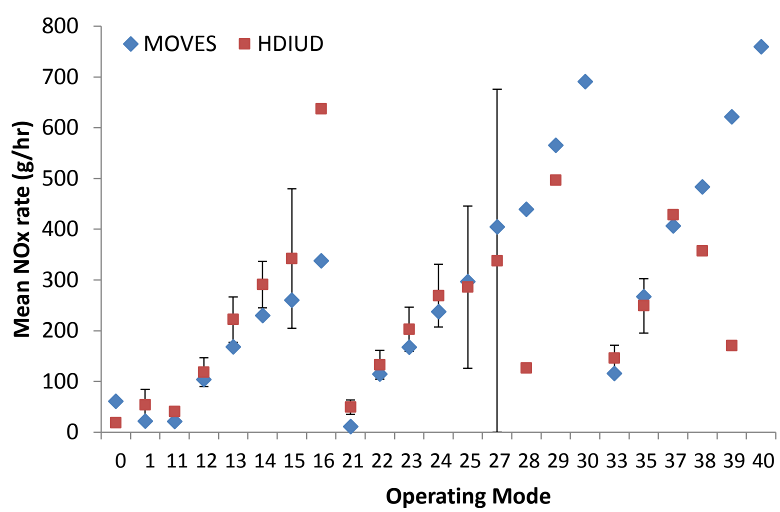


Figure 15. Comparison of Means: MOVES rates vs. HDIU (n=71) for model years 2007-2009 MHD trucks



2.1.1.5.3 Light-Heavy Duty Trucks

In MOVES2010, the LHD rates were not based on actual measurements – they were scaled from MHD rates and forecast based on standards, for model years 2003-2006 and 2007-2009, respectively, as described in Section 2.1.1.3.3. The comparison to HDIU data for model years 2003-2006 (Figure 16) shows that existing MOVES rates are generally higher than the HDIU results. Thus, the LHD rates for model years 2003-2006 were updated based on HDIU data in MOVES2014. In contrast, MOVES compares well with the HDIU data for model years 2007-2009 (Figure 17), and thus, MOVES2010 rates for this model-year group were retained in MOVES2014.

Figure 16. Comparison of Means: MOVES rates vs. HDIU (n=15) for model years 2003-2006 LHD trucks

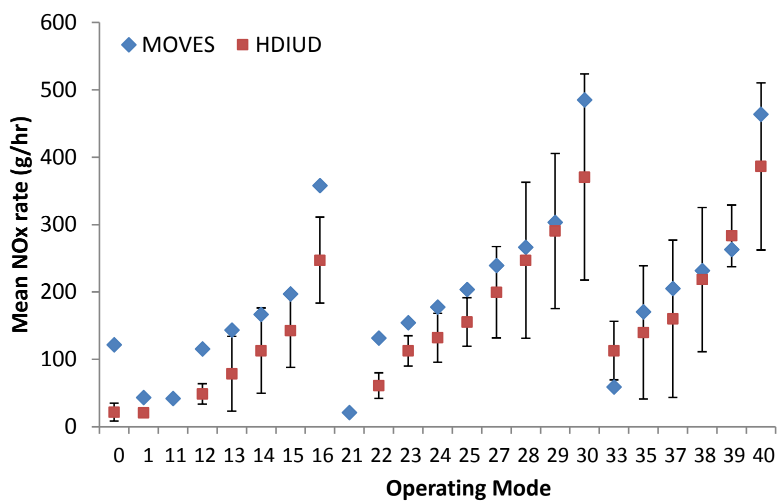
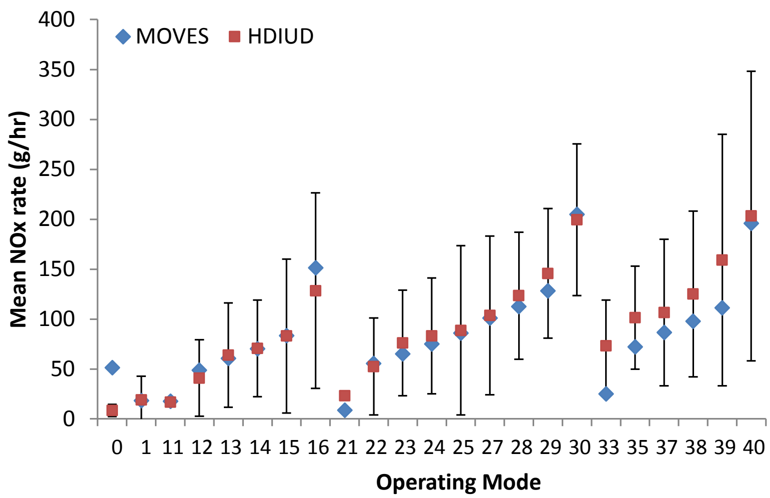


Figure 17. Comparison of Means: MOVES rates vs. HDIU (n=24) for model years 2007-2009 LHD trucks



2.1.2 Particulate Matter (PM)

In this section, particulate matter emissions 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 are primarily carbonaceous, measured by elemental carbon (EC) and organic carbon (OC). Particles also contain a complex mixture of metals, elements, and other ions, including sulfate. The total $PM_{2.5}$ emission rates are typically filter-based, which measure the mass of all the chemical components in the particle-phase. As described above for NOx, the heavy-duty diesel PM emission rates in MOVES are a function of: (1) source bin, (2) operating mode, and (3) age group.

We classified the data into the following model year groups for purposes of emission rate development. These groups are generally based on the introduction of emissions standards for heavy-duty diesel engines. They also serve as a surrogate for continually advancing emission control technology on heavy-duty engines. Table 12 shows the model year group range and the applicable brake-specific emissions standards.

Table 12. Model year groups used for analysis based on the PM emissions standard

Model Year Group Range	PM Standard [g/bhp-hr]
1960-1987	No transient cycle standard

1988-1990	0.60
1991-1993	0.25
1994-1997	0.10
1998-2006	0.10
2007+	0.01

2.1.2.1 Data Sources

All of the data used to develop the MOVES PM2.5 emission rates was generated in the CRC E-55/59 research program[25]. The following description by Dr. Ying Hsu and Maureen Mullen of E. H. Pechan, in the "*Compilation of Diesel Emissions Speciation Data – Final Report*" provides a good summary of the program. It is reproduced in the following paragraphs immediately below:

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

The tables below provide a greater detail of 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 13.

Table 13. Vehicle and Test Counts by Regulatory Class and Model Year Group

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

Counts of tests are provided by test cycle in Table 14.

Table 14. Vehicle Test Counts by Test Cycle

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

2.1.2.2 Analysis

2.1.2.2.1 Calculate STP in 1-hz data

Within source bins, data was further sub-classified on the basis of operating mode. For motor vehicles, 23 operating modes are defined in terms of scaled tractive power (STP), vehicle speed and vehicle acceleration. These modes are defined above in Table 9.

The first step in assigning operating mode is to calculate scaled tractive power (STP) for each emissions measurement. At a given time *t*, the instantaneous STP_t represents the vehicle's tractive power scaled by a constant factor. STP is calculated as a third-order polynomial in speed, with additional terms describing acceleration and road-grade effects. The coefficients for this expression, often called road load coefficients, factor in the tire rolling resistance, aerodynamic drag, and friction losses in the drivetrain. We calculated STP using the equation below:

$$STP_t = \frac{Av_t + Bv_t^2 + Cv_t^3 + mv_t a_t}{f_{scale}}$$ **Equation 13**

where

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

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

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

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

f_{scale} = fixed mass factor (see Table 8),

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

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

The values of coefficients *A*, *B*, and *C* are the road load coefficients pertaining to the heavy-duty vehicles[26] as determined through previous analyses for EPA's Physical Emission Rate Estimator (PERE). This method of calculating STP calculates tractive power using the same equation used to calculate vehicle-specific power (VSP) in the development of emission rates for light-duty vehicles except that the scaling factor is used in the denominator, instead of the actual test weights of individual vehicles[27].

Note that this approach differs from that the NO_X emission rates analysis described in Section 2.1.1.2, since the particulate data was collected on a chassis dynamometer from vehicles lacking electronic control units (ECU). Grade effects are not explicitly included in either case because grade does not come into play in chassis dynamometer tests, and it is already accounted for if STP is calculated through engine speed and torque from the engine control unit.

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 PM2.5 reading was negative or zero, or if corresponding full-cycle filter masses were not available. Table 15 provides vehicle and test counts by vehicle class and model year. The HDDV6 and HDDV7 groups were combined in the table because there were only seven HDDV6 vehicles in the study.

Table 15. Vehicle and Test Counts by Heavy-Duty Class and Model Year

Model Year	HDDV6/7		HDDV8	
	No. Vehicles	No. Tests	No. Vehicles	No. Tests
1969	-	-	1	6
1974	1	10	-	-
1975	-	-	2	10
1978	-	-	1	5
1982	1	5	-	-
1983	1	10	1	6
1985	1	28	1	10

1986	1	3	1	4
1989	2	11	1	4
1990	1	12	1	3
1992	1	11	1	11
1993	1	11	1	3
1994	1	9	3	15
1995	2	24	3	13
1998	2	20	3	28
1999	-	-	3	43
2000	2	18	5	44
2001	1	5	2	21
2004	-	-	4	29
2005	-	-	1	6

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

$$PM_{\text{normalized},\,i,\,j} = \frac{PM_{\text{filter},\,j}}{\sum^{j} PM_{\text{TEOM},\,i}} PM_{\text{TEOM},\,j,\,i} \qquad \textbf{Equation 14}$$

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 PM2.5 filter mass on j,

$PM_{normalized,i,j}$ = an estimated continuous emission result (PM2.5) emission result on vehicle j at second i.

2.1.2.2.3 Compute Average Normalized TEOM measures by MOVES Bin

After normalization, the data were classified by regulatory class, model-year group and the 23 operating modes. Mean average results, sample sizes and standard deviation statistics for PM2.5

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, these mean values were adopted as the MOVES emission rates for total PM2.5. In cases of insufficient data for particular modes, a regression technique was utilized to impute missing values.

2.1.2.3 Hole filling and Forecasting

2.1.2.3.1 Missing operating modes

Detailed in Appendix A.4, a log-linear regression was performed on the existing PM data against STP to fill in emission rates for missing operating mode bins. Similar to the NOx rates, emission rates were extrapolated for the highest STP operating modes.

2.1.2.3.2 Other Regulatory Classes

The TEOM data was only available in quantity for MHD and HHD classes. There were no data available for the LHD or bus classes. Thus, rates for these vehicle classes were computed using simple multiplicative factors based either on engine work ratios or PM emission standards (i.e., buses versus heavy trucks). The LHD classes' emission rates were set as a ratio of the MHD emission rates, and urban bus (Regulatory class 48) emission rates were proportioned to HHD rates.

Because the certification standards in terms of brake horsepower-hour (bhp-hr) are the same for all of the heavy-duty engines, the emission rates of LHD2b3 are assumed to be equal to 0.46 * MHD emission rates. The emission rate of LHD45 is assumed to be 0.60 * MHD emission rate.

LHD2b3 emission rate = 0.46 * MHD emission rate

LHD45 emission rate = 0.60 * MHD emission rate

The values of 0.46 and 0.60 are the ratios of the MOBILE6.2 heavy-duty conversion factors[28] (bhp-hr/mile) for the lighter trucks versus the MHD trucks. These are ratios of the relative amount of work performed by a lighter truck versus a heavier truck for a given distance.

Urban Bus (Regulatory ~~C~~class48) 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 XX displays the model years for which the Urban Bus regulatory class has different PM emission standards from other heavy-duty compression-ignition engines. For the 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 XX.

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Table 16. Urban Bus PM Standards in Comparison to Heavy-duty Highway Compression Engines.

	Heavy-duty Highway Compression-Ignition Engines	Urban Buses	Ratio in standards
1991-1993[a]	0.25	0.1	0.4

1994-1995	0.1	0.07	0.7
1996-2006	0.1	0.05	0.5
[a]The 0.1 g/bhp-hr US EPA Urban Bus standard began with model year 1993. In California, the 0.1 g/bhp-hr Urban Bus standard began in 1991. MOVES assumes all Urban Buses met the stricter CA standard beginning in 1991.			

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

EPA heavy-duty diesel emission regulations were made considerably more stringent for total PM2.5 emissions starting in model year 2007. Ignoring phase-ins and banking and trading issues, the basic emission standard fell from 0.1 g/bhp-hr to 0.01 g/bhp-hr. This increase by a factor of ten in the level of regulatory stringency required the use of particulate trap systems on heavy-duty diesels. As a result, we expect the emission performance of diesel vehicles has changed dramatically.

Unfortunately, no continuous TEOM data were available for analysis on the 2007 and later model-year vehicles. However, heavy and medium heavy-duty diesel PM2.5 data are available from the EPA engine certification program on model years 2003 through 2007. These data provide a snapshot of new engine emission performance before and after the introduction of particulate trap technology in 2007. The existence of these data makes it possible to determine the relative improvement in PM emissions from model years 2003 through 2006 to model year 2007. This same relative improvement can then be applied to the existing, TEOM based, 1998-2006 model year PM emission factors to estimate in-use factors for 2007 and later vehicles.

An analysis of the available certification data is shown in Table 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 change is that the new trap equipped vehicles certify at emission levels which are much lower than the standard and thus create a much larger ‘margin of safety’ than previous technologies could achieve.

As an additional check on the effectiveness of the trap technology EPA conducted some limited in-house testing of a Dodge Ram truck, and carefully reviewed the test results from the CRC Advanced Collaborative Emission Study (ACES) phase-one program, designed to characterize emissions from diesel engines meeting 2007 standards. The limited results from these studies demonstrate that the effectiveness of working particulate traps is very high. The interested reader can review the ACES report.[29]

Table 17. The average certification results for model years 2003-2007. Average ratio from MYs 2003-2006 to MY 2007 is 27.7

Certification Model Year	Mean (g/bhp-hr)	St. Dev.	*n*

2003	0.08369	0.01385	91
2004	0.08783	0.01301	59
2005	0.08543	0.01440	60
2006	0.08530	0.01374	60
2007	0.00308	0.00228	21

2.1.2.3.4 Tampering and Mal-maintenance

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

The primary data set was collected during a limited calendar year period, yet MOVES requires data from a complete range of model year/age combinations. As a result, the T&M factors shown below in Table 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 – model year group combinations for which no data is available.

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

We followed the same tampering and mal-maintenance methodology and analysis for PM as we did for NOx, as described in Appendix A.2. The overall MOVES tampering and mal-maintenance effects on PM emissions over the fleet's useful life are shown in Table 17. The value of 89 percent for 2010+ 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).

Table 18. Estimated increases in HC and CO emissions attributed to Tampering and mal-maintenance over the useful life of Heavy-Duty Vehicles

Commented [ds1]: Should read as PM

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

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

Particulate matter from conventional diesel engines is dominantly composed of elemental carbon emissions. Elemental carbon emissions are often uses synonymously with soot and black carbon emissions. Black carbon is important because of its negative-health effects and to its environmental impacts as a climate forcer[30]. Elemental carbon from vehicle exhaust is routinely measured with filter-based measurements using thermal optical methods. Continuous surrogate measures of elemental carbon can also be made with available photoacoustic instruments.

MOVES models EC emissions explicitly at the operating mode level, because of the availability of EC emission measurements at the operating mode level, and its importance in quantifying the composition of PM emissions.

MOVES models Total PM2.5 emissions by vehicle operating mode using elemental carbon (EC) and non-elemental particulate matter carbon (NonECPM), as shown in Equation 15.

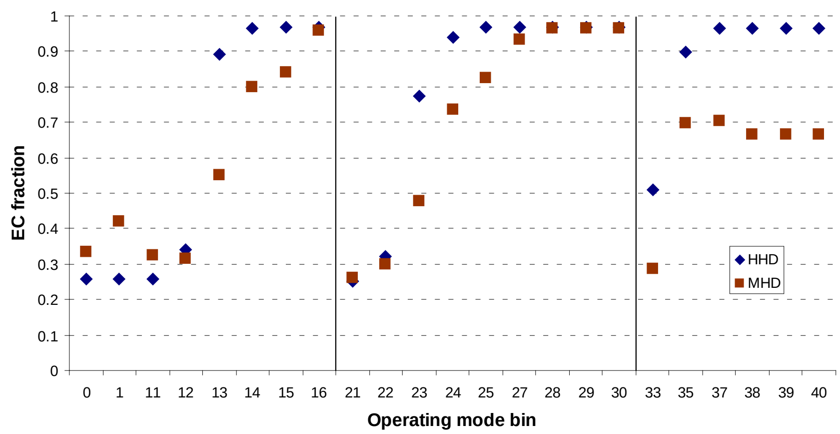
$$PM_{2.5} = EC + NonECPM$$ **Equation 15**

NonECPM is a species used to represent the fraction of PM that is not elemental carbon, computed using Equation 16.

$$\frac{NonECPM}{PM_{2.5}} = 1.0 - \frac{EC}{PM_{2.5}}$$ **Equation 16**

The EC fractions used in MOVES for pre-2007 model year trucks (i.e. before diesel particulate filters (DPFs) were standard) are shown in Figure 18. These vary according to regulatory class and MOVES operating mode. They typically range from 25 percent at low loads (low STP) to over 90 percent at highly loaded modes. All of the EC fractions were developed in a separate analysis and are documented in Appendix A.5. The primary dataset used in the analysis came from Kweon et al. (2004) where particulate composition and mass rate data were collected on a Cummins N14 series test engine over the CARB eight-mode engine test cycle. The EPA PERE model and a Monte Carlo approach were used to simulate and translate the primary PM emission results into MOVES parameters (i.e., operating modes).

Figure 18. Elemental Carbon fraction by operating mode for pre-DPF-equipped trucks



For 2007 and later model year DPF-equipped diesel engines, we used the elemental carbon fraction of 9.98% measured in Phase 1 of the Advanced Collaborative Emissions Study (ACES) Report[31]. Diesel particulate filters preferentially reduce elemental carbon emissions, resulting in the low percentage of elemental carbon emissions. The average EC/PM fraction is based on the 16-hour cycle which composes several different operating cycles. Because the fraction is based upon a range of driving conditions, we applied the constant 9.98% EC/PM fraction across all operating modes for the 2007+ diesel emissions rates.

The nonECPM fraction of emissions contains organic carbon (OC), sulfate, and other trace elements and ions. MOVES uses the fuel sulfur content to adjust the sulfate emission contribution to NonECPM as discussed in the MOVES2014 Fuel Adjustment Report. MOVES uses speciation profiles to estimate the composition of organic carbon, ions, and elements in NonECPM as discussed in the MOVES2014 TOG and PM Speciation Report.

2.1.2.4 Sample results

Figure 19 and Figure 20 show how PM rates increase with STP. As with the NO_x plots, the highest operating modes in each speed range will rarely be attained due to the power limitations of heavy-duty vehicles, but are included in the figures for completeness. At high speeds (greater than 50 mph; operating modes ≥ 30), the overall PM rates are lower than the other speed ranges. For pre-2007 model years the PM rates are dominated by EC. With the introduction of DPFs in model year 2007, we model the large reductions in overall PM rates and the smaller relative EC contribution to PM emissions.

Figure 19. Particulate Matter rates by operating mode representing Heavy heavy-duty vehicles (model year 2002 at age 0-3 years)

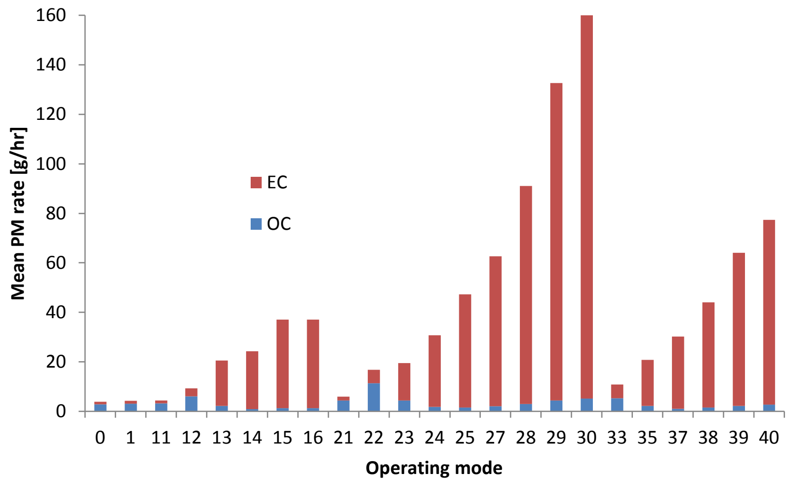


Figure 20. Particulate Matter rates by operating mode for Heavy heavy-duty vehicles (model year 2007 at age 0-3 years)

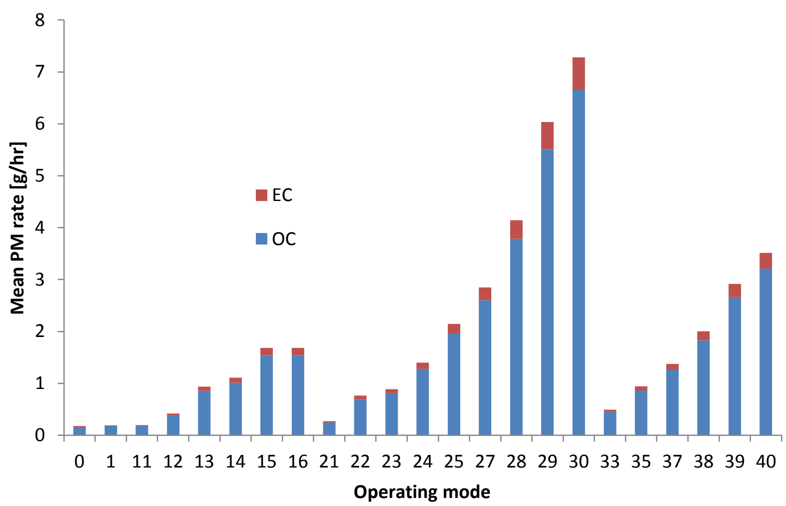


Figure 21 shows an example of how tampering and mal-maintenance estimates increase PM with age. The EC/PM proportion does not change by age, but the overall rate increases and levels off after the end of useful life. This figure shows the age effect for MHD. The rate at which emissions increase toward their maximum depends on regulatory class.

Figure 21. Particulate Matter rates by age group for Medium heavy-duty vehicles (model year 2002, operating mode 24)

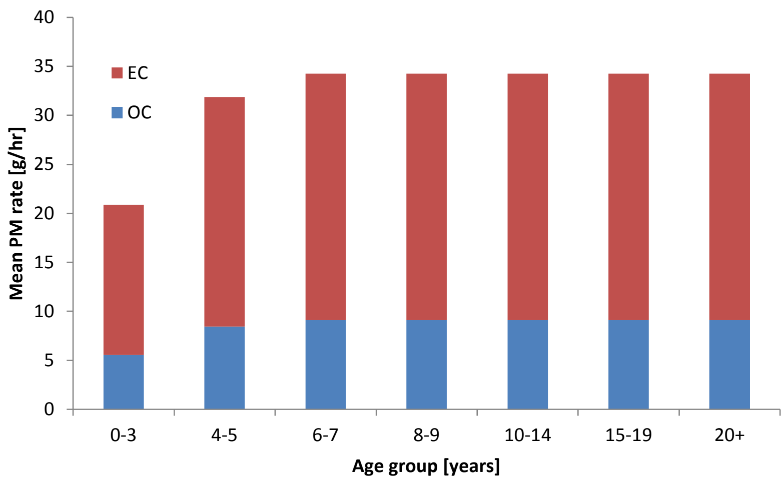
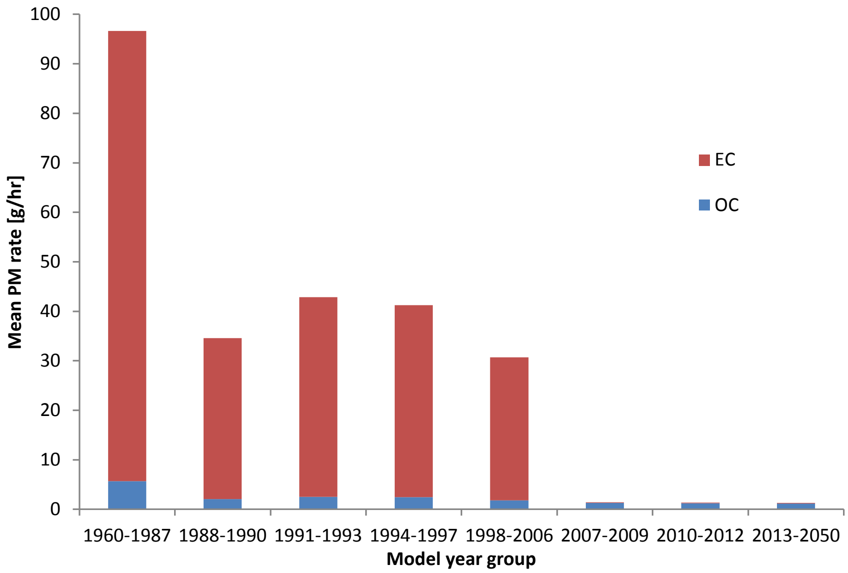


Figure 22 shows the effect of model year on emission rates. Emissions generally decrease with new PM standards. The EC fraction stays constant until model year 2007, when it is reduced to less than ~10% due the implementation of diesel particle filters. The overall PM level is substantially lower starting in model year 2007. The emission rates shown here for earlier model years are an extrapolation of the T&M analysis since young-age engines from early model years could not be tested in the E-55 program.

Figure 22. Particulate Matter rates for Heavy heavy-duty vehicles by model year group (age 0-3 years, operating mode 24)



2.1.3 Hydrocarbons (HC) and Carbon Monoxide (CO)

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

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

- 1960-1989
- 1990-2006
- 2007+

2.1.3.1 Data Sources

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

1. **CRC E-55/59[25]:** 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)[32]:** 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)[33]:** NYSDEC sponsored this study to investigate the nature and extent of heavy-duty diesel vehicle emissions in the New York Metropolitan Area. West Virginia University tested 25 heavy-heavy and 12 medium-heavy duty diesel trucks under transient and steady-state drive cycles.
4. **West Virginia University:** Additional historical data collected on chassis dynamometers by WVU is available in the EPA Mobile Source Observation Database.

The on-road data used for the NOx analysis was not used since HC and CO were not collected in the MEMS program, and the ROVER program used the less accurate non-dispersive infrared (NDIR) technology instead of flame-ionization detection (FID) to measure HC. To keep HC and

CO data sources consistent, we used chassis test programs exclusively for the analysis of these two pollutants. Time-series alignment was performed using a method similar to that used for light-duty chassis test data. The numbers of vehicles in the data sets are shown in Table 18.

Table 19. Numbers of vehicles by model year group, regulatory class, and age group

Model year group	Regulatory class	Age group						
		0-3	4-5	6-7	8-9	10-14	15-19	20+
1960-2002	HHD	58	19	16	9	16	6	7
	MHD	9	6	5	4	12	15	6
	Bus	26			1	3		
	LHD45	2			1			
	LHD2b3	6						
2003-2006	HHD	6						

2.1.3.2 Analysis

As for PM, STP was calculated using an equation similar to the light-duty VSP equation, but normalized with average regulatory class weight instead of test weight, as described by Equation 17.

$$\mathrm{STP}_t = \frac{Av_t + Bv_t^2 + Cv_t^3 + mv_t a_t}{f_{scale}}$$ **Equation 17**

The track road-load coefficients *A*, *B*, and *C* pertaining to heavy-duty vehicles[26] were estimated through previous analyses for EPA's Physical Emission Rate Estimator (PERE). [21]

Using a method similar to that used in the NOx 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 used in development of the NOx rates. Instead of using our results to directly populating all the emission rates, we directly populated only the age group that was most prevalent in each regulatory class and model year group combination. These age groups are shown in Table 19.

Table 20. Age groups used directly in MOVES emission rate inputs for each regulatory class and model year group present in the data

Regulatory class	**Model year group**	**Age group**
HHD	1960-2002	0-3
HHD	2003-2006	0-3
MHD	1960-2002	15-19
BUS	1960-2002	0-3

LHD41	1960-2002	0-3

We then applied tampering and mal-maintenance effects through that age point, either lowering emissions for younger ages or raising them for older ages, using the methodology described in Appendix A.2. The tampering and mal-maintenance effects for HC and CO are shown in Table 20.

Table 21. Tampering and mal-maintenance effects for HC and CO over the useful life of trucks

Model years	Increase in HC and CO Emissions (%)
Pre-2003	300
2003-2006	150
2007-2009	150
2010 and later	33

We multiplied these increases by the T&M adjustment factors in Table 60 in Appendix A.2.1 to get the emissions by age group.

With the increased use of diesel oxidation catalysts (DOCs) in conjunction with DPFs, we assume an 80 percent reduction in zero-mile emission rates for both HC and CO starting with model year 2007.

2.1.3.3 Sample results

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

In Figure 23 and Figure 24, we see that HC and CO mean emission rates increase with STP, though there is much higher uncertainty than for the NOx rates. This pattern could be due to the smaller data set or may truly reflect a less direct correlation between HC, CO and STP. In these figures, the data for HHD and bus classes were combined to generate one set of rates for HHD and buses.

Figure 23. THC emission rates [g/hr] by operating mode for model year 2002 and age group 0-3

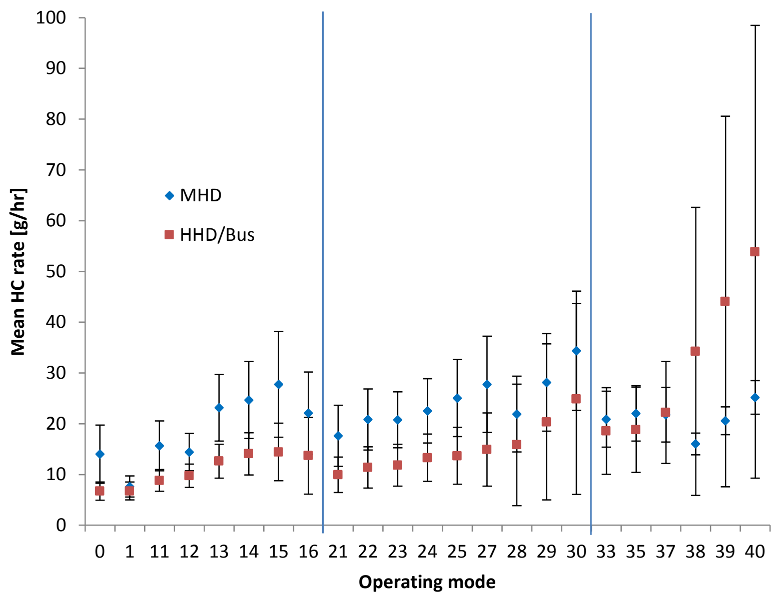


Figure 24. CO emission rates [g/hr] by operating mode for model year 2002 and age group 0-3

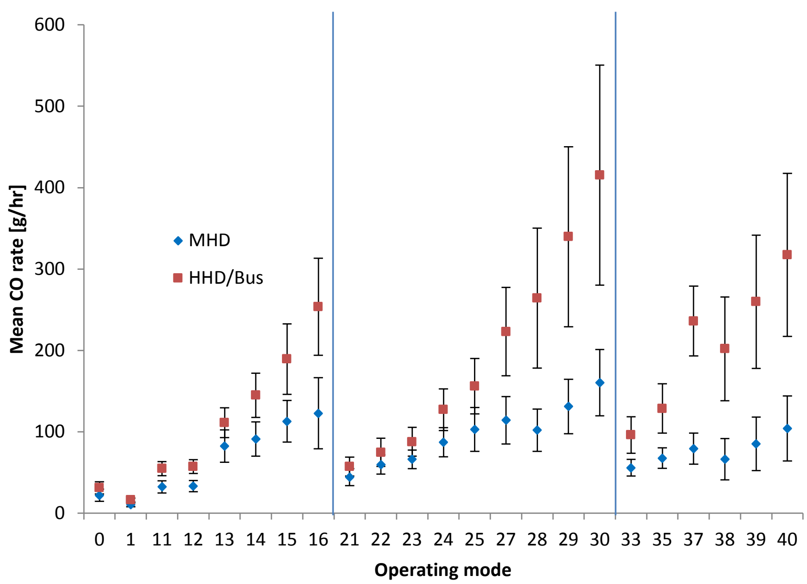


Figure 25 and Figure 26 show HC and CO emission rates by age group. Due to our projections of T&M effects, there are large increases as a function of age. Additional data collection would be valuable to determine if real-world deterioration effects are consistent with those in the model, especially in model years where diesel oxidation catalysts are most prevalent (2007 and later).

Figure 25. THC emission rates [g/hr] by age group for model year 2002 and operating mode 24

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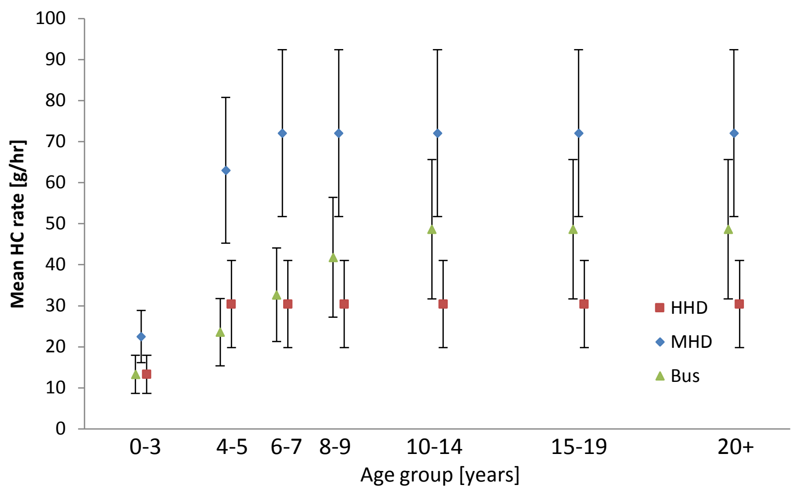


Figure 26. CO emission rates [g/hr] by age group for model year 2002 and operating mode 24

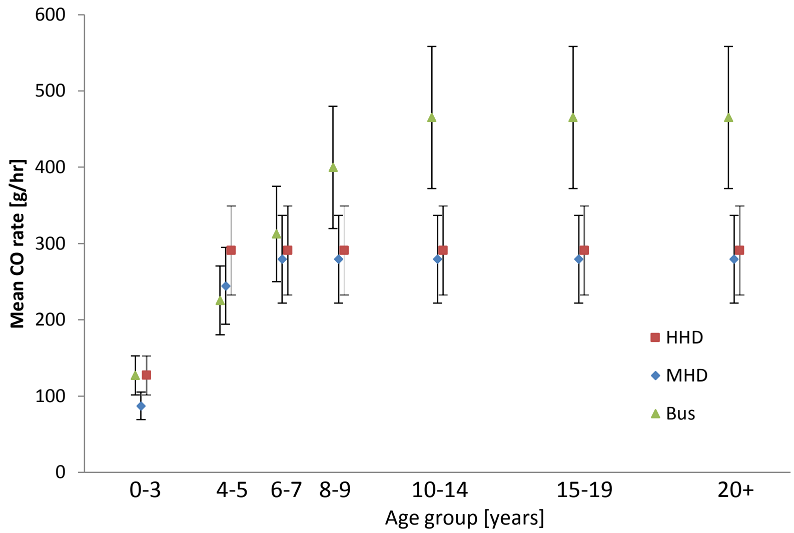


Figure 27 and Figure 28 show sample HC and CO emission rates by model year group. The two earlier model year groups are relatively similar. The rates in the model year group reflect the use of diesel oxidation catalysts. Due to the sparseness of the data and the fact that HC and CO emission do not correlate as well with STP (or power) as NOx and PM do, uncertainties are much greater. Rates from HHD regulatory class were used for buses. All regulatory classes have the same rates for model years 2003 and later.

Figure 27. THC emission rates by model year group for operating mode 24 and age group 0-3

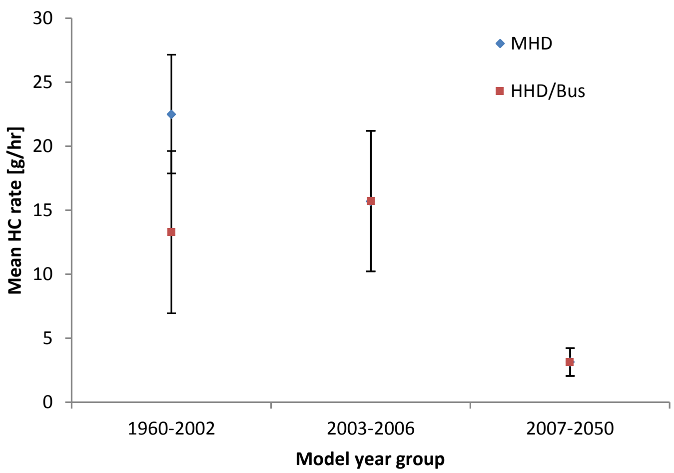
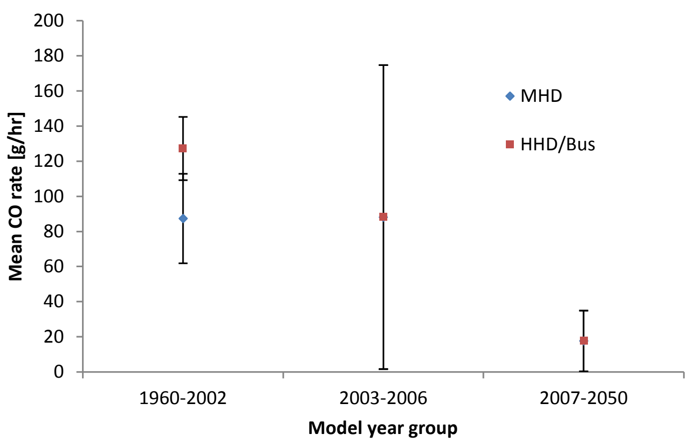


Figure 28. CO emission rates by model year group for operating mode 24 and age group 0-3



2.1.4 Energy

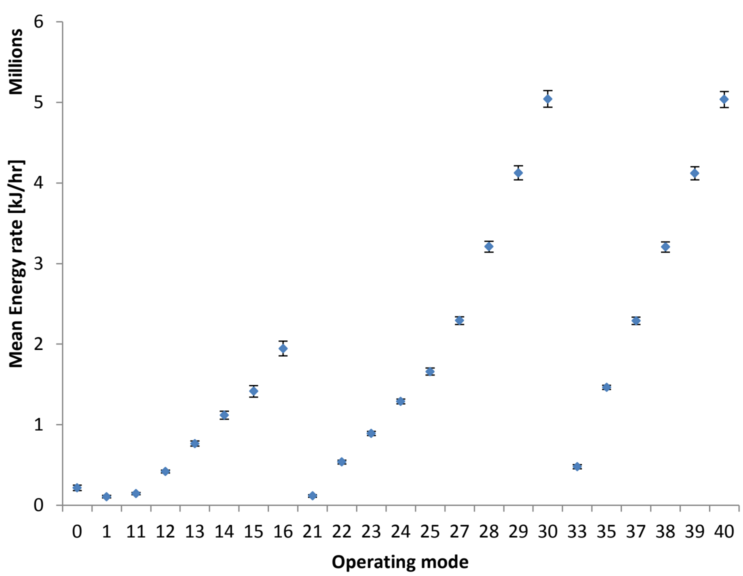
The new data used to develop NO_x rates also allowed us to develop new running-exhaust energy rates. These were based on the same data, STP structure and calculation steps as in the NOx analysis; however, unlike NO_x, we did not classify the energy rates by model year or by age, because neither variable had a significant impact on energy rates or CO_2.

As for previous versions of MOVES, CO_2 emissions were used as the basis for calculating energy rates. To calculate energy rates [kJ/hour] from CO_2 emissions, we used a heating value (HV) of 138,451 kJ/gallon and CO_2 fuel-specific emission factor (f_{CO2}) of 10,084 g/gallon for diesel fuel, using Equation 18.

$$\bar{r}_{energy} = \bar{r}_{CO_2} \frac{HV}{f_{CO_2}} \qquad \textbf{Equation 18}$$

This analysis updates the running-exhaust energy rates estimated for MOVES2004 for diesel HHD, MHD, and bus regulatory classes.[22] The revised inputs are shown in Figure 29.

Figure 29. Diesel running exhaust energy rates for MHD, HHD, and buses



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.

2.2 Start Exhaust Emissions

The ‘start’ process occurs when the vehicle is started and is operating in some mode in which the engine is not fully warmed up. For modeling purposes, we define start emissions as the increase in emissions due to an engine start. That is, we use the difference in emissions between a test cycle with a cold start and the same test cycle with a hot start. There are also 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 counterpart document *Development of Emission Rates for Light-Duty Vehicles in the Motor Vehicle Emissions Simulator*. Start exhaust energy rates were not updated from previous MOVES analyses.

2.2.1 HC, CO, and NOx

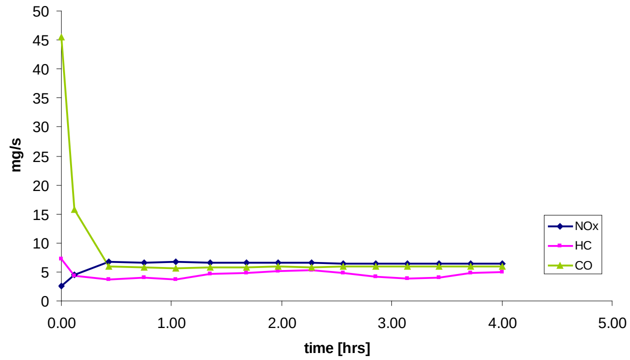
For light-duty vehicles, start emissions are estimated by subtracting FTP bag 3 emissions from FTP bag 1 emissions. Bag 3 and Bag 1 are the same dynamometer cycle, except that Bag 1 starts with a cold start, and Bag 3 starts with a hot start. A similar approach was performed for LHD vehicles tested on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

Table 22. The average start emissions increases for light-heavy duty vehicles (g)

HC	CO	NOx
0.13	1.38	1.68

For HHD and MHD trucks, data were unavailable. To provide at least a minimal amount of information, we measured emissions from a 2007 Cummins ISB on an engine dynamometer at the EPA National Vehicle and Fuel Emissions Laboratory in Ann Arbor, Michigan. Among other idle tests, we performed a cold start idle test at 1,100 RPM lasting four hours, long enough for the engine to warm up. Essentially, the “drive cycle” we used to compare cold start and warm emissions was the idle cycle, analogous to the FTP and ST01 cycles used for LHD vehicles. Emissions and temperature stabilized about 25 minutes into the test. The emission rates through time are shown in Figure 30. The biggest drop in emission rate through the test is with CO, whereas there is a slight increase in NOx (cold start NOx is lower than hot start NOx), and an insignificant change in HC.

Figure 30. Trends in the stabilization of idle emissions from a diesel engine following a cold start. Data were collected from a 2007 Cummins ISB measured on an engine dynamometer



We calculated the area under each trend for the first 25 minutes and divided by 25 minutes to get the average emission rate during the cold start idle portion. Then, we averaged the data for the remaining portion of the test, or the warm idle portion. The difference between cold start and warm start is in Table 22. The NOx increment is negative since cold start emissions are lower than warm start emissions.

Table 23. Cold-start emissions increases in grams on the 2007 Cummins ISB

HC	CO	NOx
0.0	16.0	-2.3

We also considered data from University of Tennessee[34], 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 hot-start 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-idle emissions from the warm idle emissions to estimate the cold start increment. We found that several trucks produced lower NOx emissions during cold start (similar to our own work), and several trucks produces higher NOx emissions during cold start. Due to these conflicting results, and the recognition that many factors affect NOx emission during start (e.g. air-fuel ratio, injection timing, etc), we set the cold-start increment to zero. Table 23 shows our final MOVES inputs for HHD and MHD diesel start emissions increases. The HC and CO estimates are from our 2007 MY in-house testing.

Table 24. MOVES inputs for HHD and MHD start emissions (grams/start)

HC	CO	NOx
0.0	16.0	0.0

2.2.2 Particulate Matter

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

Data from engine dynamometer testing performed on one heavy-heavy-duty 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 PM2.5 emissions (filter measurement - FTP cycle) was 0.10985 grams. The data are shown here:

Cold start FTP average	=	1.9314 g PM2.5
Warm start FTP average	=	1.8215 g PM2.5
Cold start – warm start	=	0.1099 g PM2.5

We applied this value to 1960 through 2006 model year vehicles. A corresponding value of 0.01099 g was used for 2007 and later model year vehicles (90 percent reduction due to DPFs). We plan to update this value when more data becomes available.

2.2.2.1 Adjusting Start Rates for Soak Time

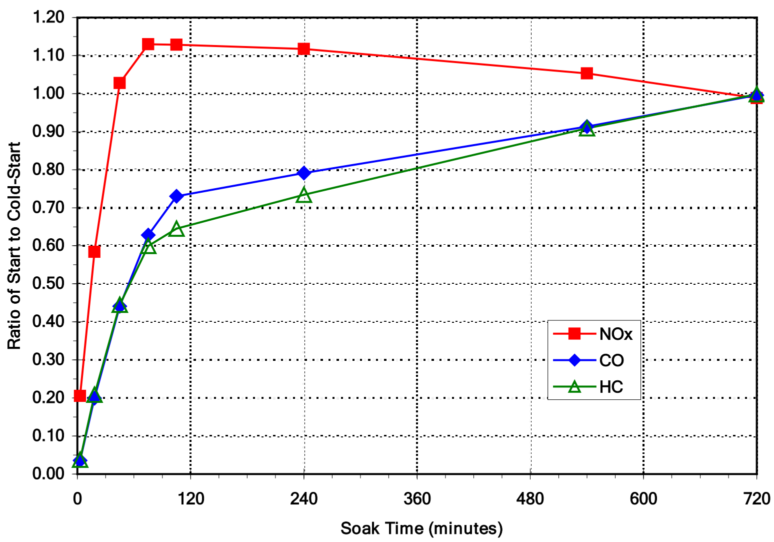
The discussion to this point has concerned the development of rates for cold-start emissions. In addition, it was necessary to derive rates for additional operating modes that account for varying (shorter) soak times. As with light-duty vehicles, we accomplished this step by applying soak fractions. As no data are available for heavy-duty vehicles, we applied the same fractions used for light-duty emissions. Table 24 describes the different start-related operating modes in MOVES as a function of soak time. The value at 720 min (12 hours) represents cold start. These modes are not related to the operating modes defined in Table 9, which are for running exhaust emissions.

Table 25. Operating modes for start emissions (as a function of soak time)

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

The soak fractions we used for HC, CO, and NOx are illustrated in Figure 31 below. (Although, since our current estimate for NOx starts is zero, the NOx fractions are currently irrelevant.)

Figure 31. Soak Fractions Applied to Cold-Start Emissions (opModeID = 108) to Estimate Emissions for shorter Soak Periods (operating modes 101-107)



The actual PM start rates by operating mode are given in Table 25 below.

Table 26. Particulate Matter Start Emission Rates by Operating Mode (soak fraction)

Operating Mode	PM2.5 (grams per start) 1960-2006 MY	PM2.5 (grams per start) 2007+ MY
101	0.0000	0.00000
102	0.0009	0.00009
103	0.0046	0.00046
104	0.0092	0.00092
105	0.0138	0.00138
106	0.0183	0.00183
107	0.0549	0.00549
108	0.1099	0.01099

2.3 Extended Idling Exhaust Emissions

In the MOVES model, extended idling is "discretionary" idle operation characterized by idle periods more than an hour in duration, typically overnight, including higher engine speed settings and extensive use of accessories by the vehicle operator. Extended idling most often occurs during long layovers between trips by long-haul trucking operators where the truck is used as a residence, and is sometimes referred to as "hotelling." The use of accessories such as air conditioning systems or heating systems will affect emissions emitted by the engine during idling. Extended idling by vehicles will also allow cool-down of the vehicle's catalytic converter system or other exhaust emission after-treatments, when these controls are present. Extended idle is treated as a separate emission process in MOVES.

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

In the MOVES model, diesel long-haul combination trucks are the only sourceType assumed to have any significant extended idling activity. As a result, an estimate for the extended idling emission rate has not been made for any of the other source use types modeled in MOVES.

2.3.1 Data Sources

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

- Testing was conducted on twelve heavy-duty diesel trucks and twelve transit buses in Colorado (McCormick)[35]. Ten of the trucks were Class 8 heavy-duty axle semi-tractors, one was a Class 7 truck, and one of the vehicles was a school bus. The model year ranged from 1990 through 1998. A typical Denver area wintertime diesel fuel (NFRAQS) was used in all tests. Idle measurements were collected during a 20 minute time period. All testing was done at 1,609 meters above sea level (high altitude).
- Testing was conducted by EPA on five trucks in May 2002 (Lim)[36]. The model years ranged from 1985 through 2001. The vehicles were put through a battery of tests including a variety of discretionary and non-discretionary idling conditions.
- Testing was conducted on 42 diesel trucks in parallel with roadside smoke opacity testing in California (Lambert)[37]. All tests were conducted by the California Air Resources Board (CARB) at a rest area near Tulare, California in April 2002. Data collected during this study were included in the data provided by IdleAire Technologies (below) that was used in the analysis.
- A total of 63 trucks (nine in Tennessee, 12 in New York and 42 in California) were tested over a battery of idle test conditions including with and without air conditioning (Irick)[38]. Not all trucks were tested under all conditions. Only results from the testing in Tennessee and New York are described in the IdleAire report. The Tulare, California, data are described in the Clean Air Study cited above. All analytical equipment for all testing at all locations was operated by Clean Air Technologies.
- Fourteen trucks were tested as part of a large Coordinating Research Council (CRC) study of heavy duty diesel trucks with idling times either 900 or 1,800 seconds long (Gautam)[39].
- The National Cooperative Highway Research Program (NCHRP)[40] 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)[41]. The model years ranged from 1984 through 1999. One hundred seconds of idling were added at the end of the WVU five-mile transient test driving cycle.
- A Class 8 Freightliner Century with a 1999 engine was tested using EPA's on-road emissions testing trailer based in Research Triangle Park, North Carolina (Broderick)[42]. Both short (10 minute) and longer (five hour) measurements were made during idling. Some testing was also done on three older trucks.
- Five heavy-duty trucks were tested for particulate and NOx emissions under a variety of conditions at Oak Ridge Laboratories (Story)[43]. These are the same trucks used in the EPA study (Lim).
- The University of Tennessee 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)[34].

2.3.2 Analysis

EPA estimated mean emission rates during extended idling operation for particulate matter (PM), oxides of nitrogen (NOx), hydrocarbons (HC), and carbon monoxide (CO). This analysis used all of the data sources referenced above. This update reflects new data available since the initial development of extended idle emissions for the MOVES model. The additions include the testing at Research Triangle Park (Broderick), the University of Tennessee study (Calcagno), and the completed E-55/59 study conducted by WVU and CRC. In addition, the data was separated by truck and bus and by idle speed and accessory usage to develop an emission rate more representative of extended idle rates.

The important conclusion from the 2003 analysis was that factors affecting engine load, such as accessory use, and engine idle speed are the important parameters in estimating the emission rates of extended idling. The impacts of most other factors, such as engine size, altitude, model year within MOVES groups, and test cycle are negligible. This makes the behavior of truck operators very important in estimating the emission rates to assign to periods of extended idling.

The use of accessories (air conditioners, heaters, televisions, etc.) provides recreation and comfort to the operator and increases load on the engine. There is also a tendency to increase idle speed during long idle periods for engine durability. The emission rates estimated for the extended idle pollutant process assume both accessory use and engine idle speeds set higher than used for "curb" (non-discretionary) idling.

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

The idle emission rates for heavy duty diesel trucks prior to the 1990 model year are based on the analysis of the 18 trucks from 1975-1990 model years used in the CRC E-55/59 study and one 1985 truck from the Lim study. The only data available represents a curb idle condition. No data was available to develop the elevated NOx emission rates characteristic of higher engine speed and accessory loading, therefore, the percent increase developed from the 1991-2006 trucks was used.

Extended idle emission rates for 1991-2006 model year heavy duty diesel trucks are based on several studies and 184 tests detailed in Appendix *A.3 Extended Idle Data Summary*. The increase in NOx emissions due to higher idle speed and air conditioning was estimated based on three studies that included 26 tests. The average emissions from these trucks using the high idle engine speed and with accessory loading was used for the emission rates for extended idling.

The expected effects of the 2007 heavy duty diesel vehicle emission standards on extended idling emission rates are taken from the EPA guidance analysis (EPA 2003). The 2007 heavy duty diesel emission standards are expected to result in the widespread use of PM filters and exhaust gas recirculation (EGR) and 2010 standards will result in after-treatment technologies. However, since there is no requirement to address extended idling emissions in the emission certification procedure, EPA expects that there will be little effect on HC, CO, and NOx emissions after hours of idling due to cool-down effects on EGR and most aftertreatment systems. However, we do not expect DPFs to lose much effectiveness during extended idling. As a result, we project that idle NOx emissions will be reduced 12 percent and HC and CO emissions will be reduced 9 percent from the extended idle emission rates used for 1988-2006 model year trucks. The reduction estimates are based on a ratio of the 2007 standard to the previous standard and assuming that the emission control of the new standard will only last for the first hour of an eight hour idle. For PM, we assume an extended idling emission rate equal to the curb idling rate (operating mode 1 from the running exhaust analysis). Detailed equations are included in the appendix.

2.3.3 Results

Table 26 shows the resulting NOx, HC, and CO emission rates estimated for heavy-duty diesel trucks. Extended idling measurements have large variability due to low engine loads, which is reflected in the variation of the mean statistic.

Table 27. Extended idle emission rates (g/hour)

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

3 Heavy-Duty Gasoline Vehicles

3.1 Running Exhaust Emissions

3.1.1 HC, CO, and NOx

3.1.1.1 Data and Analysis

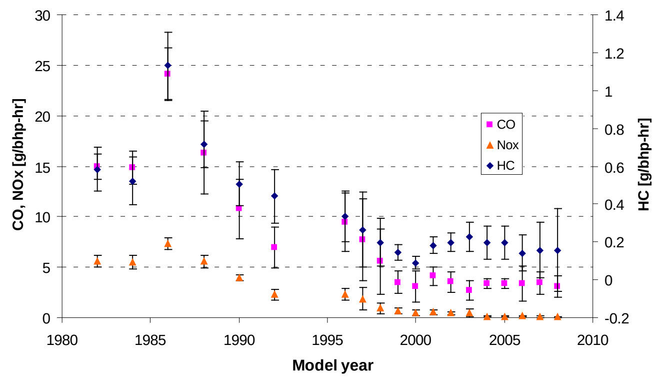
As gasoline-fueled vehicles are a small percentage of the heavy-duty vehicle fleet, the amount of data available for analysis was small. We relied on four medium-heavy duty gasoline trucks from the CRC E-55 program and historical data from EPA's Mobile Source Observation Database (MSOD), which has results from chassis tests performed by EPA, contractors and outside parties. The heavy-duty gasoline data in the MSOD is mostly from pickup trucks which fall mainly in the LHD2b3 regulatory class. Table 27 shows the number of vehicles in cumulative 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, if any, HHD gasoline trucks remaining in use.

Table 28. 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 13). To supplement the meager data available, we examined certification data as a guide to developing model year groups for analysis. Figure 32 shows averages of certification results by model year.

Figure 32. 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
- 1998-2002
- 2003-2006
- 2007 and later

Although there was little data for 2007-and-later, we made a split at model year 2007 to account for possible increases in three-way catalyst use and efficiency due to tighter NOx standards. We assumed that these catalysts in gasoline vehicles will yield a reduction in HC and CO also. We estimate that each of these three pollutants will decrease 70 percent from 2003-2006 MY levels for both running and starts, reflecting the impact of the "2008 Heavy Duty Rule"[44].

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 27. We also did not classify by regulatory class since there was only one regulatory class (LHD2b3) predominantly represented in the data.

3.1.1.2 Sample Results

Selected results are shown graphically below. The first (Figure 33) shows all three pollutants vs. operating mode for the LHD2b3 regulatory class. In general, emissions follow the expected trend with STP, though the trend is most pronounced for NO_x. As expected, NOx emissions for heavy-duty gasoline vehicles are much lower than for heavy-duty diesel vehicles.

Figure 33. Emission Rates by operating mode for MY 1994 at age 0-3 years

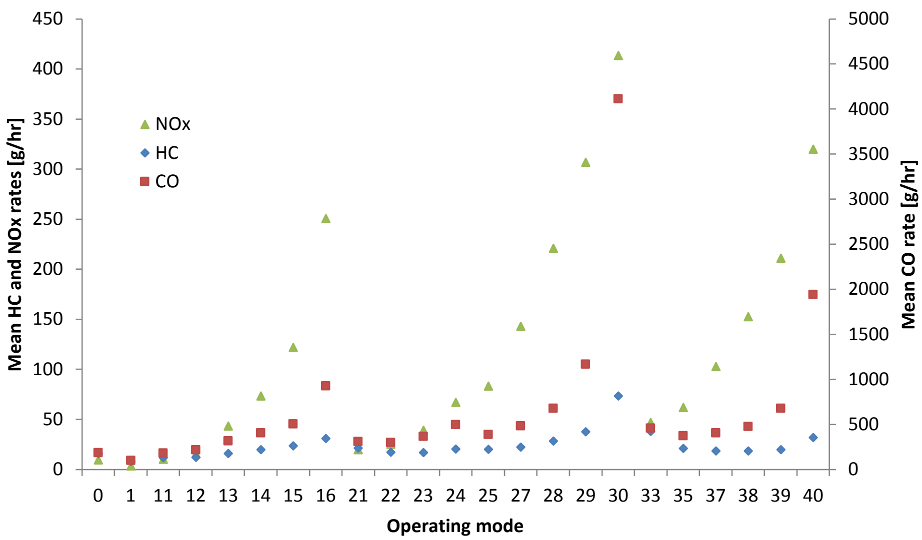


Figure 34 shows the emissions trends by age group. Since we did not use the tampering and mal-maintenance methodology as we did for diesels, the age trends reflect our coarse binning with age. For each pollutant, only two distinct rates exist – one for ages 0-5 and another for age 6 and older.

Figure 34. Emission rates by age group for MY 1994 in operating mode bin 24

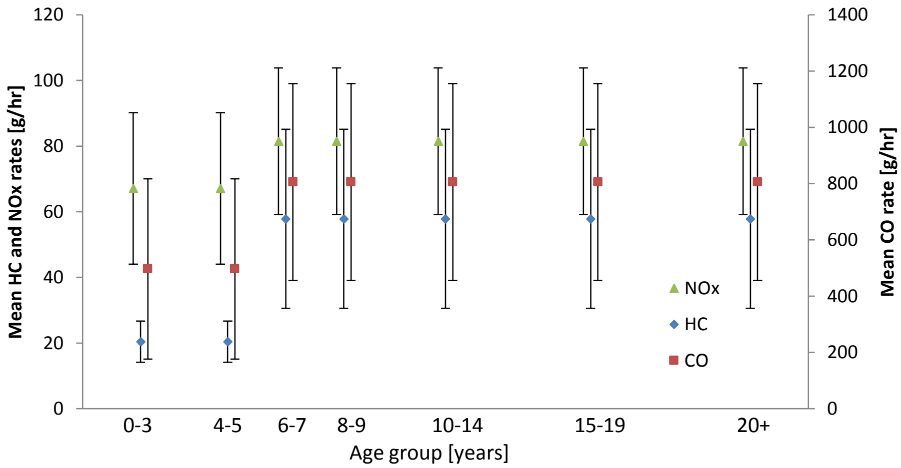
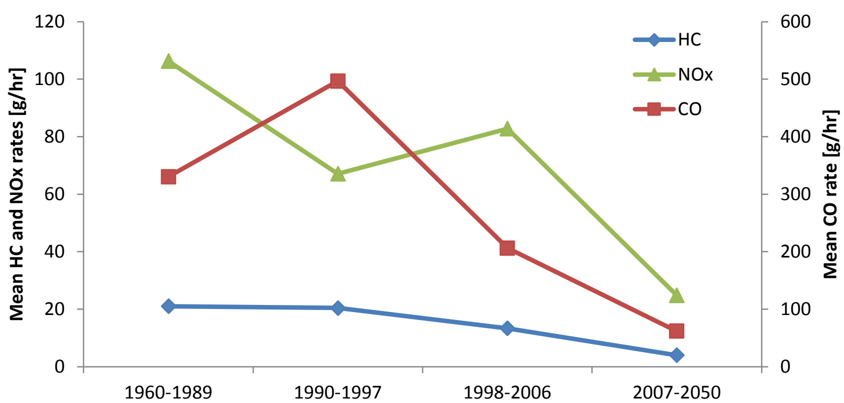


Figure 35 shows emissions by model year group. Emissions generally decrease with model year group. Uncertainties are relatively high but not shown in this plot for clarity.

Figure 35. Emission rates by model year group for age 0-3 in operating mode 24



Assumptions regarding the increased effectiveness of catalysts substantially reduce emissions estimates for 2007 model year and later.

3.1.2 Particulate Matter

Unfortunately, the PM2.5 emission data from heavy-duty gasoline trucks are too sparse to develop the detailed emission factors the MOVES model is designed for. 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 PM2.5 emissions from heavy-duty gasoline vehicles become available.

For MOVES2010, the heavy-duty gas PM2.5 emission rates will be calculated by multiplying the light-duty gasoline truck PM2.5 emission rates by a factor of 1.40, as explained below. Since the MOVES light-duty gasoline PM2.5 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 PM2.5 emission factors will also be a complete set.

3.1.2.1 Data Sources

This analysis is based on the PM2.5 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 28.

Table 29. Summary of data used in HD gasoline PM emission rate analysis

Vehicle	MY	Age	Test cycle	GVWR [lb]	PM2.5 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 12 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 Tier2 or equivalent standards.

3.1.2.2 Analysis

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 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

To compare these rates with rates from light-duty gasoline vehicles, we simulated UDDS cycle emission rates based on MOVES light-duty gas PM2.5 emission rates (with normal deterioration assumptions) for light-duty gasoline trucks. 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 UDDS emission factors for the <u>older</u> light-duty gas truck group are 36.2 mg/mi for MOVES organic carbon PM2.5 emissions and 2.641 mg/mi for elemental carbon. Ignoring sulfate emissions (on the order of 1×10^{-4} mg/mile for low sulfur fuels), these values sum to 38.84 mg/mile.

This value leads to the computation of the ratio: $\dfrac{65.22\frac{g}{mile}}{38.84\frac{g}{mile}} = 1.679$.

The simulated UDDS emission rates for the <u>newer</u> light-duty gas truck group are 4.368 mg/mi for MOVES organic carbon PM2.5 emissions and 0.3187 mg/mi for elemental carbon. Ignoring sulfate emissions (which are in the order of 1×10^{-5} mg/mile for low sulfur fuels), these values sum to 4.687 mg/mi.

This value leads to the computation of the ratio: $\dfrac{2.71\frac{g}{mile}}{4.687\frac{g}{mile}} = 0.578$.

The newer model year group produces a ratio which is less than one and implies that large trucks produce less PM2.5 emissions than smaller trucks. This result is intuitively inconsistent, and is the likely result of a very small sample and a large natural variability in emission results.

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:

$$\mathrm{Ratio}_{\mathrm{final}} = \mathrm{Ratio}_{\mathrm{older}} WtFrac + \mathrm{Ratio}_{\mathrm{newer}}(1 - WtFrac)$$

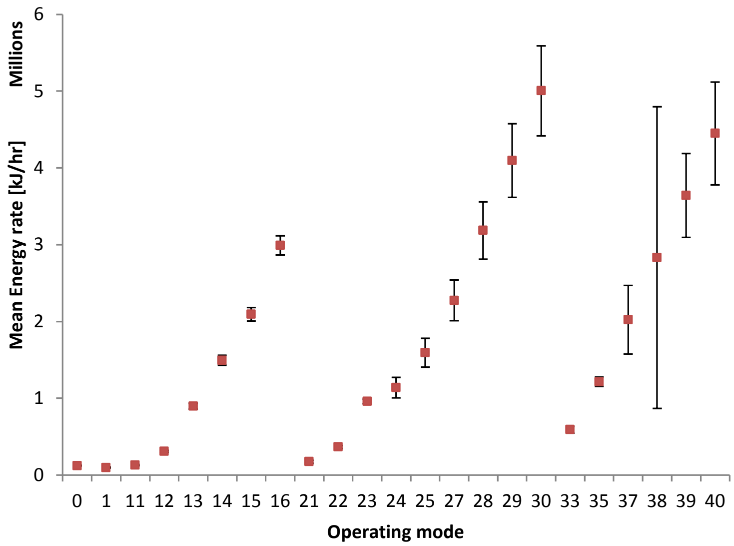
$$= 1.679 \times 0.75 + 0.578 \times 0.25 = \mathbf{1.40}$$

We then multiplied this final ratio of 1.40 by the light-duty gasoline truck PM rates to calculate the input emission rates for heavy-duty gasoline PM rates.

3.1.3 Energy Consumption

The data used to develop heavy-duty running exhaust gasoline rates were the same as those used for HC, CO, and NO_x. However, new energy rates were only developed for MHD, HHD, and bus classes. Analyses performed for LHD vehicles were not updated in this analysis. Also, similarly to the diesel running exhaust energy rates, classifications were not made based on model year group, 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 18). STP was calculated using Equation 13. Figure 36 summarizes the gasoline running exhaust energy rates stored in MOVES.

Figure 36. Gasoline running exhaust energy rates for MHD, HHD, and buses



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 2.1.1.3.3).

3.2 Start Emissions

3.2.1 Available Data

To develop start emission rates for heavy-duty gasoline-fueled vehicles, we extracted data available in the USEPA Mobile-Source Observation Database (MSOD). These data represent aggregate test results for heavy-duty spark-ignition (gasoline powered) engines measured on the Federal Test Procedure (FTP) cycle. The GVWR for all trucks was between 8,500 and 14,000 lb, placing all trucks in the LHD2b3 regulatory class.

Table 29 shows the model-year by age classification for the data. The model year groups in the table were assigned based on the progression in NOx standards between MY 1990 and 2004. Standards for CO and HC are stable over this period, until MY 2004, when a combined NMHC+ NOx standard was introduced. However, no measurements for trucks were available for MY2004 or later.

Table 30. Model-year Group by Age Group Structure for the Sample of Heavy-Duty Gasoline Engines

Model-year Group	Standards (g/hp-hr)			Age Group (Years)					Total
	CO	*HC*	*NOx*	*0-3*	*4-5*	*6-7*	*8-9*	*10-14*	
1960-1989							19	22	41
1990	14.4	1.1	6.0			1	29		30
1991-1997	14.4	1.1	5.0	73	59	32	4		168
1998-2004	14.4	1.1	4.0	8					8
Total				81	59	33	52	22	247

3.2.2 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 A.6 Heavy-duty Gasoline Start Emissions Analysis Figures.

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

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

$$\bar{x}_g = \mathrm{e}^{\ln \bar{x}_l} \qquad \textbf{Equation 19}$$

This measure is not appropriate for use as an emission rate, but is useful in that it represents the "center" of the skewed parent distribution. As such, it is less strongly influenced by unusually high or outlying measurements than the arithmetic means in Appendix A.6. 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. Assuming that emissions distributions should be strongly skewed suggests that these data are not representative of "real-world" emissions for these vehicles. This conclusion appears to be reinforced by the values in Figure 62 which represent the "logarithmic standard deviation" calculated by model-year and age groups. This measure (s_l), is the standard deviation of natural logarithm of emissions (x_l). The values of s_l are highly variable, and generally less than 0.8, showing that the degree of skew in the data is also highly variable as well as generally low for emissions data; e.g., corresponding values for light-duty running emissions are generally 1.0 or greater. Overall, review of the geometric means confirms the impression of age trends in the CO and HC results, and the general lack of an age trend in the NOx results.

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

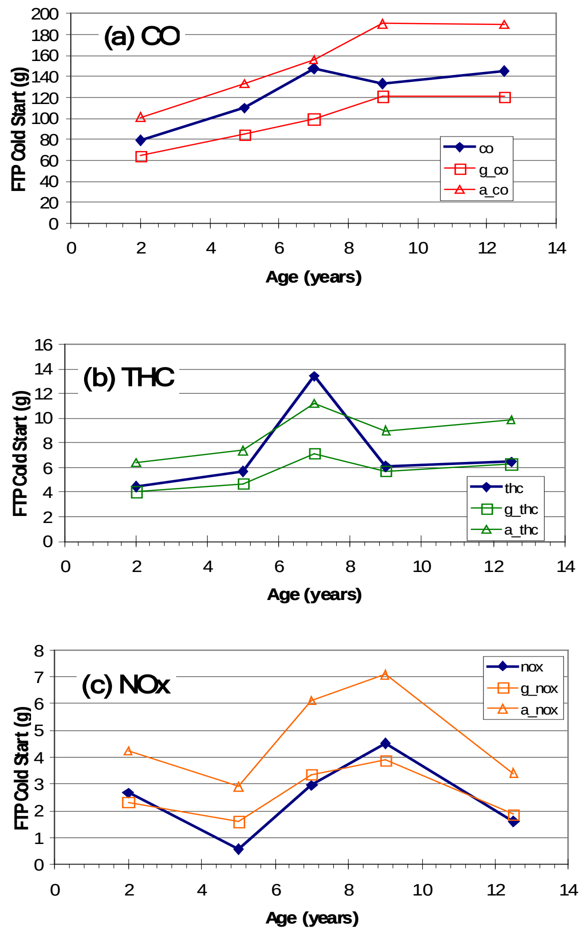
The re-estimated arithmetic means are calculated from the geometric means, by adding a term that represents the influence of the "dirtier" or "higher-emitting" vehicles, or the "upper tail of the distribution," as shown in Figure 63.

$$\bar{x}_a = \bar{x}_g e^{\frac{s_l^2}{2}} \qquad \textbf{Equation 20}$$

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 37 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 37. 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)



3.2.3 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 21.

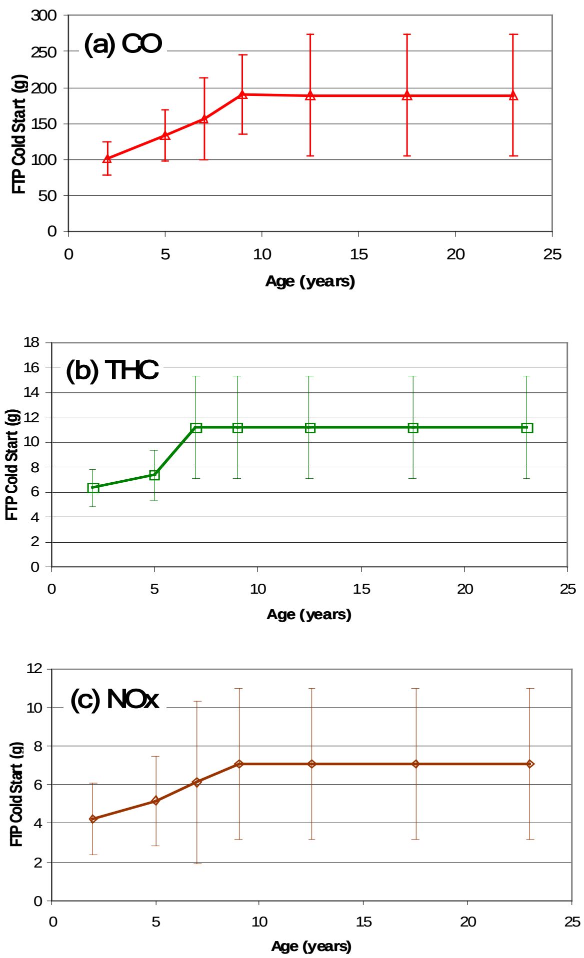
$$s = \sqrt{x_g^2 \, e^{s^2} (e^{s^2} - 1)} \qquad \textbf{Equation 21}$$

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 30 and in Figure 38. Note that these results represent only "cold-start" rates (opModeID 108).

Table 31. Cold-Start Emission Rates (g) for Heavy-Duty Gasoline Trucks, by Age Group (italicized values replicated from previous age Groups)

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

Figure 38. Cold-start Emission Rates for Heavy-Duty Gasoline Trucks, with 95% Confidence Intervals



3.2.4 *Projecting Rates beyond the Available Data*

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

3.2.4.1 Regulatory class LHD2b3

For CO the approach was simple. We applied the values in Table 30 to all model-year groups. The rationale for this approach is that the CO standards do not change over the full range of model years considered.

For HC and NOx we imputed values for the 2005-07 and 2008+ model-year groups by multiplying the values in Table 30 by ratios expressed in terms of the applicable standards. Starting in 2005, a combined HC+NOx standard was introduced. It was necessary for modeling purposed to partition the standard into HC and NOx components. We assumed that the proportions of NMHC and NOx would be similar to those in the 2008 standards, which separate NMHC and NOx while reducing both.

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

$$f_{\mathrm{HC}} = \frac{\left(\dfrac{0.14\ \mathrm{g/hp\text{-}hr}}{(0.14+0.20)\ \mathrm{g/hp\text{-}hr}}\right)(1.0\ \mathrm{g/hp\text{-}hr})}{1.1\ \mathrm{g/hp\text{-}hr}} = 0.37 \qquad \textbf{Equation 22}$$

This ratio represents the component of the 2005 combined standard attributed to NMHC.

We calculated the corresponding value for NOx as

$$f_{\mathrm{NOx}} = \frac{\left(\dfrac{0.20\ \mathrm{g/hp-hr}}{(0.14+0.20)\ \mathrm{g/hp-hr}}\right)1.0\ \mathrm{g/hp\text{-}hr}}{4.0\ \mathrm{g/hp\text{-}hr}} = 0.147 \qquad \textbf{Equation 23}$$

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

In 2008, separate HC and NOx standards were introduced. To estimate values for this model-year group, we calculated the values by multiplying the 1960-2004 value by the fractions f_{HC} and f_{NOx} where

$$f_{\mathrm{HC}} = \frac{0.14\ \mathrm{g/hp\cdot hr}}{1.1\ \mathrm{g/hp\cdot hr}} = 0.127 \qquad \textbf{Equation 24}$$

$$f_{\mathrm{NOx}} = \frac{0.20\ \mathrm{g/hp\cdot hr}}{4.0\ \mathrm{g/hp\cdot hr}} = 0.05 \qquad \textbf{Equation 25}$$

3.2.4.2 Regulatory classes LHD45 and MHD

For LHD45 and MHD, we estimated values relative to the values calculated for LHD2b3.

For CO and HC, we estimated values for the heavier vehicles by multiplying them by ratios of standards for the heavier class to those for the lighter class.

The value for CO is

$$f_{CO} = \frac{37.1\,\text{g/hp-hr}}{14.4\,\text{g/hp-hr}} = 2.58 \qquad \textbf{Equation 26}$$

and the corresponding value for HC is1.73.

$$f_{HC} = \frac{1.9\,\text{g/hp-hr}}{1.1\,\text{g/hp-hr}} = 1.73 \qquad \textbf{Equation 27}$$

We applied this ratio in all three model-year groups, as shown in Table 31.

Note that in Draft MOVES2009, the ratios in Equation 26 and Equation 27 were erroneously applied to the 2005-2007 model-year groups for LHD45 and MHD vehicles. In MOVES2010, values for these model-year groups were set equal to those for the LHD2b3 vehicles, with the rationale that the standards converge for both groups.

For NOx, all values are equal to those for LHD2b3, because the same standards apply to both classes throughout. The approaches for all three regulatory classes in all three model years are shown in Table 31.

Table 32. Methods used to Calculate and Start Emission Rates for Heavy-Duty Spark-Ignition Engines

Regulatory Class	Model-year Group	Method		
		CO	THC	NOx
LHD2b3	1960-2004	Values from Table 30	Values from Table 30	Values from Table 30
	2005-2007	Values from Table 30	Reduce in proportion To standards	Reduce in proportion To standards
	2008 +	Values from Table 30	Reduce in proportion To standards	Reduce in proportion To standards
LHD45, MHD	1960-2004	Increase in proportion To standards	Increase in proportion To standards	Same values as LHD2b3
	2005-2007	Increase in proportion To standards	Increase in proportion To standards	Same values as LHD2b3
	2008 +	Increase in proportion To standards	Increase in proportion To standards	Same values as LHD2b3

As for heavy-duty diesel and light-duty vehicles we applied the curve in Figure 31 to adjust the start emission rates for varying soak times. The rates described in this section were for cold starts (soak time > 720 minutes).

3.2.4.3 Particulate Matter

Data on PM start emissions from heavy-duty gasoline vehicles were unavailable. As a result, we used the multiplication factor from the running exhaust emissions analysis of 1.40 to scale up start emission rates for light-duty trucks.

3.3 Updates to Emission Rates in MOVES2014

Draft MOVES2009 reflected the impact of the "2008 Heavy Duty rule"[45] on gasoline fueled vehicles through a 70% reduction in start and running gaseous emissions of 2008 and later MY vehicles above 8,500 pounds. While the reduction to start rates was included in the subsequent MOVES2010 release, the reduction to running rates was inadvertently removed.

This section documents the changes that were made for MOVES 2014 using newer data on regulatory class 41 (vehicles between 8,500 and 14,000 pounds GWVR), as well as the changes that were made to implement the projected reductions in the heavier gasoline regulatory classes from the "2008 Heavy Duty rule". While the 2008 Heavy Duty rule affects emissions in all Heavy Duty (HD) gasoline categories,[ii] there are very few gasoline vehicles in the largest classes. As a result, this section focuses on revisions to MOVES regulatory class 41, which are commonly called light HD or Medium Duty vehicles (8,500 to 14,000 pound GVWR). A brief section is presented on the heavier classes.

3.3.1 Regulatory class LHD2b3

Gasoline vehicles in MOVES regulatory class 41 are a mixture of engine certified HD vehicles, chassis certified HD 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 32).[iii]

[ii] MOVES regulatory classes 41 (8,500 to 14,000 pounds GVWR), 42 (14,000 to 19,500 pounds GVWR), 46 (19,500 to 33,000 GVWR) and 47 (GVWR above 33,000 pounds).

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

Table 33. Useful Life FTP Standards[iv]

	MDPV (Tier 2 Bin 5) [46]	8.5k – 10k (Class 2B)	10k-14k (Class 3)	Engine Certified
Units	g/mile	g/mile	g/mile	g/bhp-hr
Fully Phased in MY	2009	2009	2009	2010
HC	0.09 NMOG	0.195NMHC	0.230 NMHC	0.14 NMHC
CO	4.2	7.3	8.1	14.4
NOx	0.07	0.2	0.4	0.2

The relative proportions of the vehicles within MOVES regulatory class 41 vary each year depending on demand. Consequently, we estimated proportions based on recent year data and engineering judgment. MOBILE6 documentation from 2003 indicates that MDPVs are approximately 16% of the gasoline 8,500 to 10,000 truck class.[47] In MOVES2014, we project that MDPVs are 15% of total MOVES regulatory class 41 in MYs 2008 and later. The MOBILE6 document also states that more than 95% of class 2B trucks are chassis certified.[47] Extrapolating, we estimate that 5% of all vehicles in regulatory class 41 are engine certified. Based on analysis from the recent medium and heavy duty greenhouse gas rulemaking, we assume that sales of 2B class trucks vehicles were triple that of 3 class trucks. [48] This is roughly consistent with recent model year sales totals. [49] Combining these assumptions, we get the sales fractions shown below (Table 33).

Table 34. Population Percentage

	% of Reg Class 41
MDPV	15%
Class 2B	60%
Class 3	20%
Engine Certified	5%

To generate an aggregate FTP standard for regulatory class 41, we weighted the individual certification standards shown in Table 32 using the proportions shown in Table 33.[v] While the model produces estimates of on-road emissions rather than certification emissions, the weighted certification standard is a useful benchmark for the modeled rates (Table 34).[vi]

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

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

[vi] Several simplifications were made in calculating this aggregate useful life FTP. The distinction between NMHC and NMOG was ignored in calculating the aggregate FTP, and would have yielded only minor variation in the aggregate certification standard. The engine standard was also converted to a chassis equivalent as discussed above.

Table 35. Aggregate Useful Life FTP

	Reg Class 41 g/mile
NMOG	0.18
CO	7.49
NOX	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),[50] modified to produce Scaled Tractive Power (STP) distributions, was used to generate the operating mode mix of a regulatory class 41 vehicle on the Federal Test Procedure drive cycle. For the STP modification, we changed the vehicle weight in PERE to match Source Type 32 in MOVES (2.06 Tons). We incorporated emission rates from the MOVES DB for the age 0-3 group, and added in a cold start (operating mode 108) and a hot start (operating mode 102) from the MOVES database. The modified version of PERE produced the operating mode distribution shown in Table 35.

Table 36. Bin Mix for a Regulatory Class 41 FTP

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

Using this operating mode distribution, we constructed a simulated FTP out of four components (bag 1/3 running,[vii] cold start, hot start, and bag 2 running). We constructed bag 1 (cold start + bag 1 running) and bag 3 (hot start + bag 3 running) and weighted the resulting components together according to the FTP formula,[viii] and compared the 2008 and later rates in MOVES to the aggregate standard calculated above (Table 36). MOVES 2010a estimates at age 0-3 are two

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

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

to ten times larger than the standard, which indicates that the average vehicle HD gas vehicle in MOVES2010a is significantly out of compliance with the relevant standard in this timeframe.

Table 37. Comparison between MOVES DB FTP and Aggregate FTP

	MOVES2010 FTP	Aggregate FTP Standard	Ratio – MOVES to Aggregate
NMOG	0.36	0.18	1.93
CO	14.54	7.49	1.94
NOx	2.04	0.22	9.28

3.3.1.1 Validation against In-Use Verification Program Data

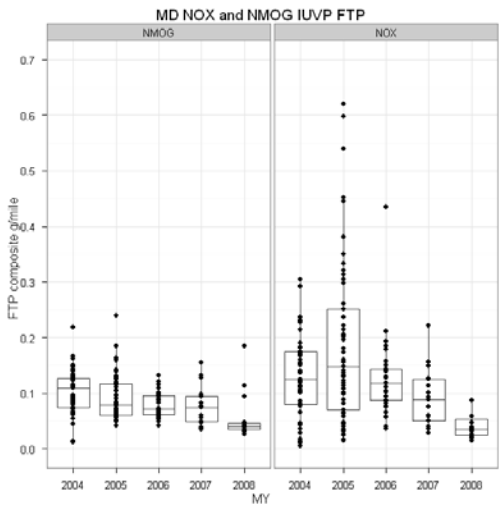
We reviewed In Use Verification Program (IUVP) data for MYs 2004-2008 vehicles (estimated test weights of 7,500 pounds to 10,000 pounds) to determine the appropriateness of the MOVES2010 emission rates.[ix] We evaluated whether vehicles during these MYS were achieving the standard, or if alternate methods 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, and accounting for the standards applicable to each vehicle, we calculate average ratios of test value to standard of 0.42 (NMOG) and 0.23 (NOx) (Table 37 & Figure 39). These ratios indicate that vehicles typically comply with the standard, with a significant amount of headroom.

Table 38. Average Compliance Margin and Headroom

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

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

Figure 39. Distribution of IUVP FTP Tests



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.[x] However, the emission rates represented by MOVES2010 are higher than those that would be expected from vehicles compliant with the standards in place in MY 2008 and later.

3.3.1.2 Producing New MOVES emission rates for MY2008 and later

Given that (a) the MOVES2010 rates are significantly above the calculated aggregate standard, and (b) the IUVP data shows that most vehicles achieve the standard, we calculated new MOVES2014 HC/CO/NOx emission rates for HD gas vehicles in 2008 and later MYs.

In conducting this analysis, we lacked any modal data on regulatory class 41 vehicles. As such, we conducted the analysis using a method that we have used repeatedly on the light duty side, which is ratioing the modal emission profile by the difference in standards.[51] By MY 2008, the medium duty vehicles are nearing the emission levels of Tier 2 Bin 8 vehicles. Consequently, we relied on the analysis of in-use Tier 2 Bin 8 vehicles conducted for the light duty vehicle emission rates.[52] We then scaled the modal data from Tier 2 Bin 8 vehicles by the ratio of FTP

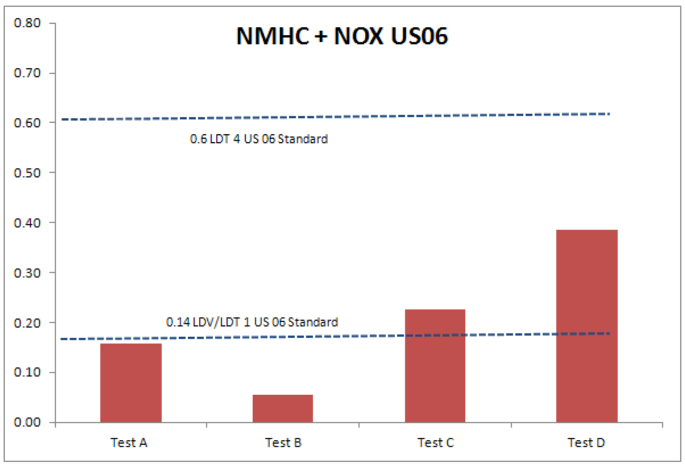
[x] Even in the absence of emission equipment deterioration, tampering and malmaintenance will increase the emissions from a on-road vehicle.

standards so that the rates would be consistent with the higher emission rates of regulatory class 41 vehicles. We restricted the scaled data so that the individual emission rates by operating mode were never scaled to be higher than MY 2006 regulatory class 41 rates.

However, there are some important regulatory differences between Tier 2 Bin 8 and regulatory class 41 vehicles. Perhaps most significantly, there is no SFTP test for regulatory class 41 vehicles other than MDPVs. As a result, we investigated whether the performance of regulatory class 41 vehicles should be adjusted for higher emissions during "off-cycle" emissions.[xi]

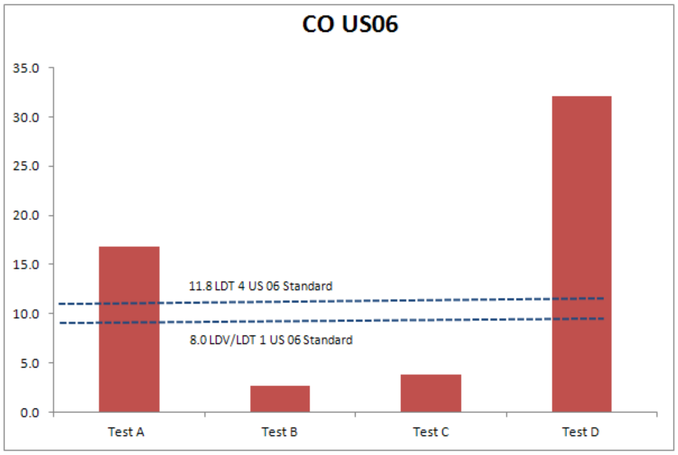
EPA has conducted internal US06 tests on MY 2010 class 2B pickup trucks. The results from these tests are shown in Figure 40 and Figure 41. Of the four trucks tested, we found that all four met the Tier 2 SFTP standard for NMHC+NOx, but that in some cases, the CO emissions were much higher than would have been expected from a light duty vehicle.

Figure 40. US06 NMHC+NOx test



[xi] In this context, off-cycle is meant to indicate high power or high speed operation. This kind of operation is typically exercised over the US06 test, but not over the FTP.

Figure 41. US06 CO test



As a result, we assume that these vehicles are not significantly controlled for CO during high power or high speed operation. In addition, the CO standard was not reduced with the introduction of the MY 2008 heavy duty standards. While we reduced the CO emissions on cycle, we preferentially maintained a higher CO emission rate in the higher power operating mode bins. Bins 27 to 30 and Bins 37 to 40 were maintained at the MOVES2010 MY 2006 rates for CO.

Table 39. Aggregate Standard Ratios against Bin 8 Modal Rates

	Aggregate FTP Standard	Bin 8 FTP Standard	Aggregate/Bin 8
NMOG	0.18	0.1	1.8
CO	7.49	3.4	2.2
NOx	0.22	0.14	1.6

We converted this ratio into a "split" ratio, where the running rates increased twice as much as the start rates, but the same overall emissions were simulated on the FTP. This split ratio is consistent with typical emission reduction trends, where running emissions are reduced about twice as much as start emissions.[53]

Applying the ratio of aggregate and Tier 2 Bin 8 standards to the Bin 8 rates in Table 38 yields emission rates that are below the calculated aggregate standard, as shown in Table 39. The calculated headroom for NOx is less than that shown in the IUVP data, and the calculated headroom for NMOG is greater than that shown in the IUVP data. For NOx, this difference is more significant. However, as stated above, the IUVP data is not fully representative of in-use vehicles. By contrast, the Bin 8 rates are based on extensive I/M testing, and are considered more representative of the entire fleet.

In terms of the phase-in, we assumed that the regulatory class 41 rates phase in at a rate of 50% in MY2008 and considered fully phased in MY2009.

We plan to continue to monitor the emission performance of these vehicles as they enter the fleet.

Table 40. Ratio of Final rates against standards

	Simulated regulatory class class 41 2010+ FTP	Aggregate 2010+ FTP Standard	Achieved / Aggregate FTP
NMOG	0.06	0.18	33%
CO	3.08	7.49	41%
NOx	0.18	0.22	84%

3.3.2 Regulatory Classes LHD34, MHD, HHD, and Buses

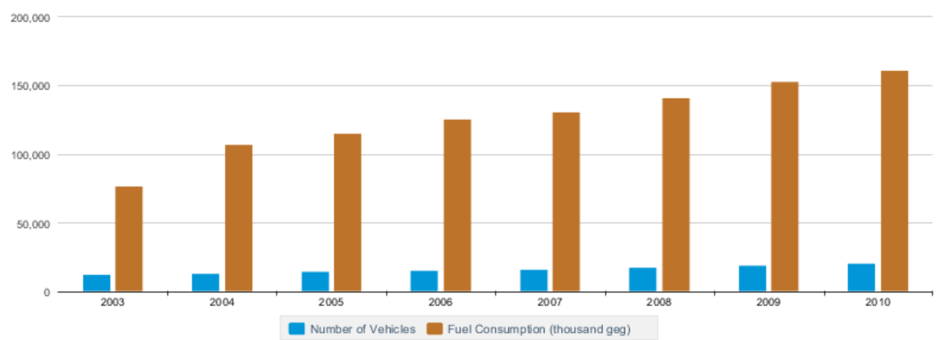
Of the on-road heavy duty vehicles GVW class 4 and above, about 15% are gasoline, as opposed to 85% diesel.[xii] The gasoline percentage decreases as the GVW class increases. Consequently, there is relatively little data on these vehicles, and we are not updating this analysis from the analysis presented in the MOVES2010 HD report.[54] Rather, we are implementing the update discussed there, a 70% reduction in the running rates, starting in MY 2008. This reduction, as discussed in that report, is consistent with the reduction in the standard.

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

4 Heavy Duty Compressed Natural Gas Transit Bus Emissions

While natural gas lacks the ubiquitous fueling infrastructure of gasoline, compressed natural gas (CNG) has grown as a transportation fuel for public transit, government, and corporate fleets. Such fleets typically utilize centralized, privately-owned refueling stations. Within this segment, some of the most rapid growth in CNG vehicles and fuel consumption has occurred among city transit bus fleets, as seen in Figure 42.[55]

Figure 42. US compressed natural gas bus population and fuel consumption by year (US EIA) [56]



MOVES2010b and earlier versions can model emissions from CNG bus fleets. However, in absence of better data, MOVES2010b used the emission rates originally developed for medium heavy-duty gasoline trucks (regulatory class 46). These rates were used for hydrocarbon (HC), nitrogen oxides (NOx), carbon monoxide (CO), and particulate matter (PM) emission rates.[57] Medium HD gasoline trucks are reasonable proxies in terms of vehicle weight and engine size, but as this report shows, there are substantial differences in the MOVES2010b emissions rates and real-world measurements of CNG transit buses. This section updates the CNG bus emission rates in MOVES based on measurements from CNG buses and future projections.

4.1 *Transit Bus Driving Cycles and Operating Mode Distributions*

4.1.1 *Heavy-Duty Transit Bus Driving Cycles*

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

The CBD cycle is defined as a driving pattern with constant acceleration from rest to 20 mph, a short cruise period at 20 mph, constant deceleration back to rest, and then repeated for 600 seconds (see Figure 43).[58] 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 44).[59]

Figure 43. Driving schedule trace of the Central Business District (CBD) cycle (DieselNet)[60]

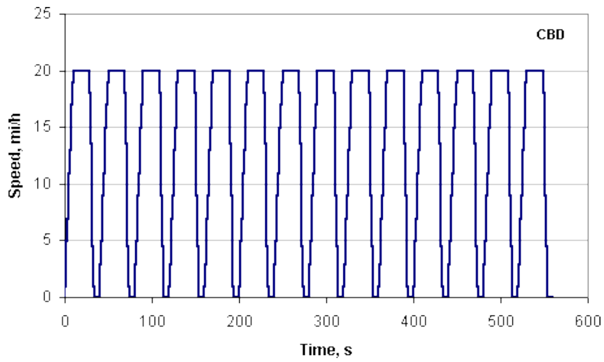
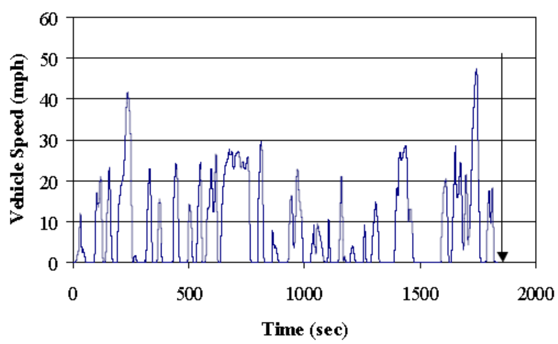


Figure 44. Driving schedule trace of the Washington Metropolitan Area Transit Authority (WMATA) cycle (Melendez et al. 2005)[61]



4.1.2 Transit Bus Operating Mode Distributions

The MOVES project level importer was used to input the second-by-second drive cycle. A single link was created, with the test cycle entered as a drive trace. Running MOVES generated the operating mode distribution, which is created by allocating the time spent in each operating mode according to the cycle speed and acceleration, as shown in Figure 45 and Figure 44. The derivation of scaled tractive power (STP) and operating mode attribution for heavy-duty vehicles are discussed earlier in this report, in Section 2.1.1.2.[62]

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. The CBD cycle had a new average test mass of 14.957 metric tons and the WMATA cycle had a new mass of 16.308 metric tons, compared to the default of 16.556 metric tons. Even though the mass correction was larger for the CBD cycle, the adjustment did not affect its operating mode distribution, while the mass correction for the WMATA cycle subtly altered its distribution and consequently changed the MOVES2010b emission rates used for comparison later in this analysis. This change in operating mode distribution can be mostly attributed to the aggressiveness of the WMATA cycle. Any changes in the road load coefficients (*A*, *B*, and *C*) were assumed to be negligible.

Figure 45. Operating mode distribution for the CBD cycle

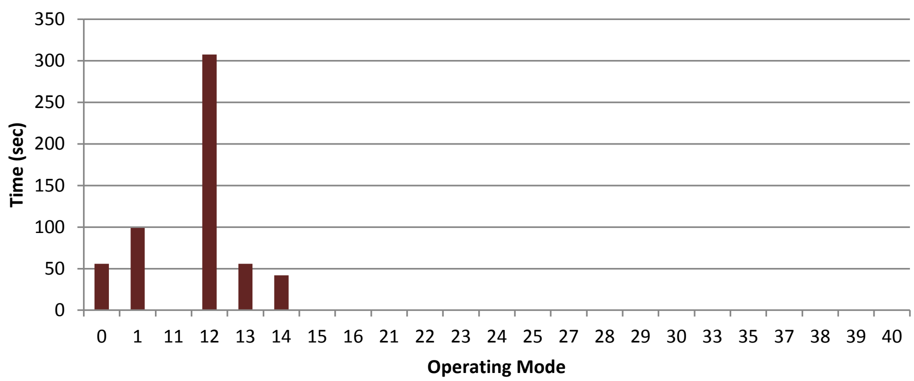
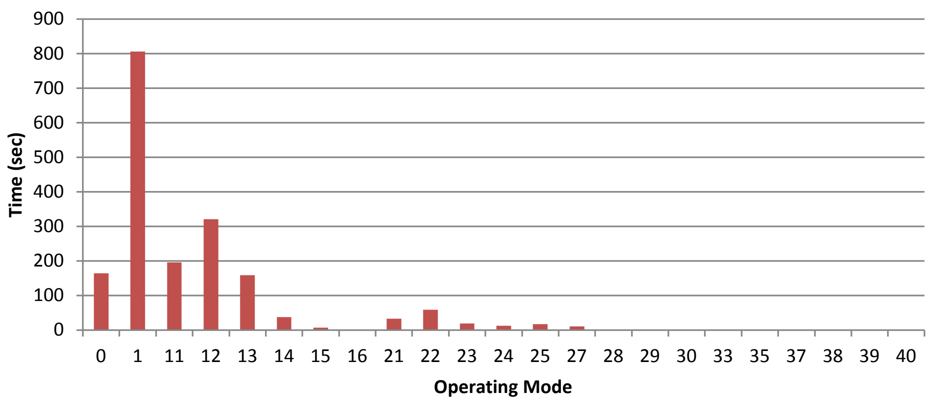


Figure 46. Operating mode distribution for the WMATA cycle



4.2 *Comparison of Simulated Cycle Emission Aggregates Based on MOVES2010b Rates to Published Chassis Dynamometer Measurements*

4.2.1 *Simulating Cycle Emission Aggregates from MOVES2010b Rates*

Having determined the total amount time spent in each operating mode over the course of each drive cycle, using the emission rates in the MOVES database (DB), we were able to simulate emissions over each cycle. Using this method, the simulated cycle emission aggregates were calculated as a function of the following parameters:

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

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

$$EF_{sim,pol,cycle} = \frac{\sum_{OM} t_{OM,cycle} r_{p,OM}}{d_{cycle}} \qquad \textbf{Equation 28}$$

where

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

d_{cycle} = distance of the cycle,

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

We compared the published test measurements to simulations using the MOVES2010b CNG transit bus rates from Equation 28. We also specified the age group and model year to match individual vehicles in the testing programs from the literature on CNG transit buses.

4.2.2 Published Chassis Dynamometer Measurements

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

1. total hydrocarbons (THC),
2. methane (CH_4),
3. carbon monoxide (CO),
4. oxides of nitrogen (NOx),
5. particulate matter (EC + non-EC), and
6. total energy consumption.

Note that 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. We then multiplied 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 and, and 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 nonmethane 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)[63] discussed later in this section. All other conversion factors to energy were taken from Melendez et al. (2005).[64]

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.

The number of unique measurements is approximately equal to the number of vehicles tested, although not exactly. Some vehicles were tested more than once because a variable in the experiment changed, such as the driving cycle or the after-treatment technology. All of the vehicles were in service with a transit agency at the time of testing. In addition, these measurements were typically reported as cycle averages based on multiple runs with the same vehicle and configuration over a specific driving cycle. Many of the testing programs also included diesel transit buses, but these vehicles were excluded from this analysis. Table 40 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.[65]

Table 41. Summary of external emissions testing programs by driving cycle and number of unique measurements

Paper/Article	Lead Research Unit	Driving Cycle(s)	Number of Unique Measurements
Melendez 2005[66]	National Renewable Energy Laboratory (NREL)	WMATA	7
Ayala 2002[67]	California Air Resources Board (CARB)	CBD	2
Ayala 2003[63]	CARB	CBD	6
Lanni 2003[68]	New York Department of Environmental Conservation	CBD	3
McCormick 1999[69]	Colorado School of Mines	CBD	3
LaTavec 2002[70]	ARCO (a BP Company)	CBD	2
McKain 2000[71]	WVU	CBD	3
Clark 1997[72]	WVU	CBD	10
TOTAL			**35**

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

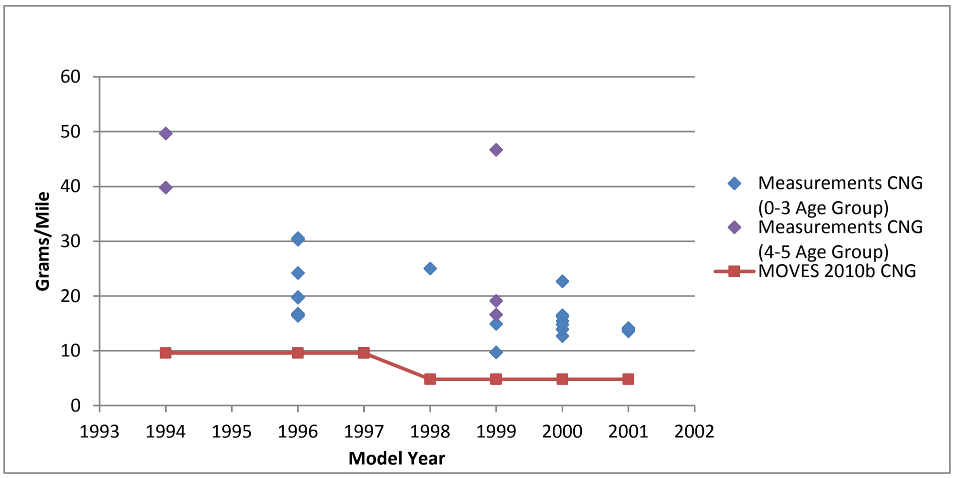
We approximated the vehicle's age by subtracting the year the study was conducted from the model year of the vehicle. Most vehicles tested were less than three years old (ageGroupID "3"), whereas 9 vehicles fell into the four to five year-old age group (ageGroupID "405"). In the CBD cycle, 5 out of 28 vehicles were in ageGroupID "405", and their performance was generally similar to the 0-3 age vehicle results. Consequently, we combined the vehicles from age group

405 with the vehicles from group 3.[xiii] Vehicle model years ranged from MY 2001 to MY 2004 for the WMATA cycle and from MY 1994 to MY 2001 for the CBD cycle.

4.2.3 Plots of Simulated Aggregates and Published Measurements

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

Figure 47. NOx emission comparisons of CNG transit bus dynamometer measurements and MOVES2010b simulated aggregates on the CBD cycle.



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xiii Note that for MY 1994 in Figure 47 through Figure 52, CNG (MHD gasoline) MOVES predictions are based off age group 405 instead of group 3.

Figure 48. CO emission comparisons of CNG transit bus dynamometer measurements and MOVES2010b simulated aggregates on the CBD cycle.

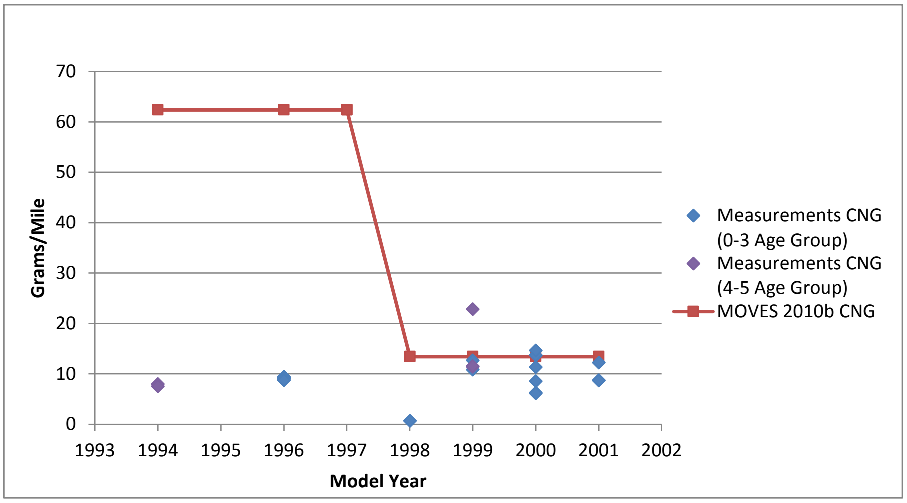


Figure 49. PM emission comparisons of CNG transit bus dynamometer measurements and MOVES2010b simulated aggregates on the CBD cycle.

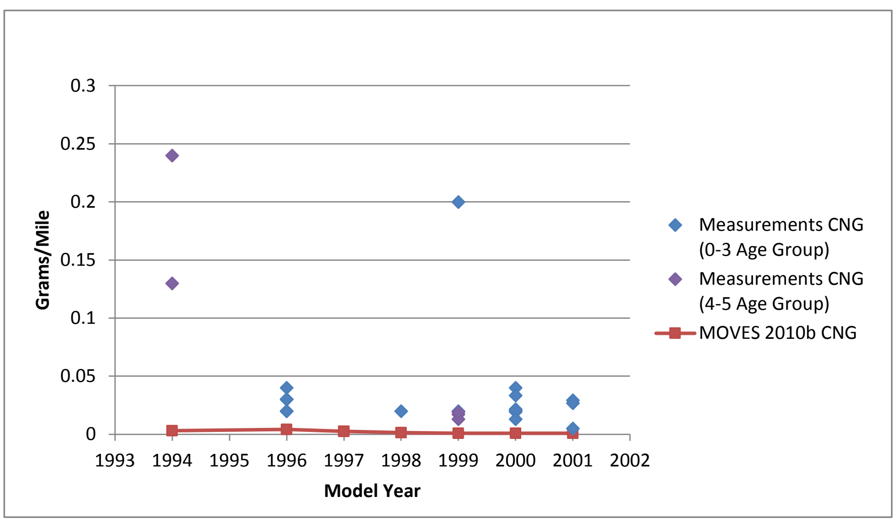


Figure 50. THC emission comparisons of CNG transit bus dynamometer measurements and MOVES2010b simulated aggregates on the CBD cycle.

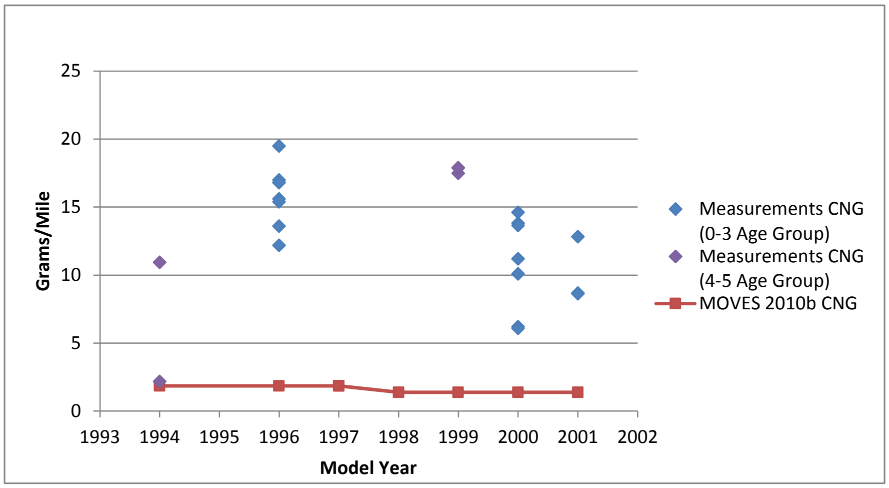


Figure 51. CH_4 emission comparisons of CNG transit bus dynamometer measurements and MOVES2010b simulated aggregates on the CBD cycle.

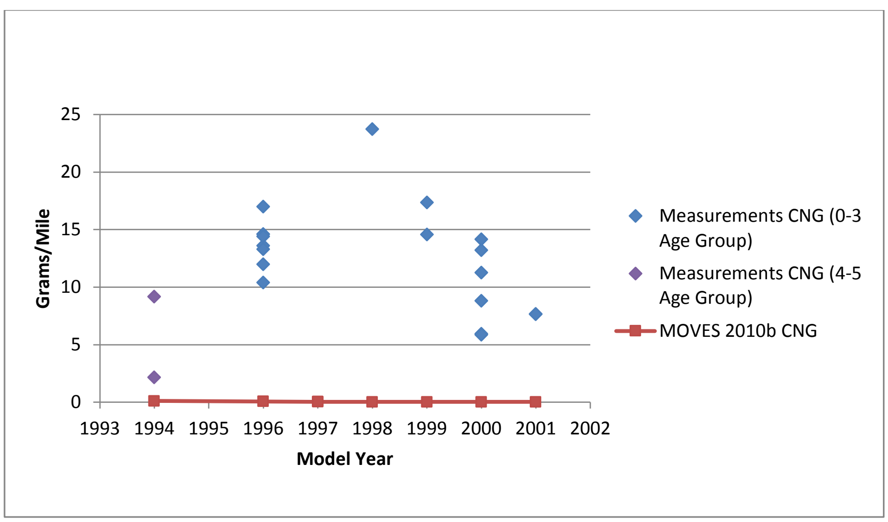
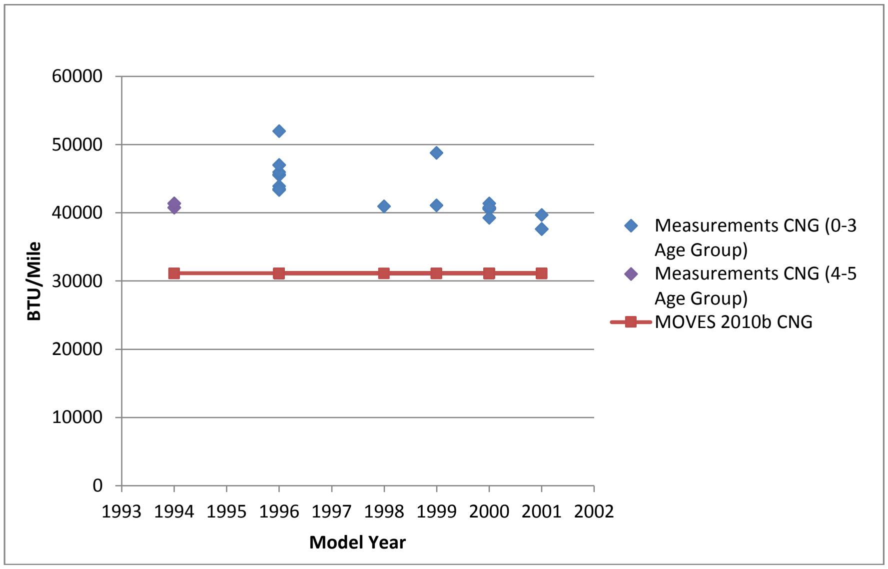


Figure 52. Total energy consumption comparisons of CNG transit bus dynamometer measurements and MOVES2010b simulated aggregates on the CBD cycle.



In Figure 47, the MOVES2010b CNG rates slightly under-predict the bus NOx measurements. As shown in Figure 48, MOVES2010b predictions for CO emissions are similar to the CNG measurements, particularly after 1999. Figure 49 shows that the MOVES2010b CNG predictions are lower for PM. As seen in Figure 50, MOVES2010b CNG predictions for THC emissions are lower than the measurements by an order of magnitude. As seen in Figure 51, this underestimate of THC is largely attributable to a significant underestimate of CNG related CH_4 in MOVES2010b. These relatively high CH_4 emissions from CNG buses compared to gasoline or diesel buses are likely from the exhaust of uncombusted natural gas, but further study is warranted. Figure 52 shows that MOVES2010b under-predicts the total energy consumption seen in the literature. We address these discrepancies by instituting the published measurements as the new MOVES2013 rates across all the pollutants and total energy discussed above.

These comparisons show that updating the MOVES2010b with these additional data from CNG buses have significant impact on the emissions inventories from CNG buses. As shown in this analysis, the existing CNG rates based on MHD gasoline trucks are not adequate surrogates. As discussed in the next section, we developed new rates based on cycle averages from the dynamometer measurements. The remainder of this report is devoted to a discussion on the development of new time-dependent emission rates (g/hr) for CNG buses.

4.3 Development of New Running Exhaust Emission Rates for CNG Transit Buses

4.3.1 Determining Model Year Groups

Ideally, new MOVES emission rates are developed through analysis of second by second data of vehicles of the appropriate regulatory class, model year, and age. Unfortunately, such modal data is not readily available in this case. However, we substantially improved the CNG bus emission rates in MOVES2013 relative to MOVES2010b by raising or lowering the MY emission rates wholesale (as opposed to individual adjustments by operating mode).

Fundamentally, the first necessary step is assigning a set of appropriate model year groups for the data. Using too few model year groups may miss important differences in the emission rates, while using too many model year groups can give false prominence to outliers and introduce artificial "jumps" in the emission rates. We chose to group the model year groups according to similar emission rates in the criteria pollutants (THC, CO, NOx and PM).

We separated CNG buses–equipped with oxidation catalysts and those not equipped, to determine if this was a reasonable distinction, and to see if these vehicles' criteria emission rates varied by model year and by age. For some model years, there are both after-treatment equipped and non-equipped vehicles. In these years, there was not a visible difference in the criteria emission levels between the vehicles in the testing programs with after-treatment (AT) equipment and those with no after-treatment (see Figure 53 to Figure 58).[xiv] Given the small sample size, the lack of clear trends among the individual vehicle models, and our lack of data on the relative distribution of after-treatment equipped vehicles versus unequipped vehicles in each of these model years, we chose to group all the CBD measurements from the literature into one model year group, spanning from MY 1994 to MY 2001. No data on CNG buses equipped with three-way catalysts (TWC) was readily available at the time of this analysis; we will look to incorporate data from buses that have TWCs and spark ignited, stoichiometric-burn engine technology as it becomes available.

[xiv] The CNG studies have a large observed impact on several of the unregulated pollutants (e.g. formaldehyde) between after-treatment and non-equipped vehicles. This impact is discussed under the PM and HC speciation subsection.

Figure 53. NOx emissions of vehicles with after-treatment versus no after-treatment tested on the CBD cycle.

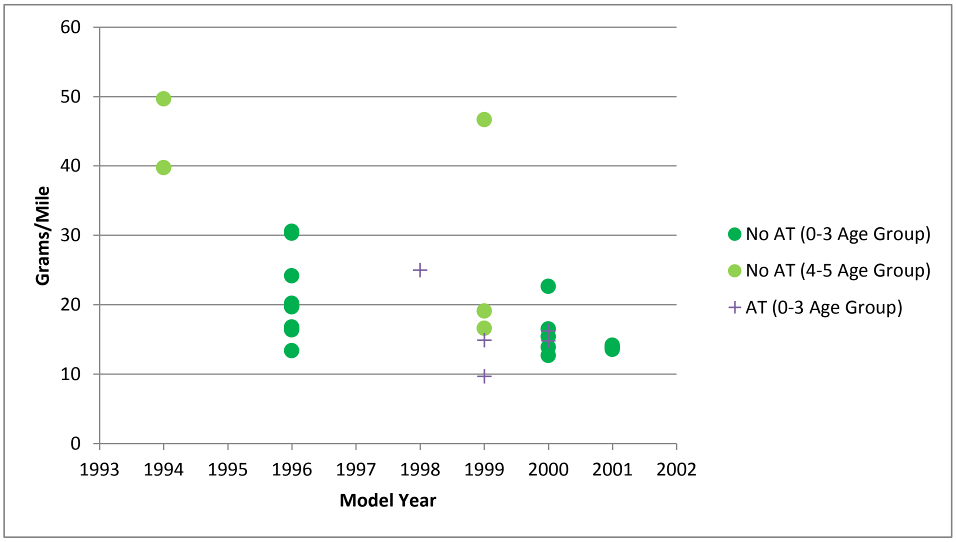


Figure 54. CO emissions of vehicles with after-treatment versus no after-treatment tested on the CBD cycle.

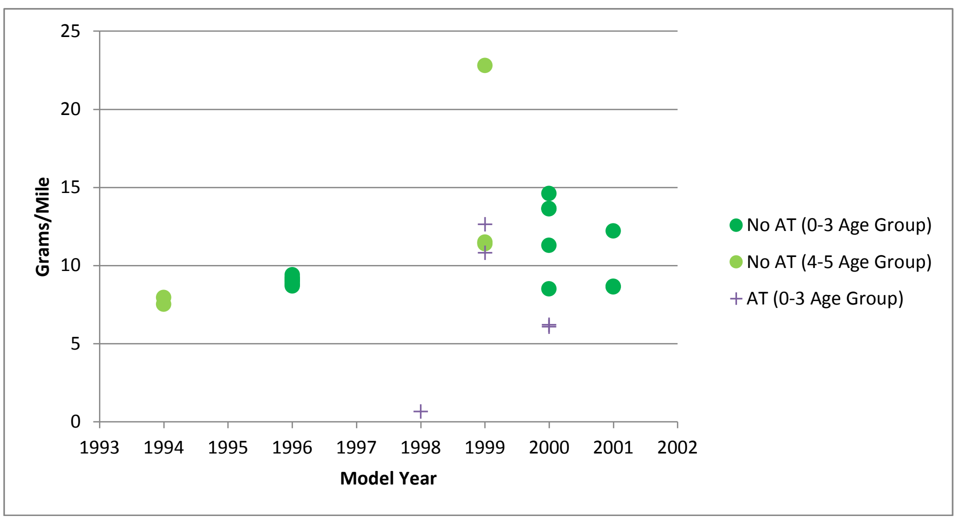


Figure 55. PM emissions of vehicles with after-treatment versus no after-treatment tested on the CBD cycle.

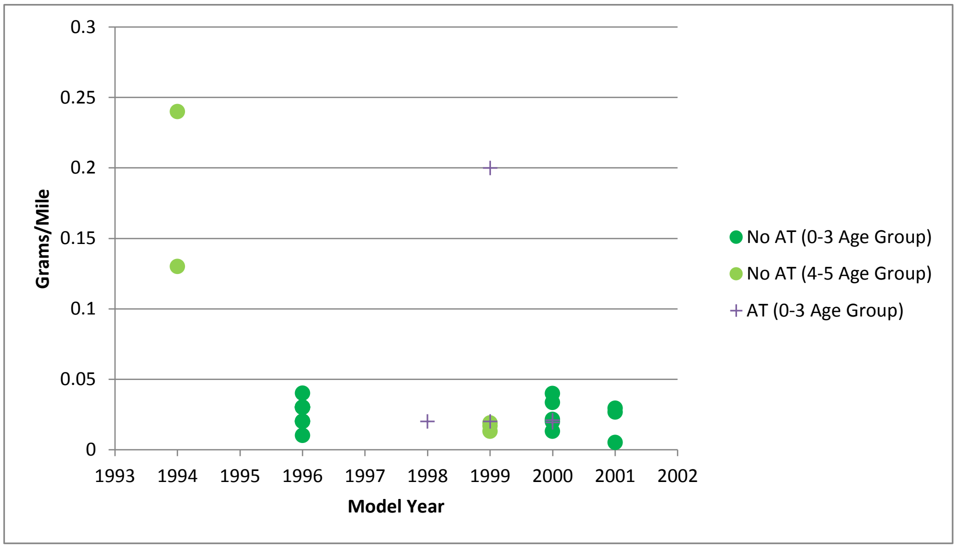


Figure 56. THC emissions of vehicles with after-treatment versus no after-treatment tested on the CBD cycle.

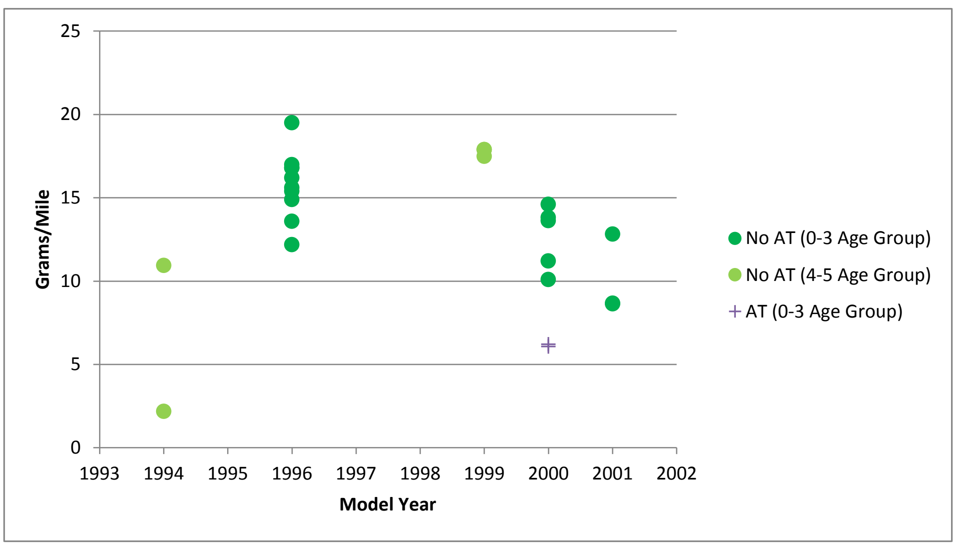


Figure 57. CH_4 emissions of vehicles with after-treatment versus no after-treatment tested on the CBD cycle.

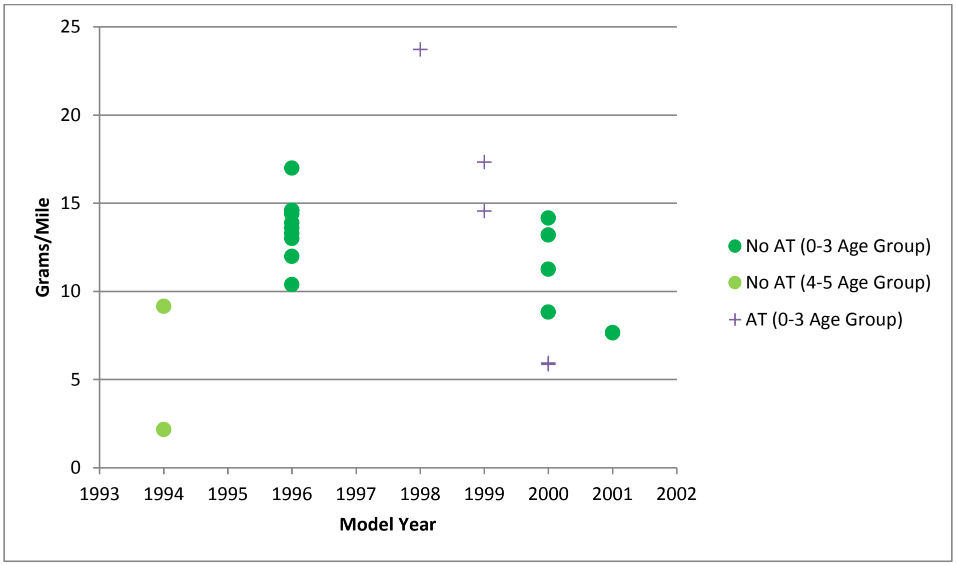
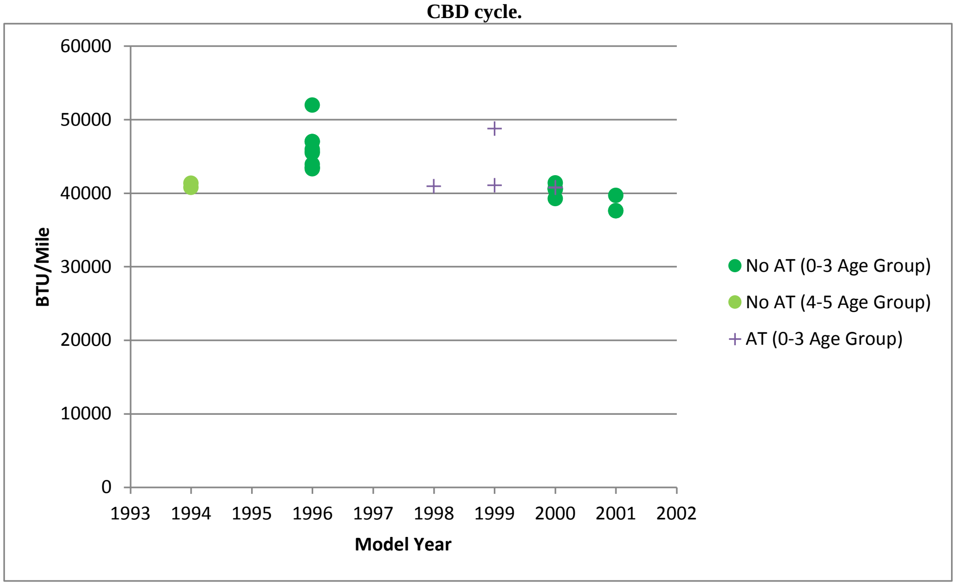


Figure 58. Total energy consumption of vehicles with after-treatment versus no after-treatment tested on the CBD cycle.



Of the surveyed data, only one study had any vehicles newer than MY 2001.[xv] This paper, a joint study between NREL and WMATA, had a small sample of vehicles from MY 2004. These vehicles have a visibly different emissions profile than the other vehicles.[73] While these buses were only tested on the WMATA driving cycle, they were all equipped with oxidation catalysts and had substantially lower emissions from the 1994-2001 buses, particularly for PM emissions. As a result, a second model year group runs from MY 2002 to MY 2006 based on a group of MY 2004 WMATA buses. This MY group ends before MY 2007 when a new series of stringent transit bus standards went into effect.[74] These standards are aimed at diesel transit buses, but they apply to CNG buses as well. We did, however, throw out the CO rate (0.14 g/mi) for these WMATA vehicles, which, according to certification data[xvi], was a full order of magnitude lower than the other 2004 models.

4.3.2 Scaling Model Years After 2007

Without published data on in-use vehicles past MY 2004, we use proxies to estimate emissions rate changes since then. Changes in emission certification levels should serve as a strong surrogate for how real vehicles on the road were performing. Certification levels are reported in grams per brake horsepower-hour and are not directly used in formulating MOVES emission rates because they do not include real-world effects such as vehicle mileage or deterioration.[75, xvii] These effects were present in the testing programs, so we created scaling factors that we could apply to the measured data from the testing programs to estimate rates after MY 2004.

Natural gas transit bus emission certification data by model year is publicly available on the EPA's Office of Transportation and Air Quality website.[76] Analysis of these data showed that from MY 2002 to MY 2012 there have been changes in certification levels for all the pollutants considered in this report. In particular, NOx and PM levels have dropped dramatically over the past decade. This effect is largely attributable to increasingly strict transit bus standards, which have affected both diesel and CNG buses. Table 41below indicates the number of CNG transit bus models certified for each model year.

[xv] A number of papers have discussed more recent vehicles. Examples include "Clark, N., Wayne, W., Khan, A., Lyons, D. et al., "Effects of Average Driving Cycle Speed on Lean-Burn Natural Gas Bus Emissions and Fuel Economy," SAE Technical Paper 2007-01-0054, 2007. 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.

[xvi] This rate seemed low without explanation, and was not supported by additional test results, and therefore, was not incorporated into the model.

[xvii] As with other MOVES emission rates, the certification rates were not used as a direct estimate of on-road emissions. Rather, we use vehicles from "the wild." However, in absence of contradictory evidence, changes in on-road emission rates, and changes in certification level may be reasonably assumed to correlate.

Table 42. A summary of the number of certified CNG transit buses by model year (USEPA OTAQ).

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

To improve the accuracy of the scaling factor we weighted the emission levels with projected US sales figures for the certified CNG buses. These figures are confidential business information and cannot be shared publicly but have been incorporated as ratios to calculate the MY group 2007-2012 emission rates. The aggregated certification levels with these annual sales weighted averages for MY group 2002-2006 and MY group 2007-2012 as well as the measured cycle averages for MY group 1994-2001 and MY group 2002-2006 are shown in Table 43 below.

Methane levels are not reported in the certification data, so we estimate CH_4 rates for MY group 2007-2012 through an analysis of the CH_4 to THC ratio by model year from the dynamometer measurements. The CH_4/THC ratio for every model year fell within one standard deviation of the average ratio across all model years. We left the CH_4/THC ratio constant from MY group 2002-2006 to MY group 2007-2012 and estimated the new CH_4 rate (given in Table 44) off that previous ratio. This constant ratio was also justification for basing our THC scaling factor on the non-methane hydrocarbon (NMHC) levels (reported as an organic material non-methane hydrocarbon equivalent or OMNMHCE) from the certification data. That is, if the CH_4/THC ratio remains constant and then the NMHC/THC ratio must also remain constant, so we scaled our THC rate for MY group 2007-2012 off the OMNMHCE certification levels.

Table 43. Emission rates and certification levels of CNG transit buses according to model year group.

MEASURED AND CERTIFICATION WEIGHTED SALES AVERAGES							
Driving Cycle	**Age Group**	**Model Year Group**	**NOx**	**CO**	**PM**	**THC**	**CH_4**
Certification (g/bhp-hr) [1]	0-3	2002-2006	1.208	1.355	0.0078	0.147	
Certification (g/bhp-hr) [1]	0-3	2007-2012	0.2902	3.032	0.0033	0.057	
WMATA (g/mi)	0-3	2002-2006	9.080	2.166	0.00433	11.16	10.60
WMATA (g/mi)	0-3	2007-2012	2.182	5.929	0.00181	4.332	4.117

1. Organic material non-methane hydrocarbon equivalent (OMNMHCE)

The certification data is in blue text and the rates scaled from the certification data is highlighted in yellow. We scaled the newer model year rates r_p based off the measurements in the MY group 2002-2006 in proportion to the ratio of certification levels CL_p from MY group 2007-2012 to MY group 2002-2006. In this case,

$$r_{p,MY2007-2012} = r_{p,MY2002-2006} \cdot \frac{CL_{p,MY2007-2012}}{CL_{p,MY2002-2006}}. \quad \textbf{Equation 29}$$

As mentioned before, the measured CO rate for MY group 2002-2006 was omitted (in red text). We replaced it with a value equal to the ratio between the sales-weighted average for the MY 2004 certification level of all models and the certification level for that particular MY 2004 John Deere bus with the anomalous CO rate.

The estimated CO rate for MY group 2007-2012 is notably greater than the previous MY group, but this change was reflected in our certification level proxies, and may be attributable to either the after-treatment or changes in engine calibration.

Note that there was limited data on older vehicles in the literature, so the ratios that were developing using vehicles in the 0-3 age group have been applied to all other age groups. Therefore, we are assuming that CNG buses exhibit deterioration rates in control equipment proportional to medium heavy-duty gasoline trucks.

Since there is no certification on greenhouse gases, namely methane and carbon dioxide (CO_2), until 2011, we chose to maintain the same total energy consumption rate from MY group 2002-2006 to MY 2007-2012.

4.3.3 Creating CNG Running Rates for Future Model Years

Table 43 shows CNG transit bus emissions on each drive cycle calculated using MOVES2010b rates for each MY group. These calculations are shown using a single model year within the group. The table also shows the emission rates estimated from our meta-analysis of the literature. The ratios between these rates were applied to the 1997, 2004 and 2009 MOVES2010b CNG bus rates in order to calculate the MOVES2013 rates.[xviii]

Table 44 Summary of MOVES2010b and MOVES2013 CNG Transit Bus Rates

	MOVES2010b CNG Rates (g/mile)								
MY	Age Group	Cycle	NOx	CO	PM_Non EC	PM_EC	TOTAL ENERGY (BTU/mi)	THC	CH4
1997	0-3	CBD	9.63	62.39	0.00240	0.00018	31137	1.84	0.0485
2004 and 2009	0-3	WMATA	5.45	18.92	0.00353	0.00026	35489	1.43	0.0322
	Proposed MOVES2013 CNG Rates (g/mile - measured/estimated from analysis)								
MY	Age Group	Cycle	NOx	CO	PM_Non EC	PM_EC	TOTAL ENERGY (BTU/mi)	THC	CH4
1994-2001	0-3	CBD	20.8	9.97	0.03722	0.00379	42782	13.2	12.1
2002-2006	0-3	WMATA	9.08	2.17	0.00385	0.00048	40900	11.2	10.6
2007 and later	0-3	WMATA	2.18	5.93	0.00161	0.00020	40900	4.33	4.12
	Ratios used to generate MOVES2013 Rates								
MY	Age Group	Cycle ratioed	NOx	CO	PM_Non EC	PM_EC	TOTAL ENERGY	THC	CH4
1994-2001	all	CBD	2.163	0.159	15.48	21.62	1.374	7.165	249.59
2002-2006	all	WMATA	1.667	0.114	1.092	1.871	1.152	7.794	329.66
2007 and later	all	WMATA	0.4002	0.313	0.4556	0.7810	1.152	3.024	128.05

[xviii] Diesel transit bus rates were initially considered as the MOVES baseline for scaling new rates because these vehicles share regulatory and design characteristics with CNG buses. However, in the MOVES database, diesel vehicles have rates of zero for several start emission processes. Rates of zero cannot be scaled, and the difference in emission profile was deemed more significant than the difference in vehicle usage characteristics.

The model year basis for scaling was selected based on temporal similarity. For instance, our choice to use MY 1997 for MY group 1994-2001 was due to it being a median year in the group. For MY group 2002-2006, we selected MY 2004 because that was the year all the vehicles in that group were manufactured. As for MY group 2007-2012, MY 2009 was also chosen simply for being one of the two model years near the median for the group.[xix]

4.4 Start Exhaust Emission Rates for CNG Buses

In the absence of any measured start exhaust emissions from CNG transit buses, their start rates are copies of heavy-duty diesel start rates because the CNG buses in the literature reviewed have compression ignited engines, and therefore must adhere to the same standards as diesel buses. We believe this is as an environmentally conservative approach, rather than assuming zero CNG start emissions. MOVES still estimates that the majority of emissions from CNG buses are from running emissions, which are based on CNG test programs. We readily acknowledge that the diesel start rates may not accurately represent CNG start rates. This assumption will be revisited for future releases of MOVES as more CNG buses are equipped with spark ignited engines and as new data on CNG start rates becomes available.

~~In the absence of any measured start exhaust emissions from CNG transit buses, their start rates are copies of heavy-duty diesel start rates because the CNG buses in the literature reviewed have compression ignited engines, and therefore must adhere to the same standards as diesel buses. Despite being an environmentally conservative approach, we readily acknowledge that the diesel start rates may not accurately represent CNG start rates and that these diesel surrogates may lead to flawed CNG bus emission inventories. This assumption will be revisited for future releases of MOVES as more CNG buses are equipped with spark ignited engines and as new data on CNG start rates becomes available.~~

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4.5 PM and HC Speciation for CNG Buses

MOVES estimate methane and nonmethane hydrocarbons (NMHC) through the use of CH4 /THC ratios. Table 44 shows updated CH_4/THC ratios in MOVES2013. These ratios have been calculated by taking the proposed CH_4 rate over the proposed THC rate for any given model year group. The change in CH_4/THC ratio is attributable to the deterioration of the after-treatment equipment, but no data is available on the ratio of aged CNG transit buses. In absence of data, we assume that the change in the THC emission rate is proportional to the changes in the methane emission rate, and keep this ratio constant at all ages. This assumption is consistent with a decrease in combustion efficiency.

Table 45 A comparison of CH4/THC ratios from current MOVES2010b CNG bus rates versus proposed MOVES2013 rates from measurements

[xix] In MOVES2010b, the CNG bus rates were constant after 2004.

Model Version	Model Year	Age Group	CH4/THC Ratio
MOVES2013	1994-2001	0-3	0.9165
MOVES2013	2002-2006	0-3	0.9498
MOVES2013	2007-2012	0-3	0.9515

MOVES calculates emissions of total organic gases (TOG), nonmethane organic gases (NMOG) and volatile organic carbons (VOC) using information regarding the hydrocarbon speciation of emissions. Studies have shown that the speciation of hydrocarbon can be drastically different between uncontrolled CNG buses, and CNG buses with oxidation catalysts, and CNG buses. For example, formaldehyde emissions can be quite large from uncontrolled CNG buses[65, 77] (Kado et al. 2005[77], Hesterberg et al. 2008, [68]), but are significantly reduced with oxidation catalysts**Error! Bookmark not defined.**. Formaldehyde has as a large impact on the NMOG/NMHC ratio because formaldehyde has a small response to THC-FID measurements[78].

We used hydrocarbon speciation measurements from the Ayala et al. (2003) using measurements from the 2000 MY Detroit Diesel Series 50G engine with and without an oxidation catalyst collected on the CBD cycle. We used the speciated measurements made on a single vehicle to isolate the impact of the oxidation catalyst. We used the CBD test cycle to be consistent with our analysis of the criteria emission rates. The NMOG and VOC conversion factors are located in Table 45. The NMOG values are calculated following EPA's regulation requirements, and uses the default THC-FID response values for formaldehyde and acetaldehyde. The VOC emissions are calculated from subtracting the ethane from the NMOG values, consistent with the EPA's definition of VOC[79]. The emissions of hazardous air pollutants, including formaldehyde and acetaldehyde, are also estimated from this study as documented in the MOVES2014 Toxics Emissions Report.

Table 46 NMOG and VOC Conversion values for CNG transit emissions with no control and with oxidation catalyst from Ayala et al. (2003) Error! Bookmark not defined.

Measured values (mg/mile)	No control	Oxidation Catalyst
THC	8660	6150
CH_4	7670	5900
C_2H_6	217	72.2
Formaldehyde	860	38.4
Acetaldehyde	50.7	32.6
Calculated values (mg/mile)		
NMHC	990	250
NMOG	1881.0	309.0
VOC	1664.0	236.8
Ratios		
NMOG/NMHC	1.90	1.24

VOC/NMHC	1.68	0.95

In MOVES2014, we apply the uncontrolled NMOG and VOC factors to the pre-2002 model year vehicles. This analysis demonstrated that majority of the 2001 and earlier model year vehicles were uncontrolled CNG buses. The study conducted on MY 2004 buses[73], suggested that 2002-2006 model year vehicles are equipped with oxidation catalysts. Therefore we apply the oxidization catalyst profile to CNG emissions for the 2002 to 2006 MY group. At the time of the analysis, we did not have information on 2007 and later CNG buses, and also applied the oxidation catalyst from the compression ignition results to 2007 and later groups.

The composition of $PM_{2.5}$ emissions are estimated from CARB's measurements,[80] (Okamoto, 2006) on the 2000 MY Detroit Diesel Series 50G with and without the oxidation catalyst. The EC/PM2.5 fraction is reported in Table 46, and are used to estimate the base PM components in MOVES: elemental carbon (EC) and non-elemental carbon (nonECPM) rates. By using the single bus, we again isolate the impact of the control, without confounding differences in different engine technologies. Similar for the HC speciation, we apply the uncontrolled EC/PM fraction to the pre-2002 MY CNG buses, and the oxidation catalyst equipped EC/PM profile for the 2002 and later buses.

Table 47 MOVES2014 EC/PM Fraction for CNG transit bus emissions

(Pre-2002 MY)	(2002+ MY)
9.25%	11.12%

The CARB measurements are also used to estimate the individual PM2.5 composition, including organic carbon, elements, and sulfate as discussed in the TOG and PM2.5 speciation report. Stoichiometric spark ignition CNG engines with three-way catalysts have been introduced in 2007 and later buses. Future work should be done to improve the emission rates and speciation profiles used in MOVES to represent emissions from recent technology CNG buses.

4.6 Nitrogen Emissions for CNG Buses

No data were available on nitrous oxide and ammonia emissions rates. As such, we used the nitrous oxide and ammonia emissions for heavy-duty gasoline vehicles documented in separate reports[1,2]. 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) is used, along with the 0.008 HONO fraction assumed for other source types[2]. These assumptions yield the NOx fractions in Table 47 are used for all model year CNG transit buses.

Table 48 NOx fractions CNG transit buses

NO	86.5%
NO_2	12.7%
HONO	0.8%

4.7 Comparison to MOVES2010b Diesel Transit Bus Rates

Many MOVES users have inquired about the impacts of switching from a diesel transit bus fleet to a CNG fleet on their emissions inventory. However, direct comparisons between CNG and diesel transit buses may be confounded because the MOVES2010b heavy-duty diesel rates are applied to the engine family rather than transit buses exclusively. That being said, the MOVES2010b diesel transit bus rates are shown in Table 48:

Table 49 MOVES2010b diesel transit bus emission rates based on simulated cycle aggregates

MOVES2010b EMISSION RATES FOR DIESELTRANSIT BUSES (g/mi)								
Driving Cycle	Age Group	Model Year	NOx	CO	PM	HC	CH_4	Total Energy (BTU/mi)
CBD	0-3	1997	44.33	4.624	0.8877	0.7412	0.0056	33468
WMATA	0-3	2004	20.30	3.621	1.039	1.2229	0.0088	37592
WMATA	0-3	2009	10.15	0.7243	0.0383	0.2446	0.1430	37592

4.8 Application to Other Age Groups and Model Years

We applied these ratios in Table 43 and Table 44 to all ages of CNG bus emission running rates in MOVES2010b. In this step, the deterioration assumptions used in the MOVES2010b running rates are incorporated into the MOVES2013 CNG emission rates. This may or may not be a valid assumption, but as with the methane to THC ratio, available data is limited. For completeness, CNG buses prior to MY 1994 use the same rates as MY group 1994-2001. Rates for buses built after MY 2012 maintain the same rate as MY group 2007-2012. As new certification data arrives and more testing programs are run, these rates will be revisited in future MOVES releases.

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.[81]

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.[82] 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' (Jääskeläinen, 2012). Researchers have found that crankcase emissions vented to the atmosphere can be the dominant source of emissions to in-cabin diesel particulate matter concentrations [83] [84] [85].

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.[86] Most manufacturers have adopted open crankcase filtration systems (Jääskeläinen, 2012). 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 (Jääskeläinen, 2012). 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.[87]

A summary of published estimates of diesel crankcase emissions as percentages of the total emissions (exhaust + crankcase) are provided in Table 49. For the conventional diesel technologies, hydrocarbon and particulate matter emissions have the largest contributions from crankcase emissions. There is a substantial decrease in PM emissions beginning with the 2007 model year diesel engines. The 2007 diesel technology reduces the tailpipe emissions more than the crankcase emissions, resulting in an increase in the relative crankcase contribution for HC, CO, and PM emissions. NOx emissions for the 2007 and later are reported as a negative number. In reality, the crankcase emission contribution cannot be negative, and the negative number is attributed to sampling variability from the tests with and without the crankcase emissions.

Table 50 Literature review on the contribution of crankcase emissions to diesel exhaust.

Study	Model Year	Type	# Engines/ Vehicles	HC	CO	NOx	PM
Hare and Baines, 1977[91]	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[83], Ireson et al. 2011[84]	2000, 2003	Conv. Diesel	2				13.5% - 41.4%
Clark et al. 2006[90], Clark et al. 2006[88]	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

In MOVES, crankcase emissions are calculated by chaining to the emission calculators that calculate start, running, or extended-idle emissions. For these processes, crankcase emissions are calculated as a fraction of tailpipe exhaust emissions. Crankcase emissions are calculated for selected pollutants, including THC, CO, NO_x, and $PM_{2.5}$.

As discussed in the background, the 2007 heavy-duty diesel emission regulations impacted the technologies used to control exhaust and crankcase emissions. The regulations also expanded the types of emissions data included in certification tests, by including crankcase emissions in the regulatory standards, which previously included only tailpipe emissions. Because heavy-duty diesel engine manufacturers are using open-filtration crankcase systems, the crankcase emissions are included in the emission certification results. In MOVES2014, the base exhaust rates for 2007 and later diesel engines are based on certification levels.

In response to the changes in certification testing, we changed the data and the methodology with which crankcase emissions are modeled in MOVES. For 2007 and later diesel engines, the crankcase emissions are included in the base exhaust emission rates. A new crankcase calculator in MOVES2014 divides the base exhaust emission rates into components representing the contributions from exhaust and crankcase emissions. The exhaust emission ratio is equal to 1.0 for all pre-2007 diesel engines, and less than 1.0 for all 2007 and later diesel engines, to account for the inclusion of crankcase emissions in the base rates. Unfortunately, due to budget and time constraints, only the $PM_{2.5}$ species are incorporated using the new crankcase calculator in MOVES2014. An overview of the crankcase calculator is provided in the MOVES2014 TOG and PM Speciation Report[89] and the MOVES2014 Software Design Reference Manual.

MOVES2014 continues to use the MOVES2010 crankcase calculator for the gaseous crankcase pollutants, THC, CO, and NOx. The MOVES2010 calculator chains the crankcase emission rates to the base exhaust emissions, but it does not allow the ability to reduce the exhaust emission contribution, which is desired for the 2007+ diesel technologies. The 2007+ diesel subsection discusses how MOVES2014 handles THC, CO, and NOx to avoid double-counting crankcase emissions. We anticipate that future versions of MOVES will include the updated crankcase calculator for all crankcase emission pollutants, including THC, CO, and NOx.

5.3 Conventional Heavy-Duty Diesel

Error! Reference source not found. includes the crankcase/tail-pipe emission ratios used for conventional diesel exhaust. For HC, CO, and NOx, we selected the values reported on the MY2006 diesel engine reported by Clark et al. 2006[90]. These values compare well with the previous HC, CO, NOx values reported much earlier by Hare and Baines (1977), [91] 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 selected a crankcase/tail-pipe ratio of 20%. Zielinska et al. 2008[83] above and Ireson et al. 2011[84] above reported crankcase contributions to total $PM_{2.5}$ emissions as high as 40%. Jääskeläinen (2012) reported that crankcase can contribute as much as 20% of the total emissions from a review of six diesel crankcase studies. Similarly, an industry report estimated that crankcase emissions contributed 20% of total particulate emissions from 1994-2006 diesel engines[92].

Table 51 MOVES2014 Conventional Diesel Crankcase/Tail-pipe Ratios

Emission Type	Crankcase/Tailpipe ratio	Crankcase/(Crankcase + Tailpipe) ratio
HC	0.037	0.036
CO	0.013	0.013
NOx	0.001	0.001
$PM_{2.5}$	0.200	0.167

As outlined in the MOVES 2014 TOG and PM Speciation Report, MOVES does not apply the crankcase/tailpipe emission ratio in Table 52 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 crankcase $PM_{2.5}$/exhaust $PM_{2.5}$ ratio is 20%, and the crankcase emissions EC/PM fraction reflects measurements from in-use crankcase emissions. Zielinska et al. 2008[83] reported that the EC/PM fraction of crankcase emissions from two conventional diesel buses is 1.57%. Tailpipe exhaust from conventional diesel engines is dominated by elemental carbon emissions from combustion of the diesel fuel, while crankcase emissions are dominated by organic carbon emissions largely contributed from the lubricating oil. [83,84]

The crankcase emission factors shown in Table 51 are derived such that the crankcase $PM_{2.5}$ emissions are 20% of the PM2.5 exhaust measurements, and have an EC/PM split of 1.57%.

The PM_{10} emission rates are subsequently estimated from the $PM_{2.5}$ exhaust and crankcase emission rates using $PM_{10}/PM_{2.5}$ emission ratios as documented in the MOVES2014 TOG and PM Speciation Report.

Table 52. MOVES2014 Exhaust and Crankcase Emission Factors for pre-2007 Diesel by Pollutant, Process, and Model Year Group.

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

5.4 2007 + Heavy-Duty Diesel

The 2007+ heavy-duty diesel THC, CO, and NOx crankcase emissions are included in the exhaust emissions. However, without the use of the updated calculator, the crankcase contribution of THC, CO, and NOx to the base exhaust emission rates cannot be properly accounted. For MOVES2014, the crankcase to tailpipe emission ratios for THC, CO, and NOx are set to 0 as shown in Table 52, and MOVES2014 produces 0 crankcase emissions for each of the pollutants. Table 52 also lists the crankcase to tailpipe emission ratios based on ACES Phase 1 tests. Based on the ACES Phase 1 program, the MOVES2014 estimate of 0 crankcase emissions is reasonable for NOx, but not for THC and CO emissions. MOVES2014 does not report crankcase emissions for THC and CO because they are included in the exhaust emission rates for 2007+ diesel. Users can use the ratios listed in Table 52 to post-process the exhaust emission rates if the crankcase contributions to THC and CO emissions are desired.

Table 53 MOVES2014 2007 and Later Diesel Crankcase/Tailpipe ratio

Emission Type	MOVES2014 Crankcase/Tailpipe ratio	ACES Phase 1 Crankcase/Tail-pipe ratio	ACES Phase 1 Crankcase/(Crankcase + Tail-pipe)l ratio
HC	0	21.95	95.6%
CO	0	0.37	27.2%
NOx	0	0.00	0.0%

For $PM_{2.5}$ emissions, we used data from the ACES Phase 1 test program to inform the crankcase and exhaust ratios for the updated $PM_{2.5}$ crankcase emissions calculator. The crankcase emissions measured in the ACES Phase 1 test program contributed 38% of the total $PM_{2.5}$ emissions on the hot-FTP driving cycle. Emission results reported from industry, have reported that the crankcase emissions can contribute to over 50% of the particulate matter emissions from 2007 and later diesel technologies[92].

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. The MOVES $PM_{2.5}$ speciation profile developed from the Health Effects Institute ACES Phase 1 combined the crankcase and tailpipe emissions. As such, MOVES2014 uses the same speciation profile for both crankcase and tailpipe emissions. The resulting exhaust and crankcase emission ratios for 2007 and later heavy-duty diesel are provided in Table 53. As shown, 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 54 MOVES2014 Exhaust and Crankcase Emission Factors for 2007 + Heavy-duty Diesel by Pollutant, Process, and Model Year Group

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

5.5 Heavy-duty Gasoline and CNG Emissions

The data on heavy-duty gasoline and CNG crankcase emissions are limited. All 1969 and later otto-cycle (spark ignition) heavy-duty engines are required to control crankcase emissions. All gasoline engines are assumed to use positive crankcase ventilation (PCV) systems, which route the crankcase gases into the intake manifold. For heavy-duty gasoline engines we use the same values of crankcase emission ratios as light-duty gasoline which are documented in the MOVES2014 light-duty emission rates report[4]. EPA assumes 4% of PCV systems have failed, resulting in the small crankcase to exhaust emission ratios shown in for 1969 and later gasoline engines. Due to limited information, we use the gasoline heavy-duty crankcase emission factors for heavy-duty CNG engines because they have low blow-by particle emissions.

Table 55 Crankcase to Tailpipe Exhaust Emission Ratio for Heavy-duty Gasoline

Pollutant	Gasoline (uncontrolled, pre-1969)	Gasoline (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 $PM_{2.5}$ subspecies crankcase and exhaust ratios used by the crankcase calculator for heavy-duty gasoline and compressed natural gas vehicles are provided in Table 55. No information is available to estimate separate speciation between exhaust and crankcase, so the factors are the same between the PM subspecies.

Table 56 MOVES2014 Exhaust and Crankcase Emission Factors by Pollutant, Process, Model Year Group, and Fuel Type, and Source Type

		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

A. Appendices

A.1 Calculation of Accessory Power Requirements

Table 57. 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 58. 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 59. 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

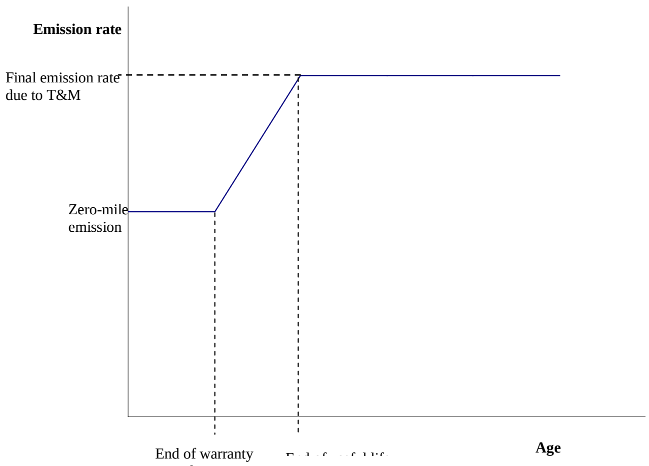
A.2 Tampering and Mal-maintenance

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.

A.2.1 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 59 shows this relationship.

Figure 59. 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[93] (Vehicle Inventory and Use Survey) data, which contains data on how quickly trucks of different regulatory classes accumulate mileage. Table 59 shows the emissions warranty period and approximate useful life requirement period for each of the regulatory classes.

Table 60. Warranty and useful life requirements by regulatory class

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

While both age 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 need 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, any 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 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 60 shows the multiplicative T&M adjustment factor by age. We determined this factor using the mileage-age data from Table 59 and the emissions-age relationship that we described in Figure 59. 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 the section *A.2.3 Analysis* below and which is listed in the corresponding running exhaust sections above.

Table 61 shows the T&M multiplicative adjustment factor by age ($f_{TM,age\ group}$).

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

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

$$\bar{r}_{pol,agegrp} = \bar{r}_{pol,ZML}(1 + f_{TM,agegroup} TM_{pol}) \qquad \textbf{Equation 30}$$

A.2.2 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[94] (2006). The basic EMFAC occurrence rates for tampering and mal-maintenance were developed from the 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

A.2.3 Analysis

A.2.3.1 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, not ULSD onroad diesel. 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 will group the LHDD, MHDD, HHDD, and Diesel bus groups together, except for 2010 and beyond. We assumed that the LHDD group will primarily use Lean NOx Traps (LNT) for the NOx control in 2010 and beyond. On the other hand, we also assumed that Selective Catalyst Reduction (SCR) systems will be the primary NOx aftertreatment system for HHDD. Therefore, the occurrence rates and emission impacts will vary in 2010 and beyond depending on the regulatory class of the vehicles.

A.2.3.2 T&M Model Year Groups

EPA developed the model year groups based on regulation and technology changes.

- Pre-1994 represents non-electronic fuel control.
- 1998-2002 represents the time period with consent decree issues.
- 2003 represents early use of EGR.
- 2007 and 2010 contain significant PM and NOx regulation changes.
- EPA issued a rule to require OBD for heavy duty trucks, beginning in MY 2010 with complete phase-in by MY 2013.

A.2.3.3 T &M Occurrence Rates

A.2.3.3.1 EPA T &M Occurrence Rate 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 EMFAC's 8 percent to 6 percent based on the UCR results.

Electronics Failed: EPA will continue to use the 3 percent frequency rate for all model years beyond 2010. CARB increased the rate to 30 percent in 2010 due to system complexity. EPA does not agree with CARB's assertion that the complexity of electronic systems will increase enough to justify a ten-fold increase in malfunction occurrence rates. We believe that the hardware will evolve through 2010, rather than be replaced with completely new systems that would justify a higher rate of failure. EPA asserts that many of the 2010 changes will 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 believes the EMFAC 20 percent EGR failure rate is too high and reduced the rate to 10 percent. All but one major engine manufacturer had EGR previous to the 2007 model year and all have it after 2007. Therefore, EMFAC's frequency rate increase in 2010 due to the increase truck population using EGR does not seem valid. However, the Illinois EPA stated that "EGR flow insufficient" is the top OBD issue found in their LDV I/M program[95] so it cannot be ignored.

NOX Aftertreatment malfunction: EPA developed a NOx aftertreatment malfunction rate that is dependent on the type of system used. We assumed that HHDD will use primarily SCR systems and LHDD will primarily use LNT systems. We estimated the failure rates of the various components within each system to develop a composite malfunction rate.

The individual failure rates were developed considering the experience in agriculture and stationary industries of NOx aftertreatment systems and similar component applications. Details are included in the chart below. We assumed that tank heaters had a 5 percent failure rate, but were only required in one third of the country and 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.

	Occurrence Rate
SCR	
Urea tank	0.5%
Tank heaters	1%
In-exhaust injectors	2%
Compressed air delivery to injector	1%
Urea supply pump	1%
Control system	5%
Exhaust temperature sensor	1%
Urea supply	1%
Overall	**13%**

LNT	
Adsorber	7%
In-exhaust injectors	2%
Control system	5%
Exhaust temperature sensor	1%
Overall	**16%**

NOx aftertreatment sensor: EPA believes the 53 percent occurrence rate in EMFAC2007 is too high and will use 10 percent. CARB assumed a mix of SCR, which uses one sensor per vehicle, and NOx adsorbers, which use two sensors per vehicle. They justified the failure rate based on the increased number of sensors in the field beginning in 2010.

We developed the occurrence rate based on the following assumptions:

- Population: HHDD: vast majority of heavy-duty applications will use SCR technology with a maximum of one NOx sensor. NOx sensors are not required for SCR – manufacturers can use models or run open loop. Several engine manufacturers representing 30 percent of the market plan to delay the use of NOx aftertreatment devices through the use of improved engine-out emissions and emission credits.
- Durability expectations: SwRI completed 6000 hours of ESC cycling with NOx sensor. Internal testing supports longer life durability. Discussions with OEMs in 2007 indicate longer life expected by 2010.
- Forward looking assumptions: Manufacturers have a strong incentive to improve the reliability and durability of the sensors because of the high cost associated with frequent replacements.

PM Filter Leak: EPA will use 5 percent PM filter leak and system failure rate. CARB used 14 percent 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.

A.2.3.3.2 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%

A.2.3.3.2 Emission Effects

NOx Emission Effects

EPA developed the emission effect from each tampering and mal-maintenance incident from CARB's EMFAC, Radian's dynamometer testing with and without the malfunction present, EFEE results, and internal testing experience.

EPA estimated that the lean NOx traps (LNT) in LHDD are 80 percent efficient and the selective catalyst reduction (SCR) systems in HHDD are 90 percent efficient at reducing NOx.

EPA developed the NOx emission factors of the NOx sensors based on SCR systems' ability to run in open-loop mode and still achieve NOx reductions. The Manufacturers of Emission Controls Association (MECA) has stated that 75-90 percent NOX reduction with open loop control and >95 percent reduction with closed loop control.[96] Visteon reports 60-80 percent NOX reduction with open loop control.[97]

The failure of the NOx aftertreatment system had a different impact on the NOx emissions depending on the type of aftertreatment. The HHDD vehicles with SCR systems would experience a 1000 percent increase in NOx during a complete failure, therefore we estimated a 500 percent increase as a midpoint between normal operation and a complete failure. The LHDD vehicles with

LNT systems would experience a 500 percent increase in NOx during a complete failure. We estimated a 300 percent increase as a value between a complete failure and normal system operation.

The values with 0 percent effect in shaded cells represent areas which have no occurrence rate.

Tamper & Malmaintenance
NOX Emission Effect

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

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.

Tamper & Malmaintenance
PM Emission Effect

	1994-97	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 Disabled	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/Low Flow	0%	0%	100%	5%	5%
EGR Disabled	0%	0%	-30%	-30%	-30%
Nox Aftertreatment Sensor	0%	0%	0%	0%	0%
Replacement Nox Aftertreatment Sensor	0%	0%	0%	0%	0%
Nox Aftertreatment Malfunction	0%	0%	0%	0%	0%
PM Filter Leak	0%	0%	0%	600%	600%
PM Filter Disabled	0%	0%	0%	1000%	1000%
Oxidation Catalyst Malfunction/Remove	0%	0%	0%	2%	2%
Mis-Fuel	30%	30%	30%	100%	100%

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 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 internal experience. We increased the HC emission effect of high fuel pressure to 10 percent 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 since this was the most significant type of tampering that occurred.

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 due to in the main body of the document in Table 11 (NOx), Table 17 (PM), and Table 20 (HC and CO).

HD OBD impacts

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

Specifically, we reduced our emissions increases for all pollutants due to tampering and mal-maintenance by 33 percent. As data are not yet available for heavy-duty trucks equipped with OBD, this number is probably a conservative estimate. Still, 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 phases in OBD implementation, that 33 percent of all engines will have OBD in 2010, 2011, and 2012 model years, and 100 percent will have OBD by 2013 model year and later. Equation 31 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 30 to determine the emission rate for any age group.

$$TM_{pol} = TM_{pol,nonOBD}\left(1 - f_{OBD}\right) + 0.67 \cdot TM_{pol,nonOBD}\, f_{OBD} \qquad \textbf{Equation 31}$$

As data for current and future model years become available, we may consider refining these estimates and methodology.

A.3 Extended Idle Data Summary

Idle HC Rates (gram/hour) Summary

Program	Condition	# Samples	Mean HC Emiss Rate
1991-2006 Low Speed Idle, A/C Off - HDT			
McCormick, High Altitude, HDT	Low Idle, AC Off	12	10.2
WVU - 1991-2004	Low Idle, AC Off	48	9.5
Storey	Low Idle, AC Off	4	28
	Overall	**64**	**10.8**

1991-2006 High Speed Idle, A/C On - HDT			
Broderick UC Davis	High Idle, AC On	1	86
Storey	High Idle, AC On	4	48
	Overall	**5**	**55.6**

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

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

Idle CO Rates (gram/hour) Summary

Program	Condition	# Samples	Mean CO Emiss Rate
1991-2006 Low Speed Idle, A/C Off - HDT			
McCormick, High Altitude, HDT	Low Idle, AC Off	12	71
Calcagno	Low Idle, AC Off	27	37
WVU - 1991-2004	Low Idle, AC Off	48	23
Storey	Low Idle, AC Off	4	25
	Overall	**91**	**33.6**

1991-2006 High Speed Idle, A/C On - HDT			
Calcagno	High Idle, AC On	21	99
Broderick UC Davis	High Idle, AC On	1	190
Storey	High Idle, AC On	4	73
	Overall	**26**	**91.2**

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

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

Idle PM Rates (gram/hour) Summary

Program	Condition	# Samples	Mean PM Emiss Rate
1991-2006 Low Speed Idle, A/C Off - HDT			
McCormick, High Altitude, HDT	Low Idle, AC Off	12	1.8
Calcagno	Low Idle, AC Off	27	2.55
WVU - 1991-2004	Low Idle, AC Off	48	1.4
Storey	Low Idle, AC Off	4	1.3
	Overall	**91**	**1.8**

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

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

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

Idle Nox Rates (gram/hour) Summary

Program	Condition	# Samples	Mean NOX Emiss Rate
1991-2006 Low Speed Idle, A/C Off			
McCormick, High Altitude, HDT	Low RPM, AC Off	12	85
Lim, EPA	Low RPM, No access	12	109
Irick, Clean Air Tech & IdleAire		49	87
WVU - 1991-2004	Low RPM, AC Off	48	83
WVU, NCHRP		2	47
Tang, Metro NY, 1984-1999		33	81
Calcagno	Low RPM, AC Off	27	120
Broderick UC Davis	Low RPM, AC Off	1	104
Storey	Low RPM, AC Off	4	126
	Overall	**188**	**94**
1991-2006 High Speed Idle, A/C Off			
Lim, EPA CCD	High RPM, No access	5	169
Calcagno	High RPM, AC Off	21	164
	Overall	**26**	**165**
1991-2006 High Speed Idle, A/C On			
Lim, EPA CCD	High RPM, AC On	5	212
Broderick UC Davis	High RPM, AC On	1	240
Calcagno	High RPM, AC On	21	223
Storey	High RPM, AC On	4	262
	Overall	**31**	**227**

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

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

2007 Extended Idle Emissions calculation:

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

- 2010: 0.2 g/bhp-hr

Idle HC Rate Reduction = 1 - [(1/8 * 0.14 g/bhp-hr + 7/8 * 0.5 g/bhp-hr) / 0.5 g/bhp-hr] = 9%

Idle NOx Rate Reduction = 1 - [(1/8 * 0.2 g/bhp-hr + 7/8 * 5.0 g/bhp-hr) / 5.0 g/bhp-hr] = 12%

A.4 Developing PM emission rates for missing operating modes

In cases where an estimated rate could not be directly calculated from data, we imputed the missing value using a log-linear least-squares regression procedure. Regulatory class, model year group and speed class (0–25 mph, 25-50 mph and 50+ mph) were represented by dummy variables in the regression. The natural logarithm of emissions was regressed versus scaled tractive power (STP) to represent the operating mode bins. The regression assumed a constant slope versus STP for each regulatory class. Logarithmic transformation factors (mean square error of the regression squared / 2) were used to transform the regression results from a log based form to a linear form. Due to the huge number of individual second-by-second data points, all of the regression relationships were statistically significant at a high level (99% confident level). The table below shows the regression statistics, and the equation shows the form of the resulting regression equation.

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 9**, page 11).

A.5 Heavy-duty Diesel EC/PM Fraction Calculation

A.5.1 Introduction

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

The subsequent sections of the memo describe the following topics:

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

A.5.2 PERE for Heavy-duty Vehicles (PERE-HD) and Its Extensions

The Physical Emission Rate Estimator (PERE) is a model employed by EPA in early development of MOVES.[98] In particular, the MOVES team employed it in development of MOVES2004 to impute greenhouse gas emission rates for combinations of SourceBin and Operating Mode for which data was unavailable or of insufficient quality.

The underlying theory behind PERE and its comparison with measured fuel consumption data is described by Nam and Giannelli (2005).[98] Briefly, PERE estimates fuel consumption and emission rates on the basis of fundamental physical and mathematical relationships describing the road load that a vehicle meets when driving a particular speed trace. Accessory loads are handled by addition of an accessory power term. In the heavy-duty version of PERE (hereafter, "PERE-HD"), accessory loads were described by a single value.

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

A.5.2.1 PERE-HD Fleet-wide Average Emission Rate Estimator

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

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

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

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

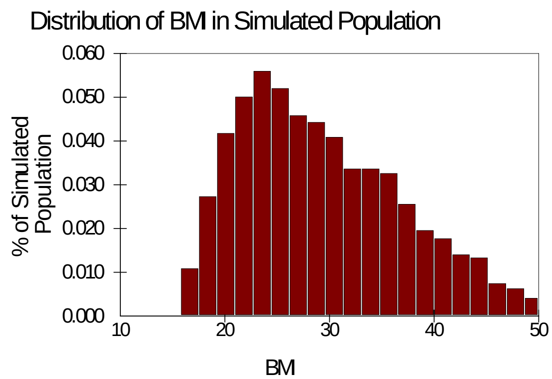
For the current application, PERE-HD (built within Microsoft Excel) was expanded to allow for a representative sample of [running weight] × [engine displacement] × [model year] combinations. A third-party add-on package to Excel, @Risk 4.5 (Palisade Corporation, 2004), allows users to supplement deterministic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

A.5.2.1.1 Monte Carlo Simulation in PERE-HD

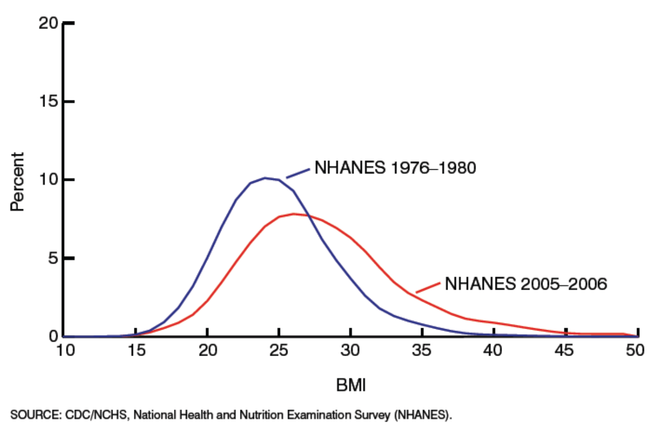
To illustrate how @Risk performs this process, we illustrate the application of a simple model, employing both deterministic calculations and stochastic Monte Carlo simulation:

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

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



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



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

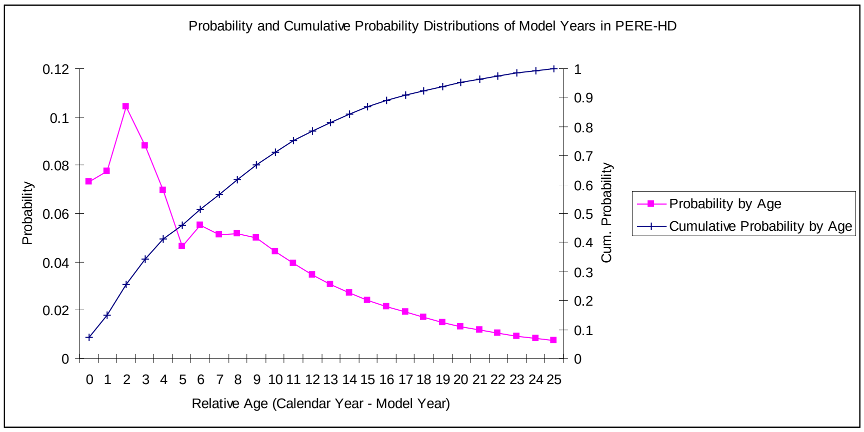
For emission modeling purposes using PERE-HD, several key inputs were modeled as probability distributions.

A.5.2.1.2 Model Year

Model year is an important factor in PERE, as the frictional losses in the model, expressed as "friction mean effective pressure" (FMEP), vary by model year, improving with later model years. As such, model year was simulated as a probability distribution, based on data from the Census Bureau's 1997 Vehicle Inventory and Use Survey (VIUS), which reports "vehicle miles traveled"

(VMT) by model year. Accordingly these data were normalized to total VMT to develop a probability distribution. Model year distributions in 1997 were normalized to the current calendar year (2008).[xx] For instance, the fraction of 1996 vehicles reported in the 1997 VIUS is treated as the fraction of 2002 vehicles in the 2003 calendar year. Although a 2002 VIUS is available, previous analyses (unpublished) have shown the "relative" model year distribution of trucks to have changed little between 1997 and 2002, though this assumption is one limitation of this analysis.

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

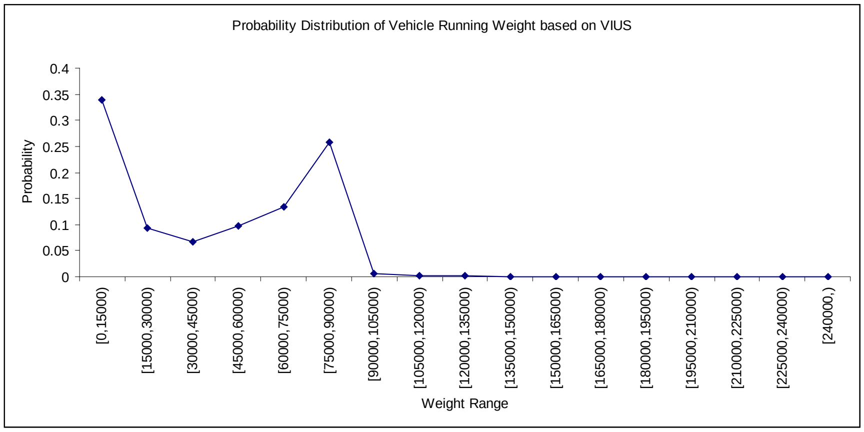


A.5.2.1.3 Vehicle Weight and Engine Displacement

Vehicle running weights and engine displacements were modeled as a two-way probability distribution with engine displacement depending on running weight. These data were derived from VIUS micro data obtained from the Census Bureau.[99] A two-way table was constructed to estimate VMT classified by combinations of [weight class] × [displacement class]. Analyses were restricted to diesel-powered trucks only.

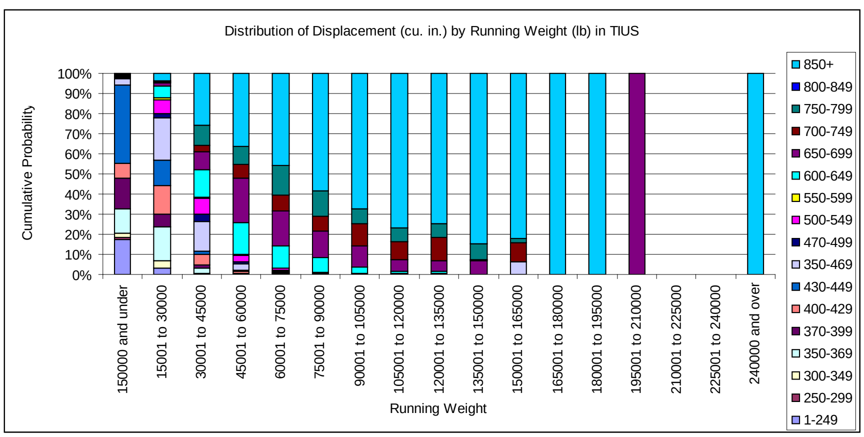
As a first step, @Risk selects a running weight from a probability distribution representing the fraction of truck VMT occurring at a given running weight:

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



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

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



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

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

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

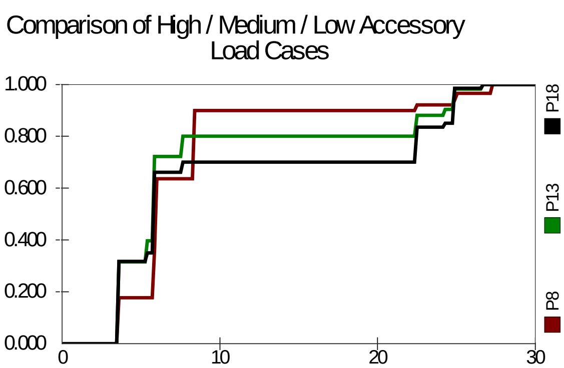
A.5.2.1.4 Accessory Load

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

Following the development of PERE-HD, a more detailed set of accessory load estimates was developed based on several accessories' power demand while in use and the fraction of time each accessory is in use (see Table 6).[100] High, medium, and low accessory use categories were estimated for three vehicle classes: HDT, MDT, and buses. For the current version of the model, only the HDT accessory load estimates were employed, though a sensitivity analysis indicated that mean EC/OM ratios were most sensitive to accessory load during idle and creep driving cycles. In the "base case," a mean ratio of 0.54 was predicted, while in the sensitivity case, a mean ratio of 0.50 was predicted. This issue may be revisited at some point, although the limited sensitivity of total results limits the importance of the accessory terms within the current exercise.

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

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



A.5.2.1.5 Driving Cycle

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

A.5.2.1.6 Other Factors

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

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

A.5.2.2 Prediction of Elemental Carbon and Organic Mass based on PERE-HD

A.5.2.2.1 Definition of Elemental and Organic Carbon and Organic Mass

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

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

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

A.5.2.2.2 EPA Carbon Analysis Techniques in Ambient Air

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

The different types of commonly used approaches for carbon include:

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

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

Among the available techniques, it has been a point of controversy among academics as to which method provides the “correct” carbon signal. Rather than addressing these arguments in detail, this analysis adopts the technique employed by the EPA ambient speciation monitoring network, TOR. Needless to say, different researchers employ different sampling, measurement and analysis techniques. Desert Research Institute (DRI) employed TOR in analyzing the Kansas City gasoline PM emission study samples[101] , while other prominent academics employ TOT, notably the University of California Riverside College of Engineering Center for Environmental Research and Technology (CE-CERT) and the University of Wisconsin-Madison (UWM) State Hygiene Laboratory. As research results from these groups is employed throughout this analysis, an inter-comparison of the methods of TOT/TOR is necessary to “recalibrate” various datasets with respect to each other.

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

The user community for MOVES is predominantly concerned with emissions that occur into ambient air. EPA regulations for demonstration of attainment of state implementation plans (SIPs) are based on monitored ambient particulate matter using Federal Reference Methods (FRM) for ambient air. FRM monitors for particle speciation in ambient air undergo analysis for EC and OC according to a defined standard operating procedure.[102] That standard operating procedure defines thermal/optical reflectance (TOR) as the desired method for analysis of ambient carbon PM.

A.5.2.2.3 TOR – TOR Calibration Curve

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

Briefly, the DOE study included emissions characterizations of 57 light-duty gasoline vehicles (LDGV) and 34 HD diesel vehicles (HDDV). The vehicles were operated on a number of different test cycles including cold-start and warm-start cycles. The data set employed in this study was generated by DRI and obtained from the DOE study web site.[103] Both EC and OC were analyzed using the same approach. All data from all vehicles were compiled.

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

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

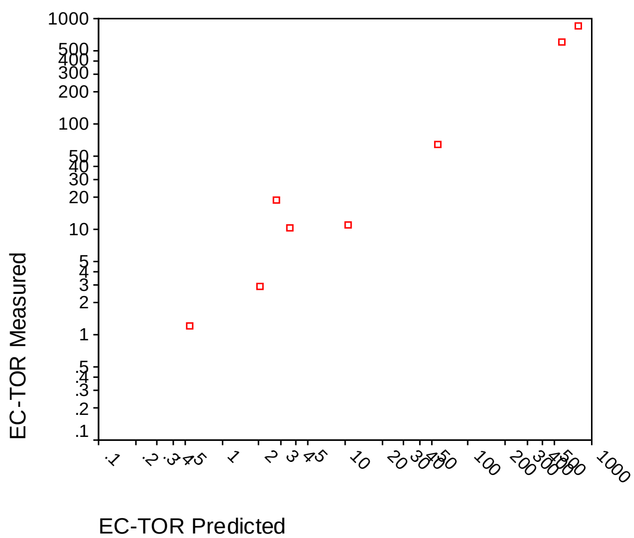
Third, those cases with RAND < 0.95 were regressed again, this time using an inverse uncertainty weighting procedure for each data point. When DRI analyzes a filter sample, it reports an analytical uncertainty associated with the primary estimate of EC and OC. Accordingly, the quality of each datum depends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

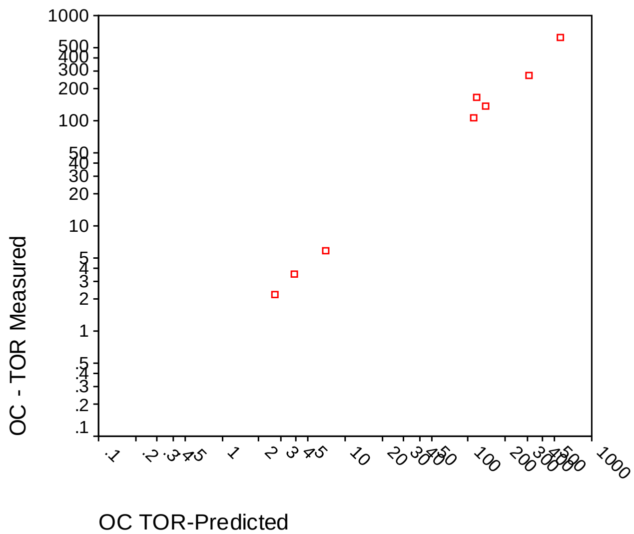
It should be noted that for each regression, the intercept term was set to zero. Models including intercepts did not have intercept terms that reached statistical significance. As such, R^2 values are not considered valid.

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

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

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





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

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

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

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

A.5.2.2.4 EC and OC Emission Rates

Selection of Engine Parameters for Predictive Modeling

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

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

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

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

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

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

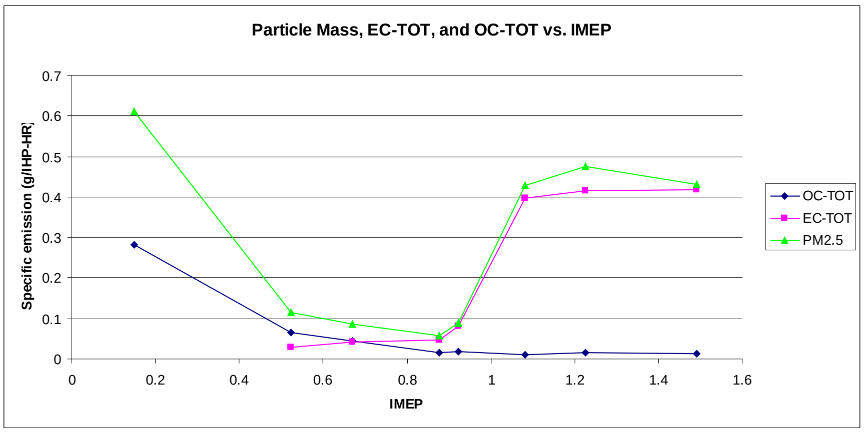
MEP can be broken into various components. "Indicated MEP" or IMEP refers to the sum of BMEP (brake MEP) and FMEP (friction MEP). Heywood (1988) writes that maximum BMEP is an indicator of good engine design and "essentially constant over a wide range of engine sizes.[cite]" Nam and Giannelli (2004) note that it can be related to fuel MEP multiplied by the indicated or thermal efficiency of an engine, and have developed trend lines in FMEP by model year. As such, since maximum BMEP is comparable across well-designed engines and FMEP can be well-predicted by Nam and Giannelli's trends within PERE, IMEP should be an appropriate metric for building an engine emission model that can be applied across vehicles with different loads and engine displacements.

Emission Data

Kweon et al. (2004) measured particle composition and mass emission rates from a single-cylinder research engine based on an in-line 2.333 liter turbo-charged direct-injection six cylinder Cummins N14-series engine, with a quiescent, shallow dish piston chamber and a quiescent combustion chamber. Emission data were obtained from all eight modes of the CARB 8-mode engine test cycle:

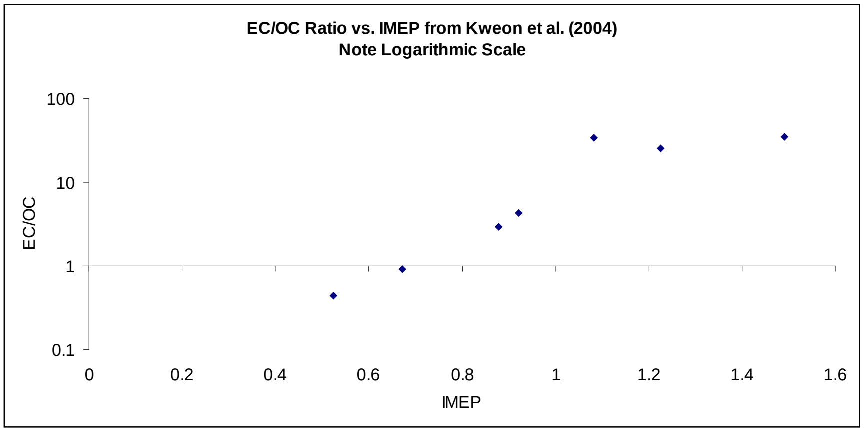
	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6	Mode 7	Mode 8
Speed	1800	1800	1800	1200	1200	1200	1200	700
Load%	100	75	50	25	100	75	50	10 (idle)
Equiv. Ratio (φ)	0.69	0.50	0.34	0.21	0.82	0.69	0.41	0.09
IMEP (MPa)	1.083	0.922	0.671	0.524	1.491	1.225	0.878	0.150

The study reports exhaust mass composition, including PM2.5, EC, and organic mass (OM, estimated as 1.2 x OC) measured with TOT (denoted here as EC-TOT and OC-TOT). In the main study, the authors report that EC and OC are highly sensitive to the equivalence ratio. However, IMEP is highly correlated with the measured equivalence ratio ($R^2 = 0.96$). As such, it is reasonable to report the data as a function of IMEP, expecting it to have approximately equal explanatory power as has the equivalence ratio variable. The figure below plots the emission data from Kweon et al. (2002) as a function of IMEP.



As shown in the figure, the EC-TOT work-specific emission rate is relatively insensitive to IMEP except between IMEP of approximately 0.85 and 1.1, where it undergoes a rapid increase. Overall, the EC-TOR/IMEP curve is S-shaped, similar to a logistic curve or growth curve. OC-TOT work-specific emissions are highest at low IMEP (i.e. idle) and are monotonically lower with higher IMEP. Total work-specific PM2.5 is not monotonic, but appears to be described by a single global minimum around IMEP ~ 0.9 and two local maxima around IMEP of 0.2 and 1.2, respectively.

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



Estimation of IMEP-based Emissions of EC and OC

To produce a relationship that generalizes the implied relationship between EC-TOT and OC-TOT work-specific emissions and IMEP in the data presented by Kweon et al. (2004), it is necessary to specify some functional form of a relationship between the two.

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

The functional form of the logistic-type curves fit to both the EC-TOT and OC-TOT data from Kweon et al. (2004) is as follows:

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

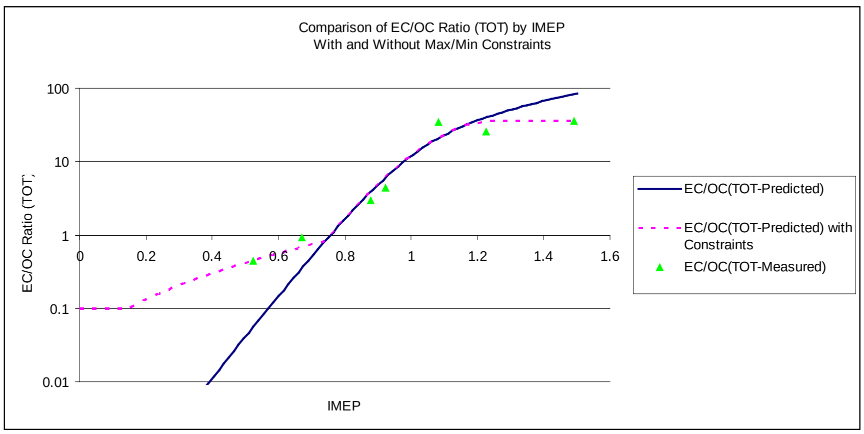
A least-squared error approach was implemented within Microsoft Excel to derive the coefficients for the logistic curves for EC-TOT and OC-TOT. The solutions to the fits are as follows:

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

Graphically, in comparison to observed values of EC-TOT and OC-TOT, the fitted curves result in predictions reasonably close to the observed values. Furthermore, when compared to the observed PM2.5 values, the sum of predicted EC-TOT and OC-TOT values predict the lack of monotonicity and patterns of maxima and minimum seen in the PM2.5 data.

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

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



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

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

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

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

Organic Carbon to Organic Mass Conversion

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

Heywood (1988) presents data on the chemical composition of diesel exhaust PM, presenting characterization of both the "extractable composition" and "dry soot" components of PM measured at idle and at 48 km/h.[104] The composition data is as follows:

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

The data for the "extractable composition" is assumed to represent the organic mass of particles. The total molar weight to carbon molar weight ratio was used to convert OC to OM. The idle data from Heywood were used when engine IMEP was 0.15 or under, corresponding to the idle mode of the cycle employed by Kweon et al. (2004). All other engine conditions employed the ratio based on the 48 km/h sample in Heywood.

A.5.3 Comparison of Predicted Emissions with Independent Measurements

To ensure that predicted EC and OC emission rates from this approach are reasonable prior to any application for MOVES, PERE-HD based EC and OC emission factors were compared with measured emission factors from an independent study. Shah et al. (2004) report EC and OC emission factor and rates for a series of heavy heavy-duty diesel trucks (HHDT) in California.[105] Shah et al. report the results of emission testing using the CE-CERT Mobile Emissions Laboratory (MEL), a 53-foot combination truck trailer containing a full-scale dilution tunnel designed to meet Code of Federal Register (CFR) requirements. The primary dilution tunnel is a full-flow constant volume sampler, with a double-wall insulated stainless steel snorkel that connects the MEL directly to the exhaust system of a diesel truck. PM collection systems were designed to meet 2007 CFR specification, including a secondary dilution system (SDS).

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

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

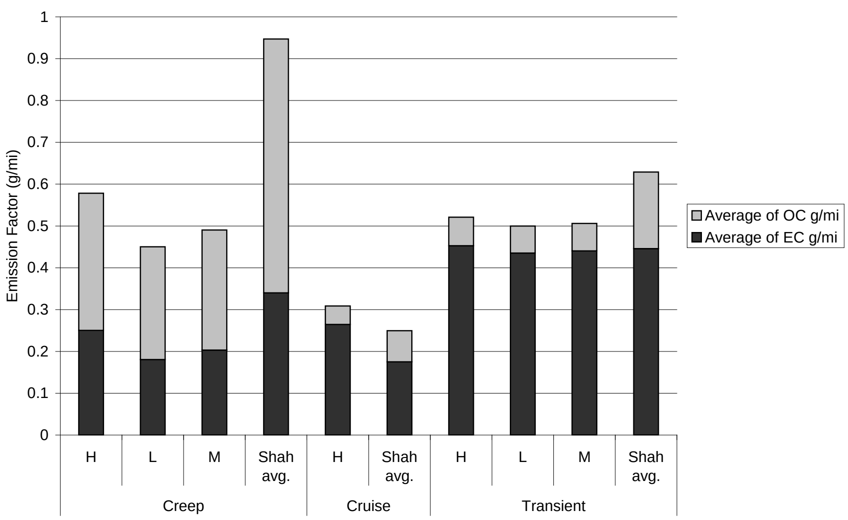
Cycle	Distance (mi)	Duration (s)	Average Speed (mph)	Maximum Speed (mph)	Maximum Acceleration (mph/s)
Cold start/idle	0	600	0	0	0
Creep	0.124	253	1.77	8.24	2.3
Transient	2.85	668	15.4	47.5	3.0
Cruise	23.1	2083	39.9	59.3	2.3

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

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

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

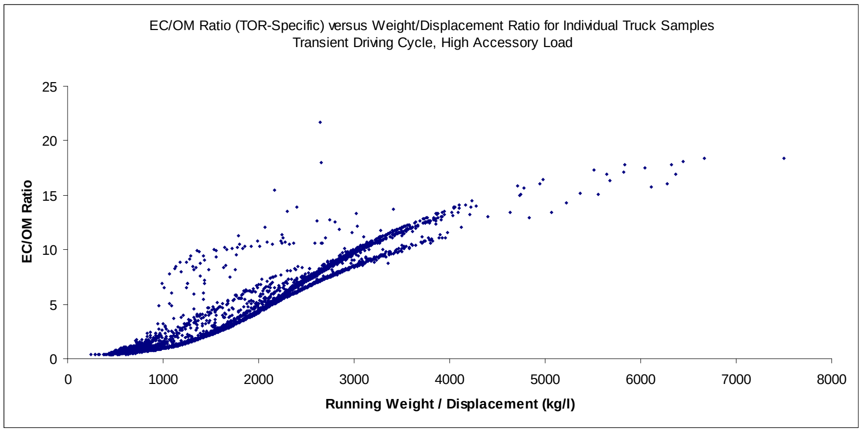
Predicted EC and OC Emission Factors(g/mi) vs. Measured Values in Shah et al. (2004)



A.5.4 Variability in Predicted EC and OC Emission Rates

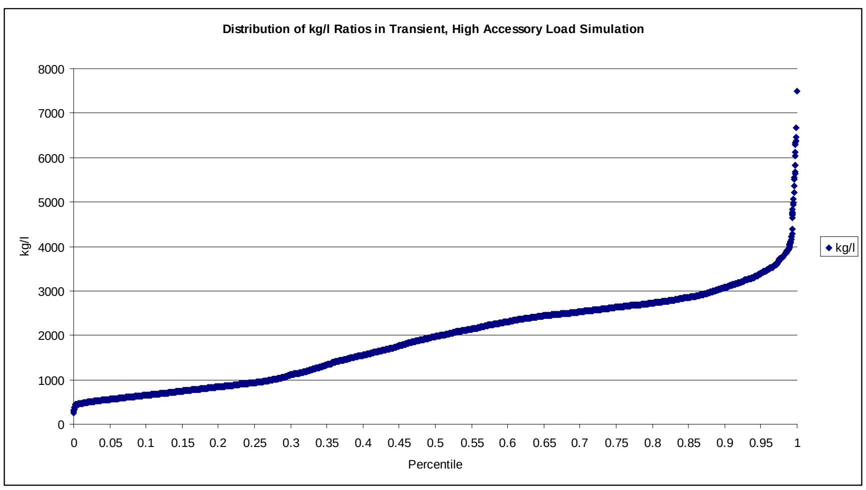
Through the modeling approach used here the influence of variability in vehicle weight and engine displacement on heavy-duty EC and OC emission rates can be assessed. It should be noted that these relationships are contingent on the particular algorithms employed in PERE-HD for estimating power and IMEP,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

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

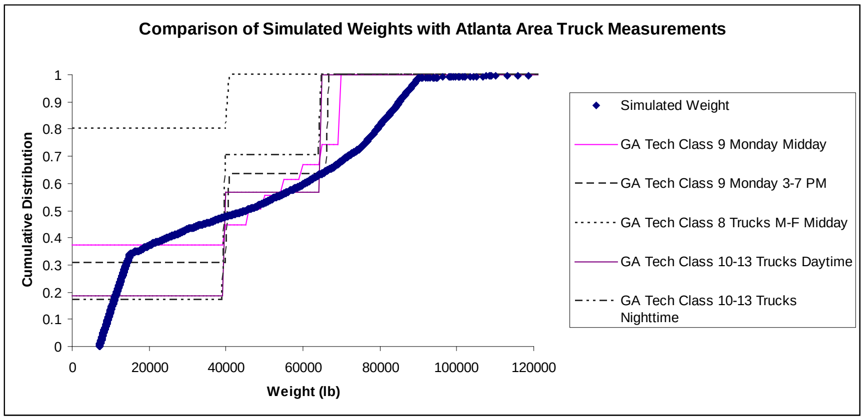


In general, these results reflect the role that running weight has on IMEP in a truck. Since IMEP correlates highly with the air/fuel ratio (or equivalence ratio φ), the data suggest that EC/OC partitioning is driven by the pyrolysis that occurs in engines under load.

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



For a 12 L engine, 3,000 kg/L would correspond to a running weight of 39600 kg (87,302 lb). Such vehicle loadings are infrequent, as they exceed Federal and state limits for vehicle weights on highways. The graph below presents the cumulative distribution of simulated weights, based on the VIUS microdata. Furthermore, the graph presents cumulative frequency distributions for several broad weight categories reported by Ahanotu (1999) for trucks in the Atlanta metropolitan area.[106] Note that in the graph, the highest weight category reported by Ahanotu (1999) is represented as 100%, although the actual maxima of observed trucks are unknown.



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

A.5.5 Calculating EC/OC fraction by Operating Mode

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

PM emissions contain additional inorganic species. However, the total carbon (TC =EC + OC) composes almost all the PM2.5 emissions from conventional diesel emissions. As such, we use the EC/TC as a surrogate for the EC/PM emissions in MOVES.

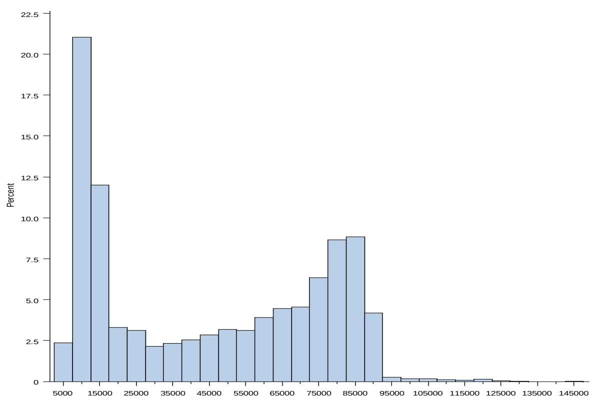
One of PERE's outputs for heavy-duty vehicles is the track road-load coefficients. For each individual weight in the distribution, PERE outputs a set of *A*/*B*/*C* coefficients similar to the ones used to calculate VSP in the HC, CO, and PM emission rate analysis. We used these coefficients and weights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

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

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

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

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



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

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

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

The resulting EC fractions by operating mode are shown in Figure 18 in the main body of this report.

A.6 Heavy-duty Gasoline Start Emissions Analysis Figures

Figure 60. Cold-Start Emissions (FTP, g) for Heavy-Duty Gasoline Vehicles, averaged by Model-year and Age Groups

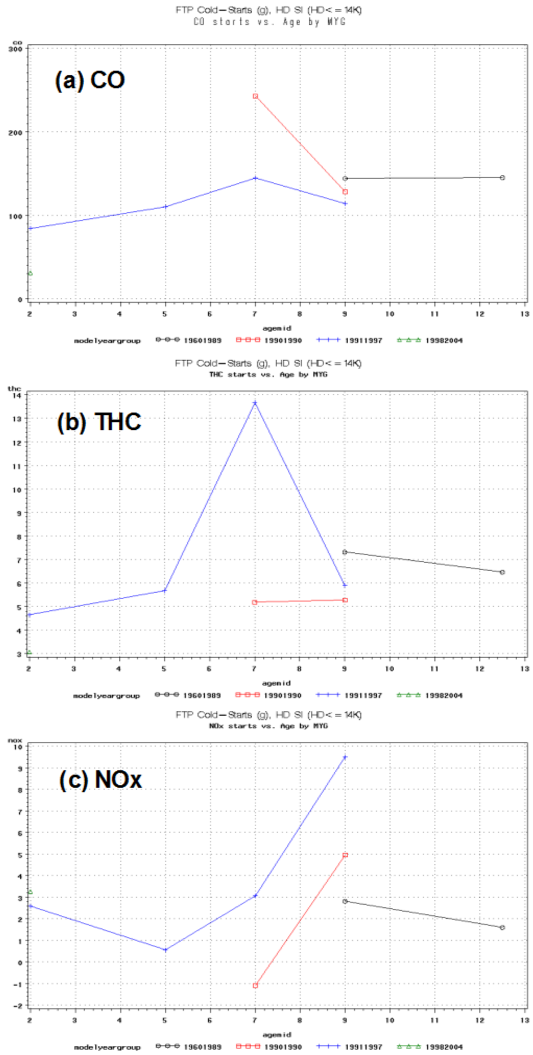


Figure 61. Cold-Start FTP Emissions for Heavy-Duty Gasoline Vehicles, GEOMETRIC MEANS by Model-year and Age Groups

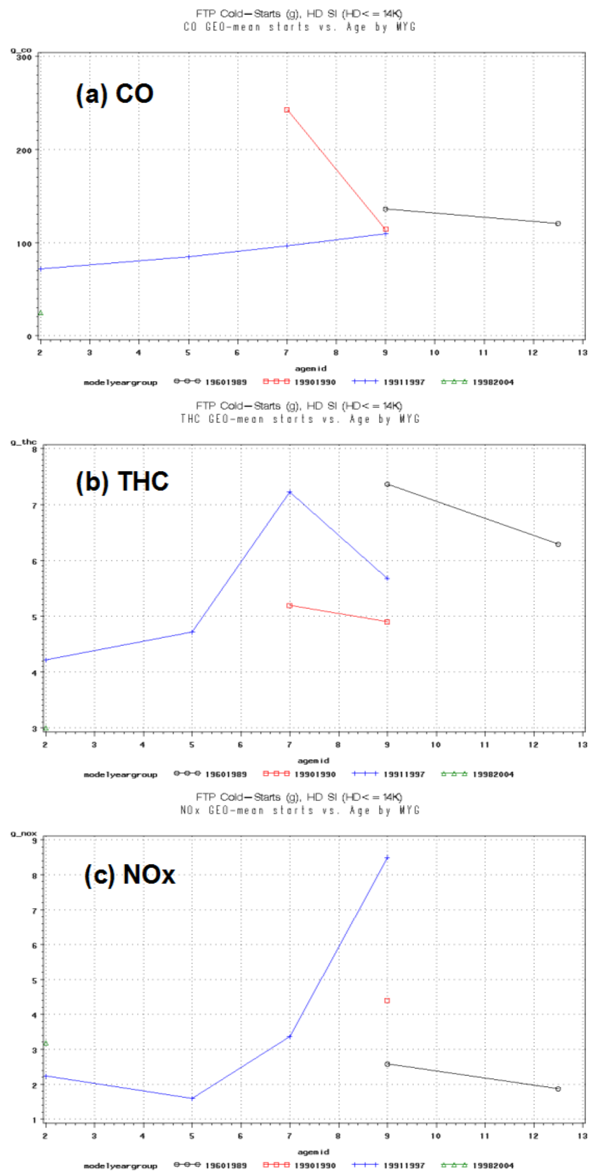


Figure 62. Cold-start FTP Emissions for Heavy-Duty Gasoline Trucks: LOGARITHMIC STANDARD DEVIATION by Model-year and Age Groups.

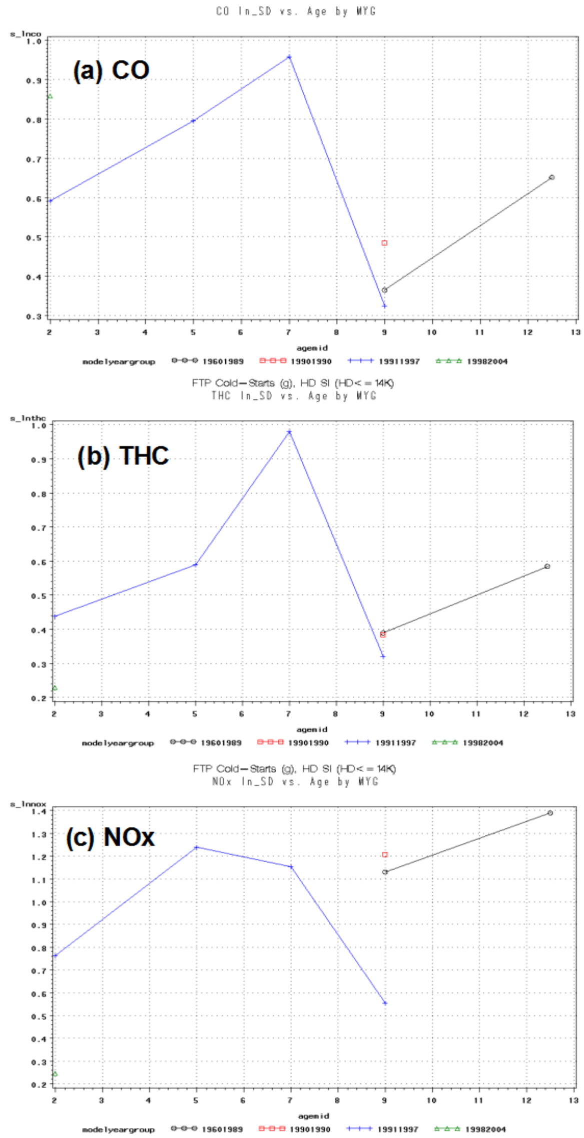


Figure 63. Cold-Start Emissions for Heavy-Duty Gasoline Trucks: RECALCULATED ARITHMETIC MEANS by Model-year and Age Groups.

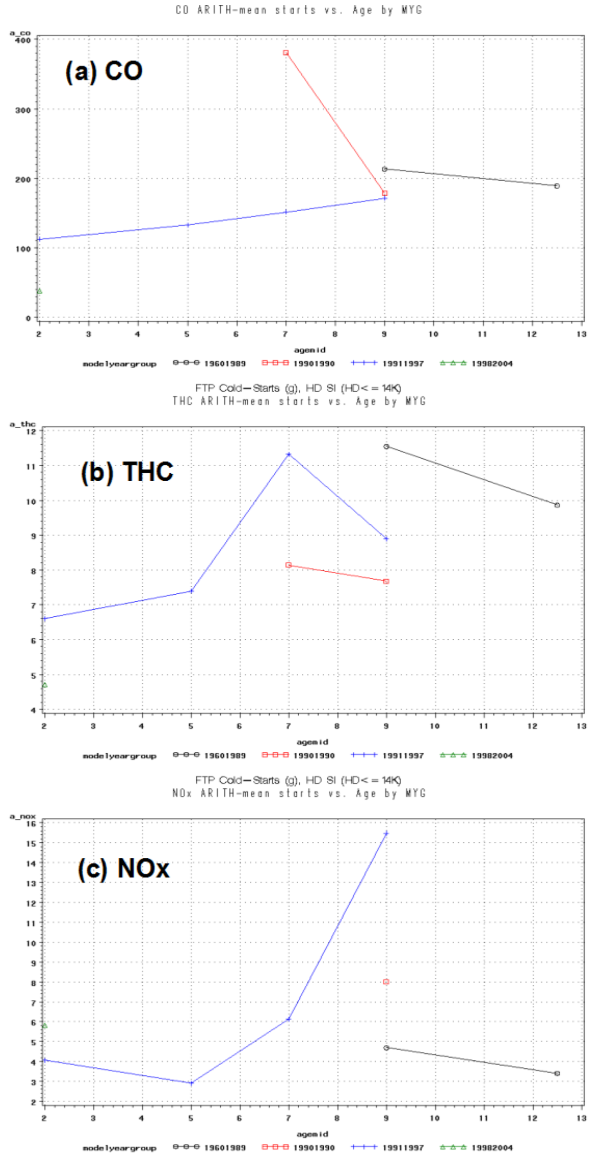


Table 62 - Emission Standards for Heavy-Duty Spark-Ignition On-road Engines

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

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